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Testing and specification for infrared (IR) optics for thermal imaging

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Abstract

The cost of Far Infrared Optics used in Night Vision Thermal Imaging Systems is an appreciable percentage of the total system cost. Testing and specification of these optical components can either increase or decrease the final cost of the system. The choice of test equipment and procedures as well as specification of unassembled elements are large factors in the cost of finished optical components. Through an understanding of the appropriate specification and a judicious choice of testing, quality Far Infrared Optics can be fabricated at reasonable cost.

Introduction

The development of night vision sights that operate in the Far Infrared portion of the spectrum, has forced Night Vision and Electro-Optics Laboratory to reevaluate its methods of specifying optics. The areas of concern were not limited to the formal government documents, such as purchase description and military specifications, but included manufacturing drawing notes, optical material specifications, and testing requirements. It is the desire of Night Vision and Electro-Optics Laboratory, in conjunction with its contractors, to develop meaningful optical requirements and specifications that insure quality at a minimum cost.

Testing of FIR Optics

When anyone starts to fabricate or test Far Infrared optics, the most obvious problem of not being able to see an image immediately dominates one's thinking. To make matters worse, one cannot see through the material to insure oneself that the optical path is unobstructed. The first reaction is to abandon previous knowledge, experience, and procedures, then panic. This is the wrong approach. One must remember that all the physical laws hold for non-visible optical systems and the testing and specification problems will diminish once one finds a technique to view the image.

The testing problem for Far Infrared optics is basically a problem of finding the right electronic equipment to suit your needs. At Night Vision and Electro-Optics Laboratory, the test facilities established to check optics is built around mini-computer controlled stepping tables. Mounted on the stepping tables are appropriate detectors for the various spectral regions of interest. This test facility is diagramed in figure 1. With the mini-computer in control, large number of samples on any line spread are quickly collected and displayed. Now the testing personnel must view the image by evaluating the measured line spread functions. The actual test facility is shown in figures 2 and 3.

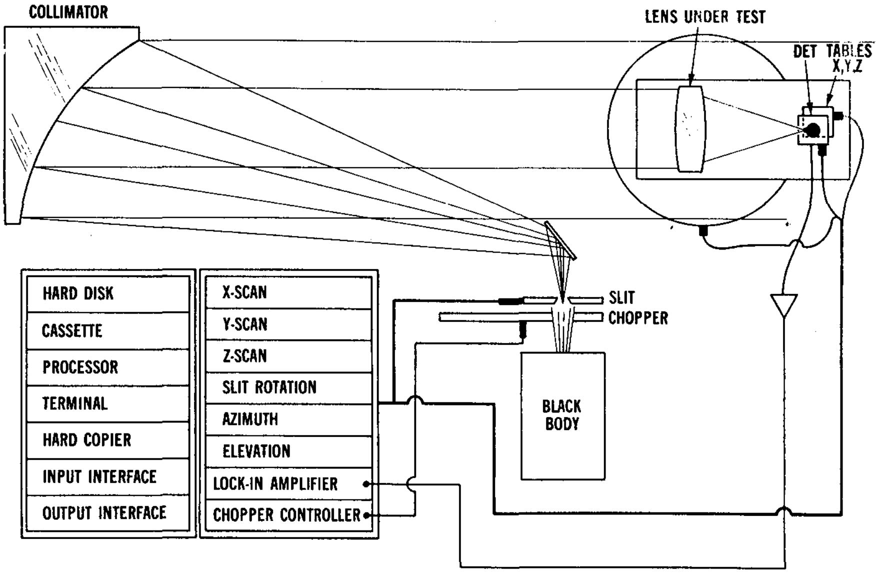

Fig. 1

Fig. 2

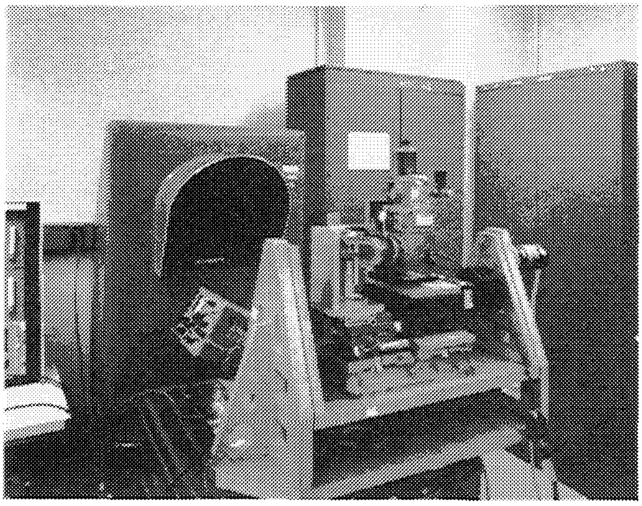

Fig. 3

An example of the type of data that can be collected on this test set will best illustrate the point of how test personnel must see the image. Consider the measurement of lens distortion; in this case, one wants to measure the change in effective focal length with field angle. One of several procedures that can be used is to load semi-field angles into the computer and have the test system locate the line spread function for each semi-field angle. Next, a table of image location versus semi-field angle is generated and the EFL for each semi-field angle is calculated. Sample results are shown in figure 4 generated from equation 1.

FIELD ANGLE DEGREES	DISTORTION X -	X+
0	0	
1	-.04660	.04660
2	-.09316	.09316
3	-.13962	.13962
4	-.18592	.18592
5	-.23192	.23192
6	-.27754	.27754
7	-.32264	.32664
8	-.36720	.36720
8.5	-.38915	.38915

$$\mathrm{EFL} = \frac{X+ - X-}{2 \tan 1^{\circ}}$$

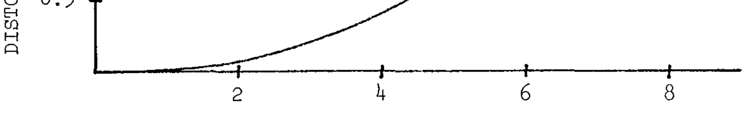

Fig. 4

$$\text{Distortion Percent} = \frac{((X+ - X-)/2) - \mathrm{EFL}\ \tan\ \theta}{\mathrm{EFL}\ \tan\ \theta} \times 100 \qquad (1)$$

A simple straight foreward routine, unless one asks what criteria of a line spread function, can be used to determine image location. Does one choose the peak of the function, halfway between the 50% or 1/3 power points or some other criteria? Figure 5 illustrates some of the possible line spreads and the inaccuracy associated with the choice of position criteria. The point must be made that despite the criteria chosen, the change in lens distortion is not significant for Far Infrared Systems. The accuracy normally associated with aerial reconnaissance lenses is not achieved and, most likely, cannot be achieved. However, sufficient accuracy is present.

This illustration on how a specific parameter can be measured can also lead to other information. Again, consider the line spread functions shown in figure 5. Let's assume that all these line spread functions are for on-axis images. Curve A is representative of a good on-axis image, the kind we accept. Curve B

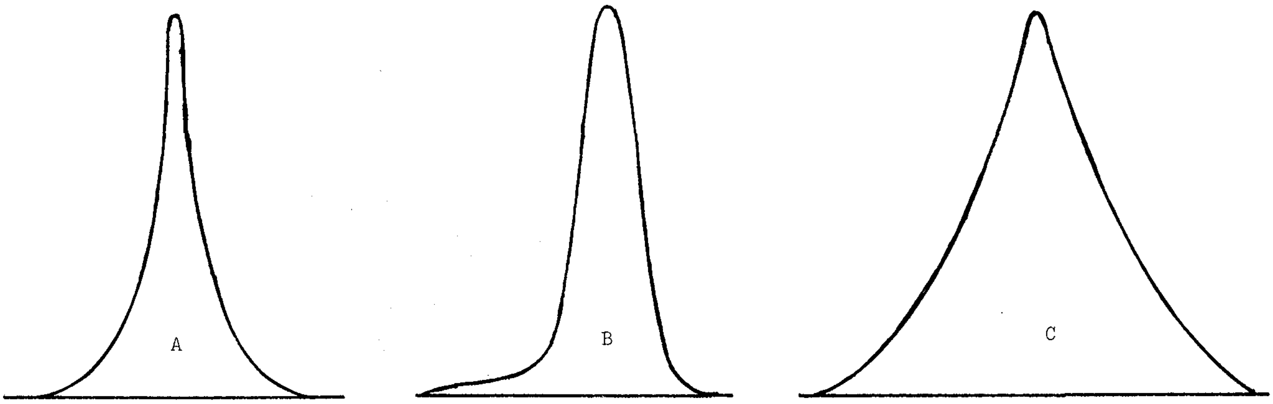

Fig. 5

is an indication that the elements are not assembled properly. Such a skewed line spread function can indicate element decentration or tilt. Curve C is a good example of what can happen to the image when an element is mounted backwards. Night Vision and Electro-Optics Laboratorys' experience in this area has been that technicians familiar with imperfections in visible optics will quickly learn to see these same lens defects in the measured line spread functions.

An area of concern associated with testing of optics in the Far Infrared region, is whether the lens is focused properly. Line spread function data from a non-focused image maybe misleading. The technique used at Night Vision and Electro-Optics Laboratory is to maximize the MTF at a given spatial frequency before any line spreads are displayed. The focusing subroutine utilized by the mini-computer takes advantage of the fact that through focus shift curves for an optical system are usually smooth functions. The subroutine evaluates the MTF in various focal planes and through a reduction in step size, the optimum focal plane can be automatically located. A more complete explanation of this subroutine will be presented in the MTF test discussion which follows.

The Far Infrared test facility presently in use was originally planned to do only MTF. However, during the concept development phase of the effort, it was determined that several other tests could be included for a little extra investment and hence, the test facility was proposed. The basic method used to measure MTF was to scan an analyser slit across the image of an object slit. This method, rather than a knife edge scan across a point, was chosen for electronic noise suppression. Disadavantages in this technique arise from the corrections that must be done to the measured data. The line spread functions must be either deconvoluted to account for the scanning slit and image slit sizes or the final MTF numbers must be corrected by the sinc function (sin X/X) for the two slits. The particular technique used is to divide the final MTF numbers by the two sinc functions. A major drawback to the chosen system is the size of the scanning slit that must be used. This scanning slit must sit in front of a finite size detector and pass energy in the spectral region of 8 to 12 microns. Choosing the size of this scanning slit raised several interesting discussions. Scanning slit size should be narrow so that f/1 lens system may be measured out to the diffraction limited spatial frequency cut off. However, the slit size cannot approach the dimensions of a single wavelength or diffraction will become dominate. Some diffraction is permissible provided the detector placed behind the slit is large enough and uniform to collect the diffracted waves. For the test set, a 2mm wide detector placed .1mm behind a 24 micron wide slit was selected. This provides a factor of 2 for 12 micron energy and the detector size and uniformity is sufficient to collect the diffracted rays. Of course, the 24 micron wide slit limits measurement of MTF out to 40 line pairs per millimeter.

MTF is calculated by the mini-computer by using a fast fourier transform on the measured line spread function. The fast fourier transform subroutine is based on the power of 2 reduction technique first developed by Cooley and Tukey. For this reason the number of data point collected for any analysis must be an integer power of two. The selection of the step size between points in the line spread function and the total number of points measured determine the spatial frequency range and points actually calculated in the MTF curve. To get to the spatial frequency step size the following formulas are used:

$$\text{Nyquest freq } F = 1/2\,\Delta x \tag{2}$$

$$2^n = \#\text{ points measured} \tag{3}$$

$$\Delta x = \text{step size} \tag{4}$$

$$\text{Spatial freq step size} = \Delta f - F/2^{(n-1)} \tag{5}$$

For example, the NV&EOL test set can use a step size as small as 1 E-5 inches and can fast fourier transform up to 1024 samples (2 to the tenth power). With this information, a table of sample point step size and frequency step size can be generated. Using the table, a test technician can determine the number of data points and the step size required to measure a lens over the spatial frequency range specified in a contract or purchase order. For an individual writting specifications for Far Infrared Lenses that will be measured using this technique it is important to specify the image distance to be scanned and the spatial frequency step size needed to insure quality lenses.

STEP SIZE	# POINTS	NYQUEST FREQUENCY	FREQUENCY STEP SIZE
1E-5 inches	512	1968.5 lp/mm	7.69 lp/mm
1E-5 "	1024	1968.5 lp/mm	3.84 lp/mm
2E-5 "	512	984.25 lp/mm	3.84 lp/mm
2E-5 "	1024	984.25 lp/mm	1.92 lp/mm
3E-5 "	512	656.2 lp/mm	2.56 lp/mm
3E-5 "	1024	656.2 lp/mm	1.28 lp/mm
4E-5 "	512	492.2 lp/mm	1.92 lp/mm
4E-5 "	1024	492.2 lp/mm	.96 lp/mm

NV&EOL normally use a step size of 3E-5 inches and take 1024 data points for its' measurements. Only 512 data points are used in the focusing subroutine.

As mentioned previously, the MTF focusing subroutine depends upon the through focus shift curve for the lens being a smooth function. A good way to explain the subroutine is to follow through the focusing of a lens. Assume that the lens has been prefocused manually so that in a scan of 512 steps a line spread function is obtained. Also assume one wants to focus the lens system for maximum response at 10 lp/mm. Consider now figure 6 which is a mini-flow diagram of the procedure. The first line spread function is measured and F.F.T.'ed at position Z1 and has a MTF at 10 lp/mm of M1. The focusing table moves a distance ΔZ and lets $Z2 = Z1 + \Delta Z$. Again a MTF is calculated at 10 lp/mm as M2. If $M1 = M2$ then simply start over at this new position. If $M1 \neq M2$, then it can only be at A or B as in graph 0 of figure 6. If $M2 > M1$ (option A) then one is moving uphill toward the peak. Therefore, one should take another step in the same direction to determine if the curve continues to increase. On the other hand, if $M2 < M1$ then one is moving down away from the peak. Therefore, one changes the sign of ΔZ (consequently direction), take two steps back, and obtain our third MTF point. At this point one relabels the points so that option B is the mirror image of option A and may use all the decision tries that option A uses.

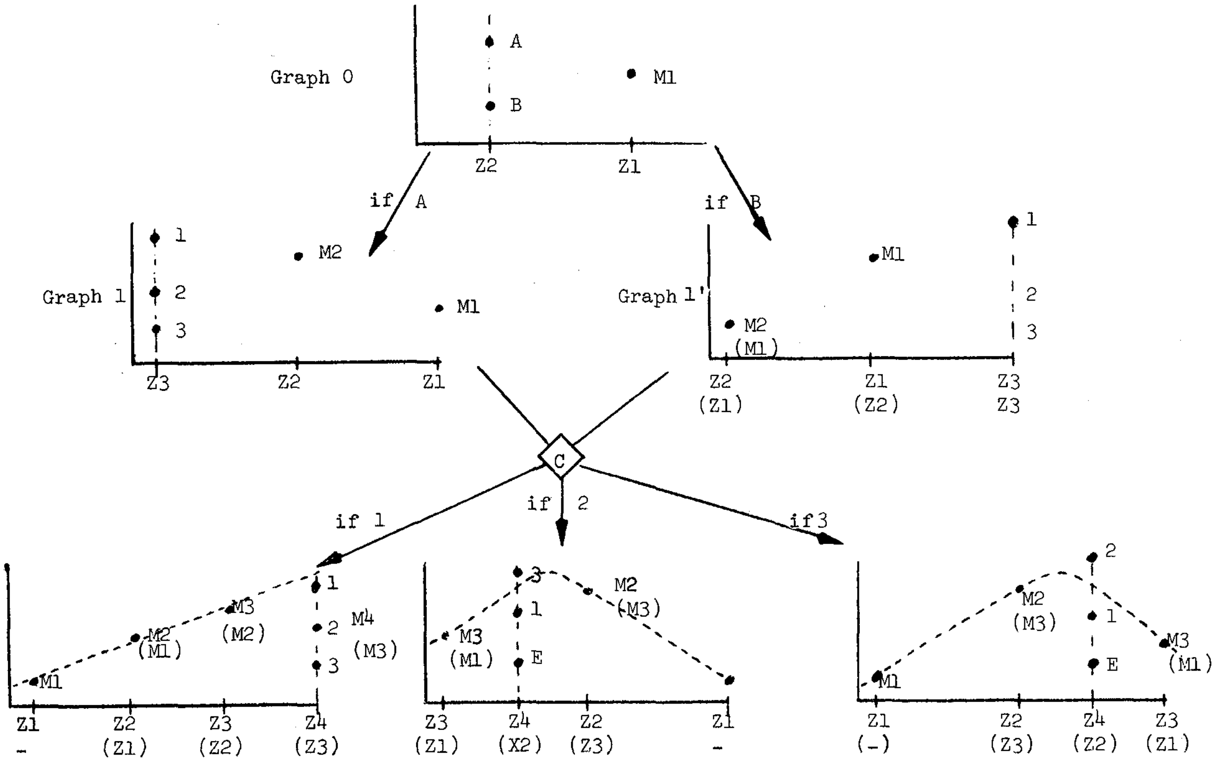

Fig. 6

From option A, or its mirror image, option B, there are three possibilities labeled 1, 2, and 3 in graph 1 and graph 1' in figure 6. (The possibility that two MTF values are exactly equal is about 32,000 to 1 and even in that event the subroutine will not get lost. It will just take longer. In this program, greater than is actually greater than or equal to). Decision point C is the next point to consider. If $M3 > M2 > M1$, one is not past the peak so take an additional step in the same direction marked M4 at Z4. After this relabel: M4 and Z4 as M3 and Z3; M3 and Z3 as M2 and Z2; M2 and Z2 as M1 and Z1; the original M1 and Z1 are dropped altogether and return to decision point C. In option 2, the MTF measured at Z3 falls between the MTF values measured at Z1 and Z2. If the through focus MTF curve is roughly symetrical and the spread in MTF values is sufficiently greater than the noise, then the peak of the through focus MTF curve should be between focus positions Z3 and Z2. The sign of the increment Δ Z is changed. The size of Δ Z is cut in half and the focal plane is moved the new Δ Z position placing the analyzing slit midway between focus positions Z3 and Z2. A new MTF value, M4, is measured and the focus positions relabeled as in graph 2' of figure 6. Again M1 and Z1 are dropped. At the end of each MTF measurement the detector slit is always moved to the relabeled Z3 position. There are three possible values for M4 measured at this new focal position and are shown in graph 2' as 1, 3, or E. The value E is below the other two values and is assumed to be in error and the MTF is taken again for the middle value. If, after the second MTF is taken for the middle value, it is still below the other two values the entire subroutine is aborted becasue of noise. The focal position is moved to the plane of highest MTF. Assuming option 1 or 3 appear, one checks to see if M1, M2, and M3 are within 2% or if Δ Z is below some specified step size (i.e., 8 microns). If either case is true then the focus subroutine is complete and control is returned to the main program. If neither case is true, return to decision point C. In option 3, the peak of the through focus MTF curve is assumed to be between position Z2 and Z1. Techniques are used that make option 3 a mirror of option 2 and thus the same decisions are used.

The final point that should be mentioned is the choise of black body temperature and detector response. Similar to the testing of visual lenses, it is important to test using the same detector response and source color temperature as the lense system sees in use. Most targets of interest to the military user are not much warmer or colder than ambient ($\simeq$ 273°K). Night Vision and Electro-Optics Laboratory has chosen to test our lenses at 300°K and the detector response is that of our common module detector. Since there are signal to noise advantages to using hotter sources ($\simeq$ 1000°C) in testing, it is interesting to consider what effect this hotter source will have. The following is a table of the diffraction limit performance for an f/1.8 lense system with a common detector and two different source color temperatures:

SPATIAL FREQUENCY	1273°K SOURCE	300°K SOURCE
4	91.5	91.5
8	83.0	82.3
12	74.6	73.5
16	66.3	64.9
20	58.2	56.5
24	50.3	48.3
28	39.0	36.7
32	31.9	29.4
36	28.5	25.9
40	22.0	19.5

This table shows the need to have an equivalent source temperature of 300°K. Running a source at only 300°K causes severe signal to noise ratio problems. Therefore, many people testing lenses use filters to alter the shape of the 1000°C source. Using this technique will reduce signal to noise problems and still measure the lenses properly.

Summary

This has been a small effort to relay some of the information gathered at Night Vision and Electro-Optics Laboratory in the testing of Far Infrared lenses. Once a person convinces himself that these lenses are the same as visual lenses and all the same rules apply, it is easy to conceive of new methods.