Passive Athermalization of an Infrared Optical System

OPTI 521 Tutorial Report

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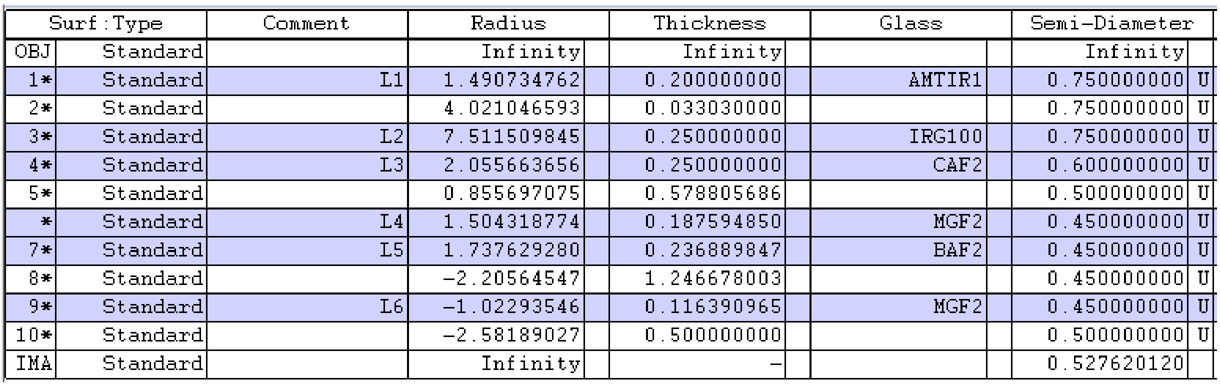
Introduction

This tutorial will cover the design of an athermal lens mount for an infrared double-Gauss 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 microns. 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. ZEMAX will be used to determine the change in focus through the expected temperature changes in Earth orbit. A lens mount composed of materials of differing coefficients of thermal expansion will then be designed to compensate the change in focus at the detector plane.

Optical Design

The optical design of this system was performed in ZEMAX. It is a double-Gauss type objective designed to image over wavelengths 3-5 microns. The lens has a total of 6 lens elements with 5 different glass types. The design also consists of two doublets that will be cemented together. The design covers a full field of view of 20 degrees and will cover a sensor with a 1 inch diagonal (0.707" x 0.707"). With an F/# of 3, the entrance pupil diameter is 1 inch and the effective focal length is 3 inches. This design can easily fit within a cube satellite that has dimensions 10 cm x 10 cm x 10 cm (4" x 4" x 4"). The lens prescription, optical layout, and performance data are given below.



Surf:Type		Comment	Radius	Thickness	Glass	Semi-Diameter	
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2*	Standard		4.021046593	0.033030000		0.750000000	U
3*	Standard	L2	7.511509845	0.250000000	IRG100	0.750000000	U
4*	Standard	L3	2.055663656	0.250000000	CAF2	0.600000000	U
5*	Standard		0.855697075	0.578805686		0.500000000	U
*	Standard	L4	1.504318774	0.187594850	MGF2	0.450000000	U
7*	Standard	L5	1.737629280	0.236889847	BAF2	0.450000000	U
8*	Standard		-2.20564547	1.246678003		0.450000000	U
9*	Standard	L6	-1.02293546	0.116390965	MGF2	0.450000000	U
10*	Standard		-2.58189027	0.500000000		0.500000000	U
IMA	Standard		Infinity	-		0.527620120	

Fig. 1 Lens Prescription (units: inches)

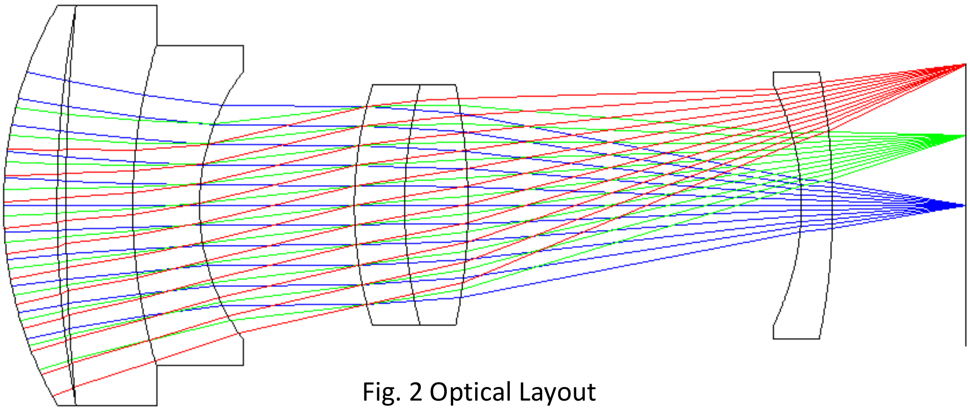
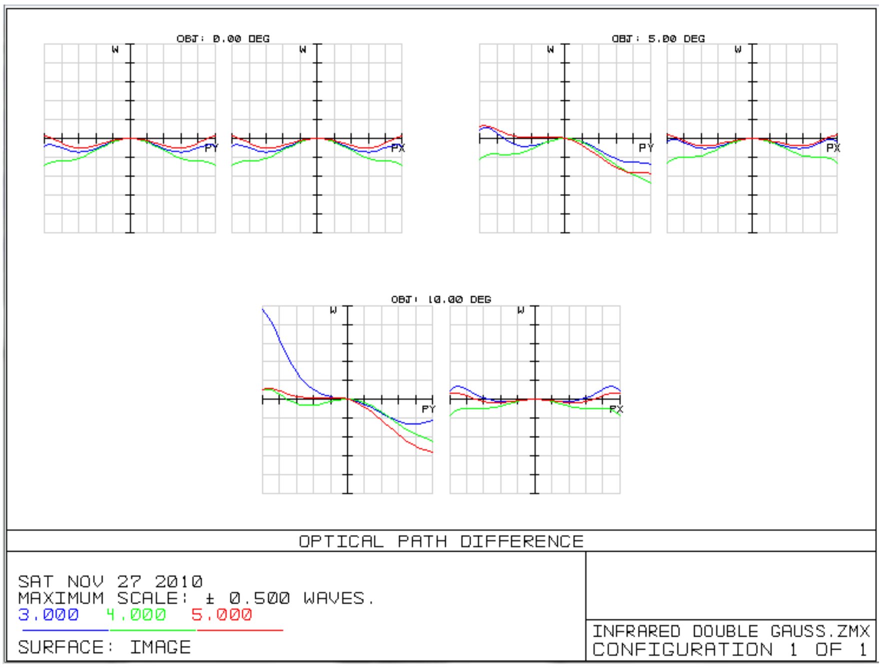


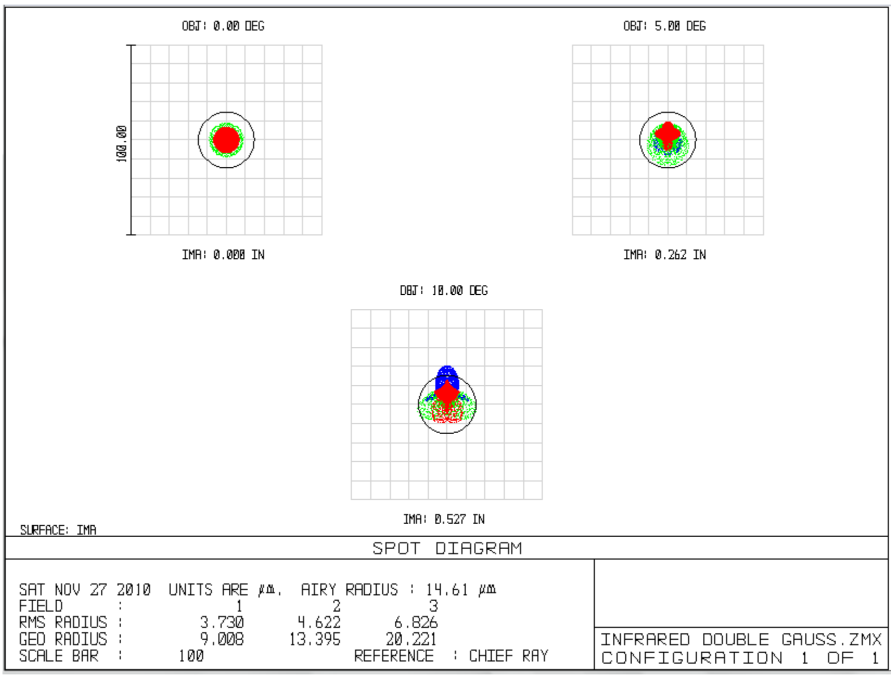
Fig. 2 Optical Layout



SAT NOV 27 2010
MAXIMUM SCALE: ± 0.500 WAVES.
3.000 4.000 5.000
SURFACE: IMAGE

INFRARED DOUBLE GAUSS.ZMX
CONFIGURATION 1 OF 1

Fig. 3 OPD Plots



SAT NOV 27 2010 UNITS ARE µm. AIRY RADIUS : 14.61 µm

FIELD :	1	2	3
RMS RADIUS :	3.730	4.622	6.826
GEO RADIUS :	9.008	13.395	20.221
SCALE BAR :	100	REFERENCE : CHIEF RAY	

INFRARED DOUBLE GAUSS.ZMX
CONFIGURATION 1 OF 1

Fig. 4 Spot Diagram

The black circle within the spot diagram is the diameter of the airy disk at a wavelength of 4 microns. Since most of the rays fall within this black circle, this system may be considered to be diffraction limited. The maximum RMS spot diameter is 13.65 microns at full-field and the minimum RMS spot diameter is 7.46 microns on-axis.

Lens Mount Design

The optical design is now transferred to Solidworks to design a simple lens mount. The material of choice for the lens mount is Aluminum 2024. As an initial design, the lens mount will be a simple barrel with retainer rings. Section views created in Solidworks of the lens mount are shown in Fig. 5 and Fig. 6.

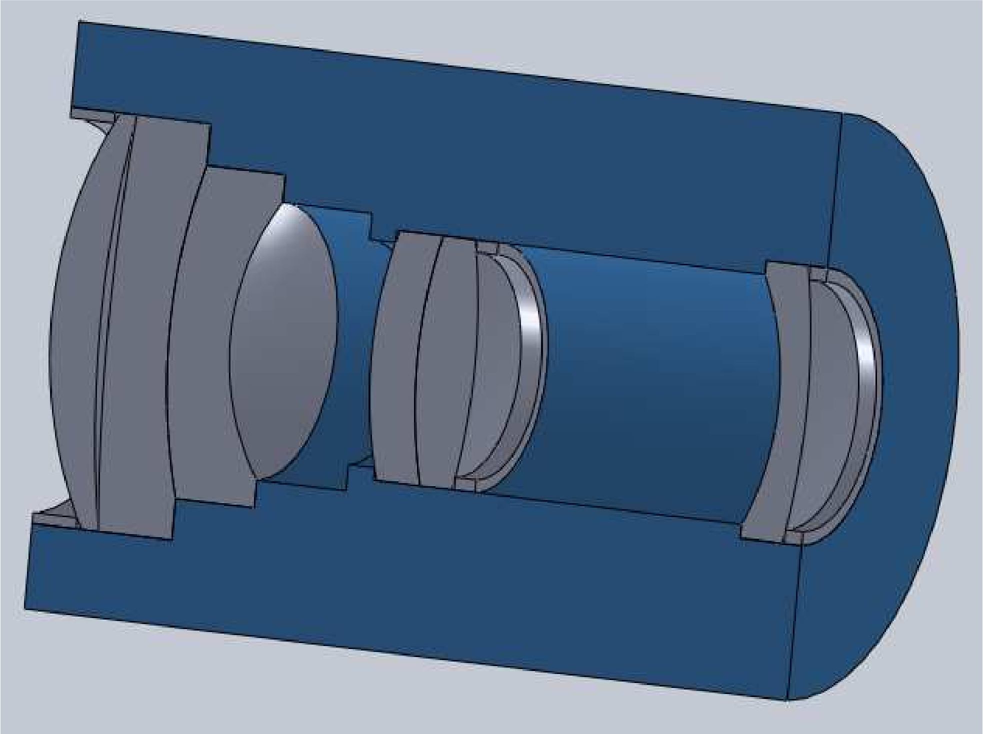


Fig. 5 3-D Shaded Section View

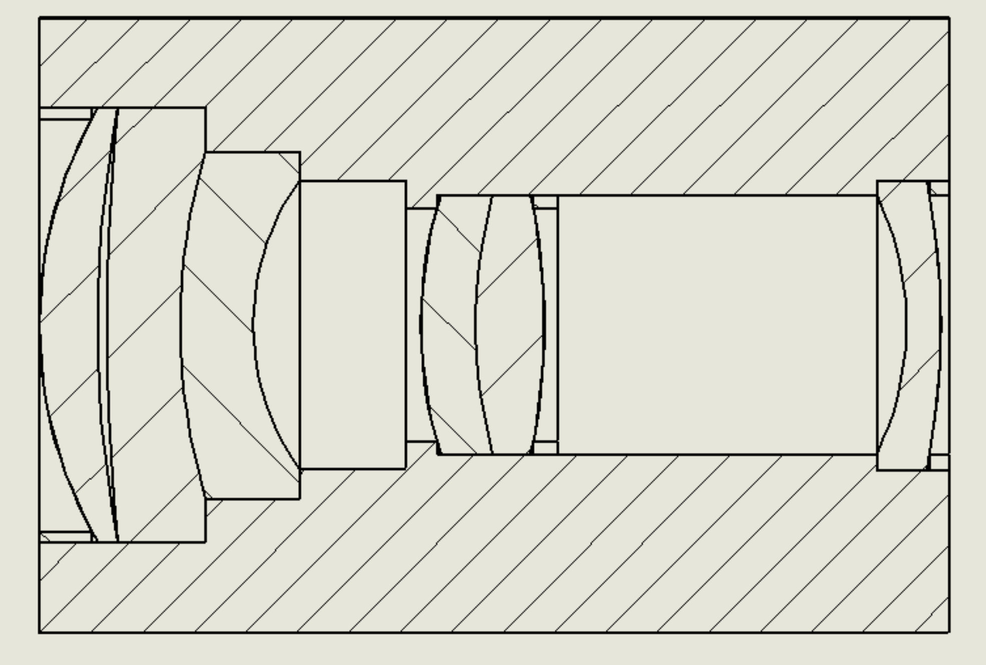
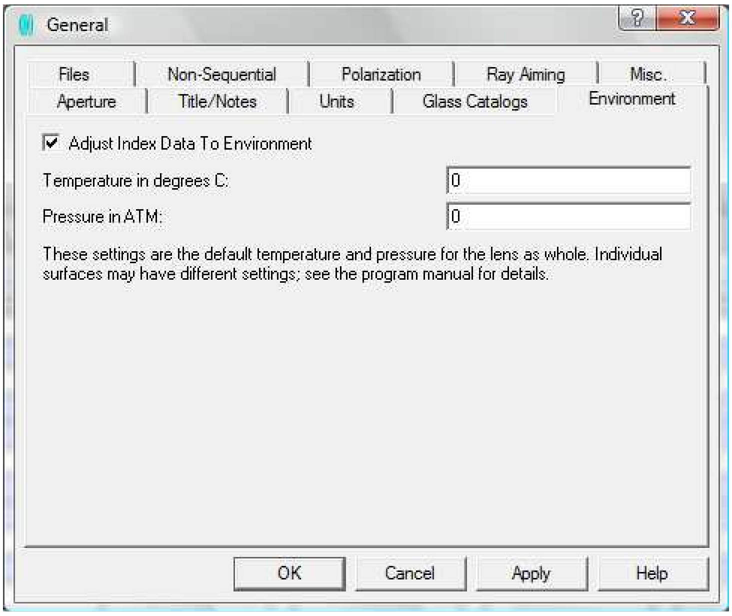


Fig. 6 Technical Drawing Section View

Thermal Analysis

A thermal analysis is performed in ZEMAX to determine the amount of defocus that will occur in a space environment. A few settings within ZEMAX need to be changed in order to make use of its thermal analysis features. First allow ZEMAX to adjust index data to the specified environment. This setting is under the general tab and is shown in Fig. 7. We will assume that the objective has a fixed focus optimized for a temperature of 0 °C and a pressure of 0 ATM.



☑ Adjust Index Data To Environment

Temperature in degrees C: 0

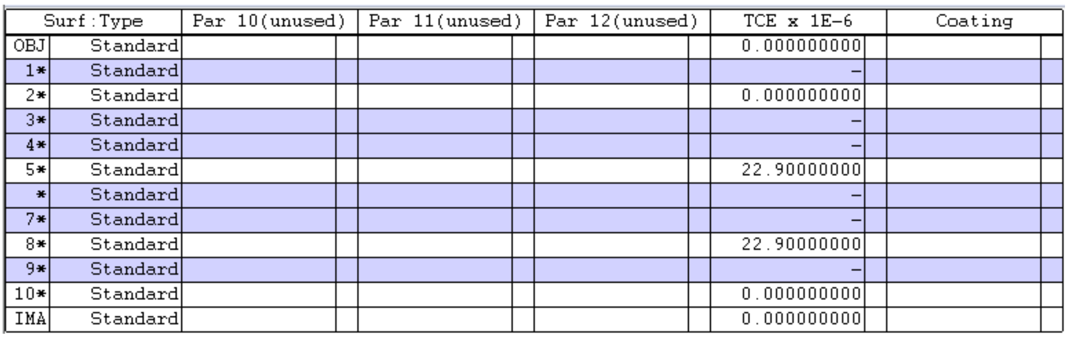
Pressure in ATM: 0

These settings are the default temperature and pressure for the lens as whole. Individual surfaces may have different settings; see the program manual for details.

Fig. 7 General Tab/ Environment

After this change, the performance of the objective degraded slightly due to the change in pressure and temperature. The back focal length is then re-optimized to achieve a minimum RMS spot size. The BFL changes from 0.5000” to 0.4985”. This provides the smallest RMS spot size at 0 °C and 0 ATM.

To simulate the expansion of the lens mount, the CTE’s of the airspaces between the lens elements are set to be equal to the CTE of aluminum 2024 ($\alpha = 22.9\ ppm/$°C). This data is entered into the Lens Data Editor on the far right side for the two large air spaces of the objective as shown in Fig. 8. The lens mount stops at the last element in this design so the CTE is left to be zero for the BFL airspace. A better approximation for the expansion of the lens mount would take into account the lens mount material around each lens element.



Surf:Type		Par 10(unused)	Par 11(unused)	Par 12(unused)	TCE x 1E-6	Coating
OBJ	Standard				0.000000000	
1*	Standard				–	
2*	Standard				0.000000000	
3*	Standard				–	
4*	Standard				–	
5*	Standard				22.90000000	
*	Standard				–	
7*	Standard				–	
8*	Standard				22.90000000	
9*	Standard				–	
10*	Standard				0.000000000	
IMA	Standard				0.000000000	

Fig. 8 Coefficient of thermal expansion of lens mount (Al 2024) in lens data editor

Large temperature changes will be expected for a space environment due to the objective entering and exiting the earth’s shadow. The equilibrium temperature of the imaging satellite will be a function of its thermal emissivity, radiation absorbtivity, and how much of the satellite is exposed to radiation. For our model, we will assume temperatures range from 0°C to 60°C.

The Multi-Configuration Editor within ZEMAX can be used to model the lens and mount over a temperature range. Thermal analysis is performed by choosing “Make Thermal” under the tools menu in the Multi-Configuration Editor as can be seen in Fig. 9.

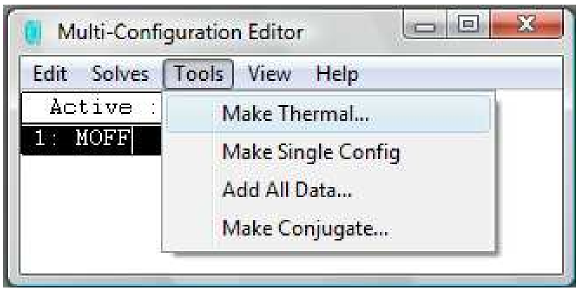
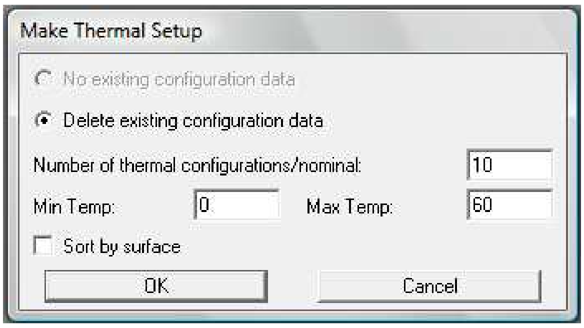


Fig. 9 Make Thermal

The Make Thermal Setup is filled out as shown in Fig. 10.


Make Thermal Setup

○ No existing configuration data

● Delete existing configuration data

Number of thermal configurations/nominal: 10

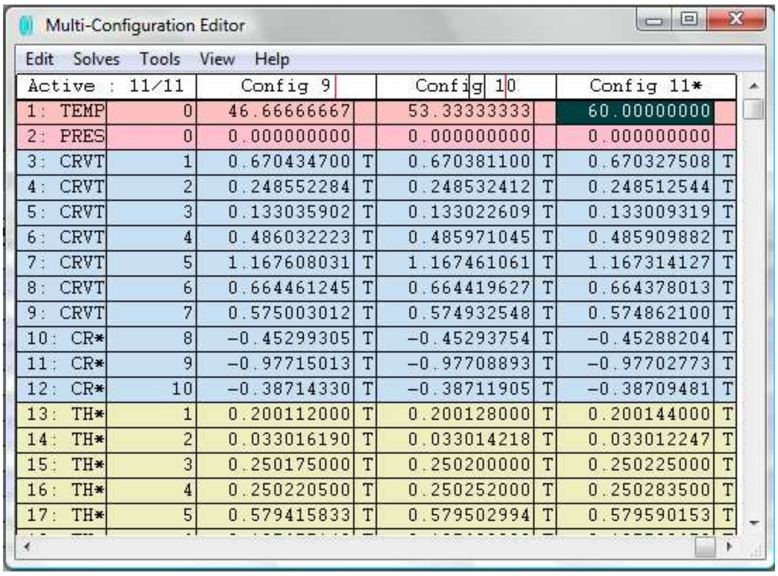
Min Temp: 0

Max Temp: 60

☐ Sort by surface

Fig. 10 Thermal Setup

ZEMAX produces 10 configurations ranging from 0°C to 60°C. Cycling through each configuration, it is possible to view the change in performance of the objective. Choose configuration 11 with a temperature of 60°C (Fig.11) and notice how all parameters change in the Lens Data Editor. Analysis of this configuration is performed by choosing “Make Single Config.” under the Tools Menu in the Multi-Configuration Editor. All parameters in the Lens Data Editor are now fixed.



Active : 11/11		Config 9		Config 10		Config 11*	
1: TEMP	0	46.66666667		53.33333333		60.00000000	
2: PRES	0	0.000000000		0.000000000		0.000000000	
3: CRVT	1	0.670434700	T	0.670381100	T	0.670327508	T
4: CRVT	2	0.248552284	T	0.248532412	T	0.248512544	T
5: CRVT	3	0.133035902	T	0.133022609	T	0.133009319	T
6: CRVT	4	0.486032223	T	0.485971045	T	0.485909882	T
7: CRVT	5	1.167608031	T	1.167461061	T	1.167314127	T
8: CRVT	6	0.664461245	T	0.664419627	T	0.664378013	T
9: CRVT	7	0.575003012	T	0.574932548	T	0.574862100	T
10: CR*	8	-0.45299305	T	-0.45293754	T	-0.45288204	T
11: CR*	9	-0.97715013	T	-0.97708893	T	-0.97702773	T
12: CR*	10	-0.38714330	T	-0.38711905	T	-0.38709481	T
13: TH*	1	0.200112000	T	0.200128000	T	0.200144000	T
14: TH*	2	0.033016190	T	0.033014218	T	0.033012247	T
15: TH*	3	0.250175000	T	0.250200000	T	0.250225000	T
16: TH*	4	0.250220500	T	0.250252000	T	0.250283500	T
17: TH*	5	0.579415833	T	0.579502994	T	0.579590153	T

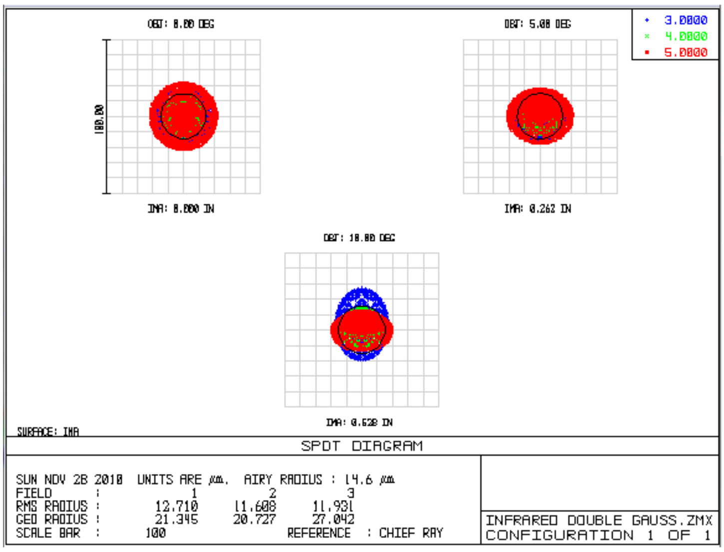
Fig. 11 Configuration 11 with 60°C temperature change

For this change in temperature of 60°C, the new spot diagram can be seen in Fig. 12. The objective is now slightly out of focus. The direction of focus shift can be seen from the rays intersecting the image plane in Fig. 13. As can be seen, the focus has shifted towards the objective. The amount of defocus can be measured by re-optimizing the back focal length to obtain a minimum RMS spot size. The change in back focal length is

$$\Delta BFL = BFL_{60°\mathrm{C}} - BFL_{0°\mathrm{C}} = \ 0.49495\text{- }0.49850\text{"=-}0.00355\text{"} = \ -90\ \mu\mathrm{m}$$

The depth of focus for diffraction limited performance of this objective at a wavelength of 4 µm is

$$\delta z = \pm 2\lambda (f/\#)^2 = \ \pm 72\ \mu\mathrm{m}$$



```
SUN NOV 28 2010  UNITS ARE µm.   AIRY RADIUS : 14.6 µm
FIELD      :          1          2          3
RMS RADIUS :     12.710     11.608     11.931
GEO RADIUS :     21.345     20.727     27.042
SCALE BAR  :    100                REFERENCE   : CHIEF RAY
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Fig. 12 Spot Diagram of Defocused Objective

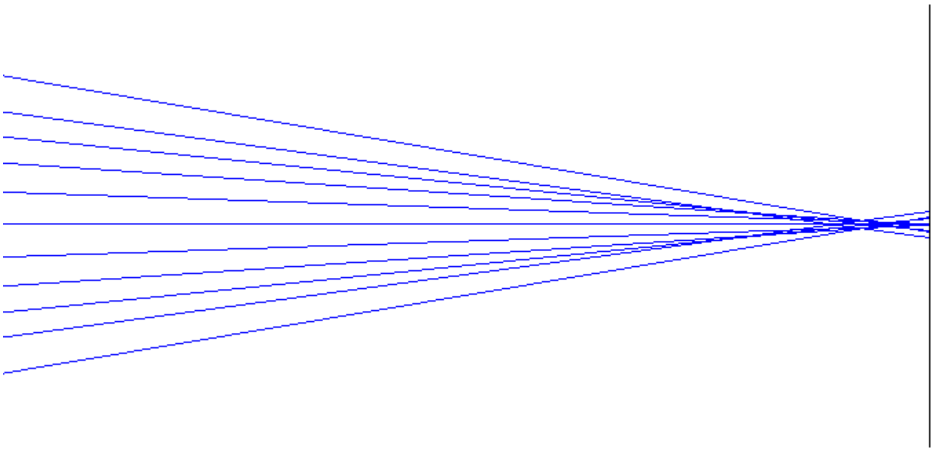

Fig. 13 Focus Shift Towards Objective

Passive Athermalization

Now that the change in BFL of the objective is known over a given temperature range, a mount can be designed to keep the objective in focus over the model temperature range. Since the focus point moved towards the objective, a mount that interfaces the objective to the detector plane will have to move the detector plane towards objective for an increase in temperature. This may be done by using a combination of low-expansion and high-expansion cylinders as shown in Fig. 14.

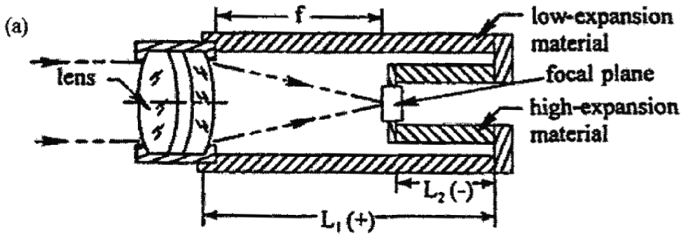

Fig. 14 Members of different CTE connected in opposition

The equations to design this structure are (see Appendix for derivation)

$$L_1 - L_2 = BFL_{0°C} = 0.49850"$$

$$|\Delta BFL| = \alpha_2 L_2 \Delta T - \alpha_1 L_1 \Delta T = \Delta T(\alpha_2 L_2 - \alpha_1 L_1) = 0.00355"$$

For the low expansion material, I chose Invar 36 and for the high expansion material I chose aluminum 6061.

$$\alpha_1 = 1.26 \frac{ppm}{°C} \ (Invar\ 36)$$

$$\alpha_2 = 23.6 \frac{ppm}{°C} \ (Al\ 6061)$$

Solving the above equations we find

$$L_2 = \frac{(0.00355") + \alpha_1 \Delta T (0.49850")}{\alpha_2 \Delta T - \alpha_1 \Delta T} = 2.6766"$$

$$L_1 = 0.49850" + L_2 = 3.1751"$$

These lengths are used to design an athermal detector interface in Solidworks. The design and its components are given in Fig. 15 and a technical drawing in Fig. 16.

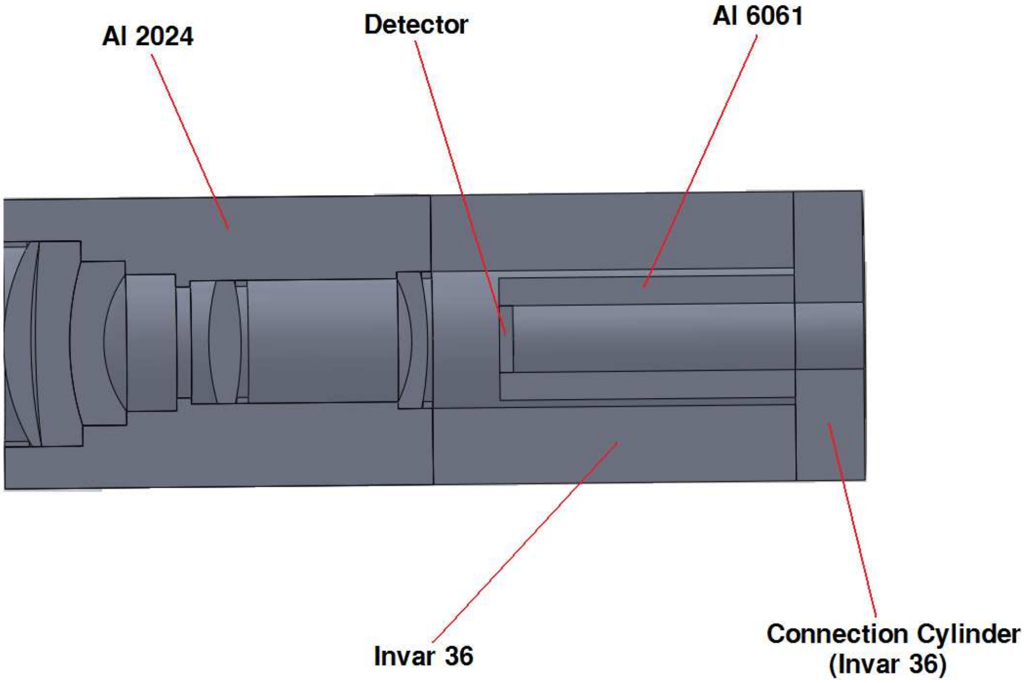

Fig. 15 Section View of Bi-metallic Compensator Mount

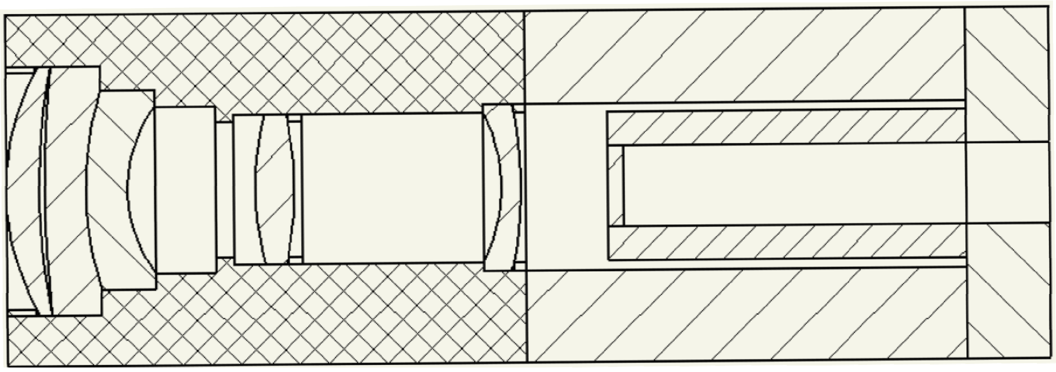

Fig. 16 Technical Drawing Section View

Conclusion

This tutorial covered the preliminary design of an athermal lens mount using Zemax and Solidworks. The mount was designed using two materials with differing CTE's. The differential expansion of these materials enables the detector plane to shift during a temperature change. For an increase in temperature, the back focal length of the objective decreases. Therefore the mount achieves passive athermalization by moving the detector plane closer to the objective for increasing temperatures.

Caution should be taken when using ZEMAX or Solidworks for thermal analysis. The index of refraction and CTE values provided by the programs are only valid over a specified range of temperatures. Independent verification of these values is highly recommended for actual applications. The verification of results given by ZEMAX should also be done through hand calculations and first order approximations.

Appendix A

Fig. 17 will be used to describe how this mount achieves passive athermalization. The length change of the Invar cylinder is described by

$$\Delta L_1 = L_1 \alpha_1 \Delta T$$

This is shown in Fig. 17 as “delta L1.” The length change of the Al 6061 cylinder is described by

$$\Delta L_2 = L_2 \alpha_2 \Delta T$$

This length change is greater than the length change of the Invar cylinder. From Fig. 17 , it can be seen that for the Al 6061 cylinder to move the detector plane closer to the objective by a distance of $|\Delta BFL|$, the following equation has to be satisfied

$$L_2 + |\Delta BFL| + \Delta L_1 = L_2 + \Delta L_2$$

$$L_2 + |\Delta BFL| + L_1 \alpha_1 \Delta T = L_2 + L_2 \alpha_2 \Delta T$$

$$|\Delta BFL| = \alpha_2 L_2 \Delta T - \alpha_1 L_1 \Delta T$$

Using this equation with $L_1 - L_2 = BFL_{0°\mathrm{C}} = 0.49850"$, we can solve for L_1 and L_2.

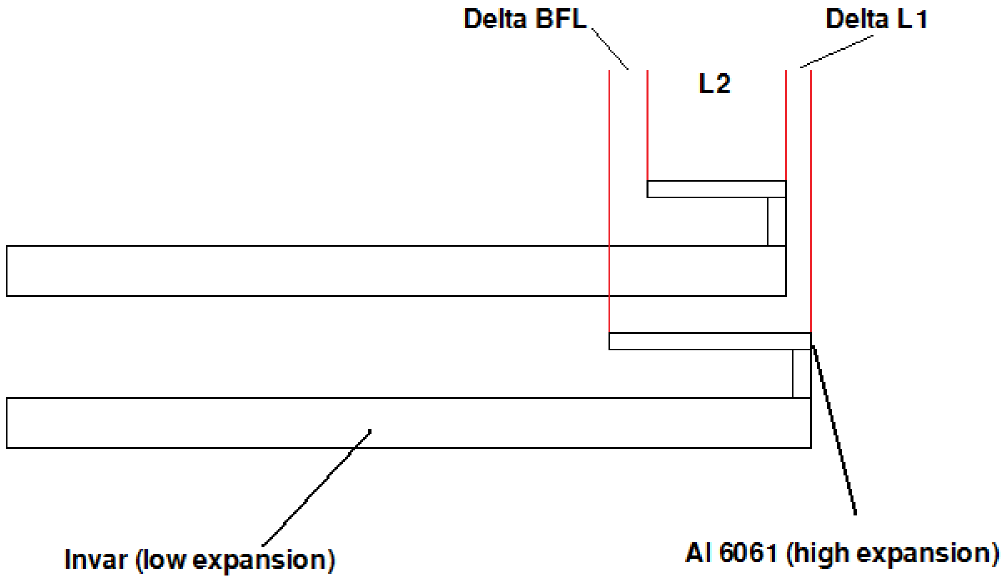

Fig. 17 Section of Invar and Al 6061 Cylinders

Appendix B

Glass Data

	Glass Type	CTE	dn/dT
Lens 1	AMTIR1	12 ppm/C	72 ppm/C
Lens2	IRG100	15 ppm/C	103 ppm/C
Lens3	CaF2	18.4 ppm/C	-10.4 ppm/C
Lens4	MgF2	9.4 ppm/C	0.88 ppm/C
Lens5	BaF2	18.4 ppm/C	-16 ppm/C
Lens6	MgF2	9.4 ppm/C	0.88 ppm/C

References

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