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Research Article

Athermalization of Optical Systems in Infrared

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Abstract

This paper will cover the design of an athermal lens mount for an infrared objective. This objective will need to be able to survive a space environment. It will experience large temperature changes and needs to remain in focus so imaging can occur continuously. The lens will image the earth through wavelengths of (3-5) micron. Normal optical glass does not transmit in this range so infrared glasses were used in the optical design. Infrared glasses tend to have high changes in refractive index under temperature changes and thus tend to cause defocus in infrared optical systems. So the athermalization becomes the difficult part and key factor in the designing of IR optical systems for working under temperature range of -20°C~60°C. ZEMAX will be used to determine the change in focus through the expected temperature changes in Earth orbit.

Keywords: *Athermalization, Optical Systems etc.*

1. Introduction

Athermalization is the principle of stabilizing the optical performance with respect to temperature. Any temperature changes experienced by the optics may be with respect to time or space or both. Time refers to a uniform heat soak across all the optics, and space refers to a gradient across the optics resulting in each lens (and housing) being a different temperature, or there being a radial change in temperature across an optic. A temperature increase will result in any or all of the following effects:

- Surface radii increase.
- Changing a spherical surface to an aspheric surface.
- Increase in the spacing between lenses.
- Increase or decrease of the refractive indices of the optics.
- Decrease in the refractive index of air.
- Strain on the optical elements resulting in warping.

The magnitude of temperature effects are controlled by the coefficients α and β. α Is the linear coefficient of thermal expansion (CTE) and is defined as:

$\alpha = 1/(L(dL/dT))$.

Where L is has the dimensions length and T temperature, and β is the thermal coefficient of refractive index and is defined as:

$\beta = dN/dT$.

Where N is the refractive index of transmitting material.

Both α and β are used to calculate the two thermo-optic coefficients (γ and δ) that determine the impact of temperature on lens performance.

Methods for quantifying and of setting affect the focus and image scale of an thermal optical system were described some time ago (J. W. Perry, 1943[1]), similar information being provided by several other authorities (D.Grey, 1948[2]; D.Volosov, 1958[3]), another paper describes the instrument thermal requirements, thermal design and analysis approach for the design process and analysis results(J.Rodriguez, 2000[4]), Schwertz Learn how developing an thermal optical system that is insensitive to an environment's thermal change and the resulting system defocus in the infrared system(K.Schwertz, 2013[5]).In this paper, A systematic approach for designing such lens system is presented . Specifically, the emphasis is placed on the doublet, triplet, and their variations are presented. The lens design principles, thermal criteria are considered simultaneously.

2. Athermal Conditions

2.1 Thermal Focus Shift of a Simple Lens

The rate of change of the power ϕ (reciprocal of the focal length f) of an optical element with temperature T can be derived by differentiating the thin lens power

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equation ϕ= c (n-1), where c is the total surface curvature of the element. For a linear thermal expansion coefficient a of the material from which the element is formed this gives (P.J.Rogers *et al*, 1995[6]):

$$As: f = \frac{1}{\phi} \quad \frac{\delta f}{\delta T} = -\frac{1}{\phi^2} . \frac{\delta \phi}{\delta T} \tag{1}$$

$$\frac{\delta \phi}{\delta T} = +\phi \left(\frac{\frac{\delta n}{\delta T}}{n-1} - \alpha \right) \tag{2}$$

$$Therefore\ : \frac{\delta f}{\delta T} = -f \left(\frac{\frac{\delta n}{\delta T}}{n-1} - \alpha \right) \tag{3}$$

The material-dependent factor inside the bracket in Eqs. (2) and (3) is known as the thermal "glass" constant (γ) and represents the thermal power change due to an optical material normalized to unit ϕ and unit change of T . Tables 1 give γ values for a selected number of infrared materials along with the relevant V value (Abbe number) and other data (P.J.Rogers *et al,* 1995[6]).

Optical materials indicates that thermal defocus (focus shift) is generally a much more serious problem in the infrared wavebands .The actual value of γ varies with both wavelength and temperature range due to variations in the value of δ n / δT and α . In general, this is unlikely to cause major problems unless a wide wavelength or temperature range is being considered (H.Köhler *et al*,1974[7]). Thermal defocus results not only from a change of optical power but also from the thermal expansion coefficient α_h of the housing. Equation (3) can be modified to allow for the effect of the latter:

Single thin lens: $\Delta f = -f.(\gamma + \alpha_h).\Delta T$ (4)

j thin lenses in contact: $\Delta f = -f.\left[f \sum_{i=1}^{j} (\gamma_i\, \phi_i + \alpha_h\right].\Delta T$ (5)

2.2 Optical Athermalization

The requirements of overall optical power, achromatism and athermalism demand that three conditions be satisfied for j thin lens elements in contact (J. T. Daiker, 2010[8]):

Power: $\sum_{i=1}^{j} \phi_i = \phi$ (6)

Achromatism: $\sum_{i=1}^{j} \frac{\phi_i}{V_I} = 0$ (7)

Athermalism: $\sum_{i=1}^{j} (\gamma_i\, \phi_i) + \phi \alpha_h = 0$ (8)

The presence of three conditions implies the need for three different materials in order to obtain an exact solution. It is possible, however, to find achromatic combinations of two materials that are also athermal, provided that a simple condition is satisfied (J. L. Rayces *et al*, 1990[9]):

$$V_1(\gamma_1 + \alpha_h) = V_2(\gamma_2 + \alpha_h) \tag{9}$$

Suitable combinations for thin-lens athermal achromats can be found by plotting a range of materials on a graph of γV against V , the slope of the line joining a chosen pair representing the required thermal expansion coef ficient of the housing *(*H.Köhler *et al,1974*[7]*)*.

A number of approximately athermal optical glass achromats exist of which those listed in Table1 with the exception of the last entry represent examples with low to moderate secondary spectrum over the visible to near infrared waveband *(*P. J. Rogers, *1992 b*[10]*)* . The data given for these achromats are: lens element total curvatures for unity focal length.

Table 1 Unity focal length athermal two –material achromatic combinations for the 3-5 micron Waveband

Material type	Material combination	Total curvatures	petzval sum	Normalized mass
materials	As2S3+Mgo	+0.7/-0.12	0.40	0.8
materials	Si+Ge	+0.71/-0.32	0.36	1.2

As shown in table 1, the infrared wavebands the options are far more limited : at least one in (3 – 5)micron waveband two-material a thermal combination exists , namely , arsenic trisulfide and magnesium oxide ,the other silicone and germanium .

Graphical methods have been described that allow investigation of preferred three material thermalized achromatic solutions (J. L. Rayces *et al*, 1990[9]).In Table 2, An alternative method is the systematic evaluation of all possible combinations of three materials selected from a short list , each combination being allocated a risk factor dependent on material characteristics and solution sensitivity (P. J. Rogers, 1990[11]).

Table 2 Unity Focal Length Three-Material Athermal Achromatic Combinations for the 3-5 micron Waveband

Material combination	Total curvatures	Petzval sum	Normalized mass
Si + Ge + ZnS	+0.72/−0.36/+0.27	0.39	1.3
ZnSe + Ge + MgO	+1.16/−0.21/−0.06	0.51	1.8
[Si + Ge + KRS5]	+0.69/−0.26/+0.08	0.34	1.0
ZnS + MgO + Ge	+1.28/−0.17/−0.16	0.52	1.5
AMTIR1 + Ge + Si	+0.56/−0.32/+0.46	0.42	1.4
Si + MgO + KRS5	+0.31/−0.08/+0.22	0.31	1.1
ZnSe + ZnS + Ge	+1.80/−0.69/−0.23	0.50	2.8
Si + CaF_2 + KRS5	+0.32/−0.25/+0.24	0.29	1.1

[ ] Low residual high-order chromatic aberration.
Source **:** From Rogers 1995.

The optical powers of the three in-contact thin-lens elements are determined by solving Eq. (6-8*)* which give for a unity focal length **(**P.J.Rogers *et al , 1995*[6]*)* :

$$\text{Given } a = \frac{V_1 V_2 - V_2 V_3}{V_1 V_3 - V_2 V_3} \quad \phi_3 = \frac{(1-b)\gamma_1 + b\gamma_2 + \alpha_h}{(1-a)\gamma_1 + a\gamma_2 - \gamma_3} \tag{10}$$

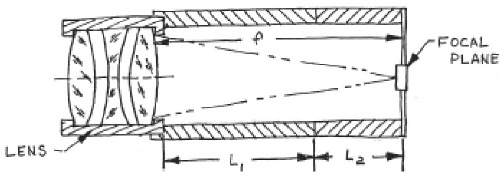
$$b = \frac{V_2}{V_2 - V_1} \qquad \phi_2 = b - a\phi_3 \tag{11}$$

$$\phi_1 = 1 - (\phi_2 + \phi_3) \tag{12}$$

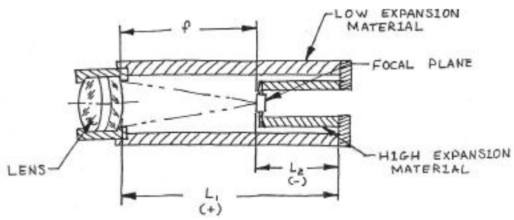
Tables 2 give a selection of lower-risk three-material solutions. Note that these tables are intended as a guide only and are based on currently available material data.

3. Result and discussion

In designing a lens thermal system, it is common to start with a known design form and to use familiar glass types. After the optical design evolves to a mature stage, then the mechanical structures are "wrapped around" the prescribed optics. IR optical system is much more appropriate to be applied in cluttered and formidable conditions. Two optical systems used ,consisted of two - three lenses with two -three kinds of material .All surfaces were sphere, which was easier to process test, making the cost inexpensive, and it could avoid using diffractive surface and aspheric surface. The infrared optical lens is designed by zemax; it meets the designing requirements and has good image quality. For example, Figure 1 shows the opto-mechanical designs suitable for athermalizing some already prescribed lens systems. In order to maintain focus over some temperature fluctuations, two structural materials with dissimilar CTE's and lengths are chosen to match the change in the focal length (P. Yoder *et al*, 2015[12]).



(a)



(b)

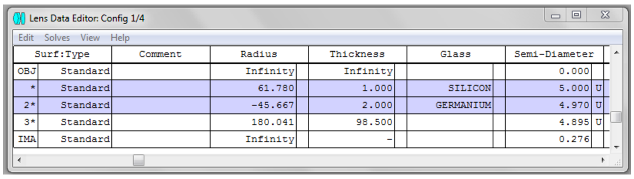
Fig. 1 Athermalizing a triplet and a doublet by matching (α1L1 ± α2L2) of the metering structure to the dF/dT of the lens systems

Ideally, one would like to use only one structural material, aluminum for example, for both mounting and athermalizing the optical system.

The thermal modeling capabilities in ZEMAX optical design software [download from: www.zemax.com], ZEMAX can model changes in refractive indices due to temperature changes and also the expansion/contraction of components.

Before doing any thermal modeling, we must make sure that all necessary operands affected by temperature change has been inserted in ZEMAX to make athermal design (J. T. Daiker, 2010[8]).

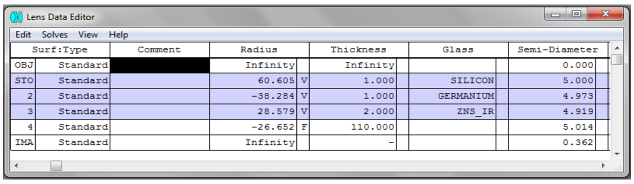
The optical design of this system was performed in ZEMAX from Table 1-2. It is a double/triplet type objective designed to image over wavelengths (3-5) microns .The lens prescription, optical layout, and performance data are given in Fig.2-4.



Lens Data Editor: Config 1/4

Surf	Type	Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		Infinity				0.000	
*	Standard		61.780		1.000		SILICON		5.000	U
2*	Standard		-45.667		2.000		GERMANIUM		4.970	U
3*	Standard		180.041		98.500				4.895	U
IMA	Standard		Infinity		-				0.276	

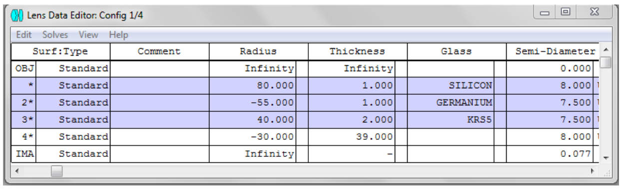
(a) Si-Ge



Lens Data Editor

Surf	Type	Comment	Radius		Thickness		Glass		Semi-Diameter	
OBJ	Standard		Infinity		Infinity				0.000	
STO	Standard		60.605	V	1.000		SILICON		5.000	
2	Standard		-38.284	V	1.000		GERMANIUM		4.973	
3	Standard		28.579	V	2.000		ZNS_IR		4.919	
4	Standard		-26.652	F	110.000				5.014	
IMA	Standard		Infinity		-				0.362	

(b) Si-Ge-Zns



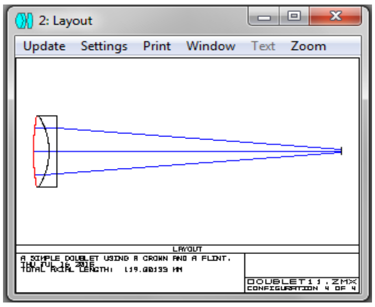
Lens Data Editor: Config 1/4

Surf	Type	Comment	Radius		Thickness		Glass		Semi-Diameter
OBJ	Standard		Infinity		Infinity				0.000
*	Standard		80.000		1.000		SILICON		8.000
2*	Standard		-55.000		1.000		GERMANIUM		7.500
3*	Standard		40.000		2.000		KRS5		7.500
4*	Standard		-30.000		39.000				8.000
IMA	Standard		Infinity		-				0.077

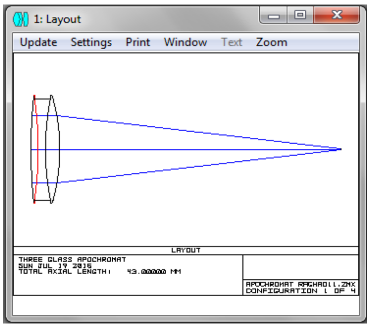
(c) Si-Ge-Krs5

Fig.2 Lens Prescription (units: inches) for double and triplet thermal design

The lens layout for double and triplet design in Fig.3.



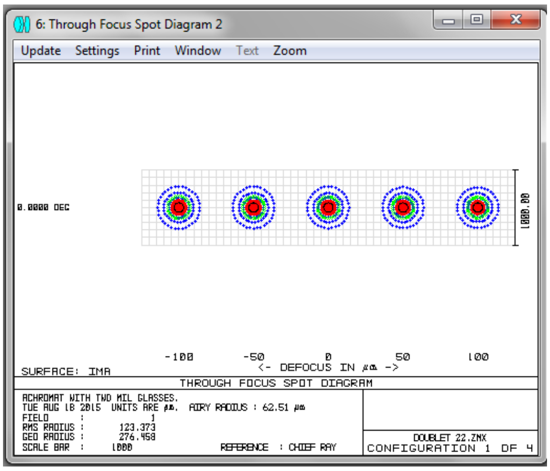
(a) double design



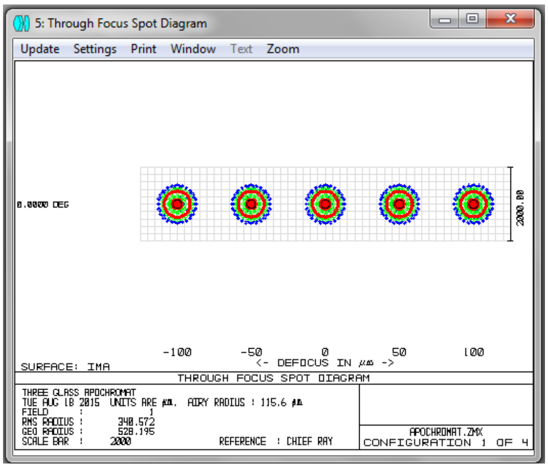
(b) Triple design

Fig.3 Optical Layout for athermal design

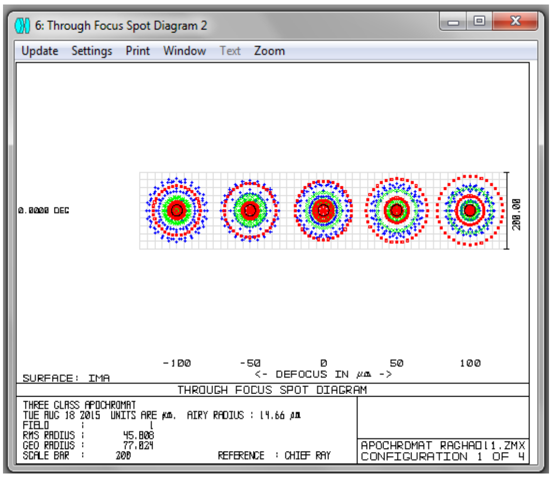
The important thing in athermal design is the RMS spot diagram, which shows that with refocusing, the optical performance holds up well over the field of view for extreme observing temperature. Blur sizes at -100^{0}C, 0^{0}C, and +100^{0}C (from left to right) shown in Fig .4.



(a) Si-Ge



(b)Si-Ge-Zns



(c) Znse-Ge-KRS5.

Fig.4 The spot diagram of a thermal design

The spot diagrams in Figure 4 show the improvement in lens performance over temperature when the lens is optimized over a temperature range, rather than just at one temperature, this report ,shows that Zemax's estimated RMS spot radius is now essentially constant over temperature, All spots are at best focus, this spots are for the athermalized lens.

Conclusion

Thermal optimization is a necessary part of optical and opto-mechanical design when any refractive optical system is to be stored and operated in a wide range of temperatures. A very sharp lens can be designed at one temperature, but it may or may not perform well when operated at significantly different temperatures, even at best focus. At extreme temperatures there is even risk for fractured or loose lens elements if thermal properties of the lens barrel are not accounted for. A lens intended for outdoor use should be optimized with full knowledge of all thermal variations for all materials employed. These thermal properties must be available and reliable for all materials used to give optimum a thermalization. The glasses used in this example lens all had thorough data for CTE and dn/dt available in the Zemax glass library, and the resulting lens would perform very well over temperature if built. A systematic design for athermalize a lens system with only one metal is presented. It is shown that the achromatic and apochromatic conditions can also be used to athermalize the lens system with the proper choice of the glass materials. The key lies in recognizing the relationships between the fractional lens power for the achromatic conditions and the opto-thermal expansion coefficient β. All possible glass combinations are "mindlessly" considered and the corresponding βsystem are calculated. Then search criteria are placed on these β system values for sorting and matching to the CTE of a desirable metal metering structure, aluminum for example.

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