# ATHERMALIZATION TECHNIQUES IN INFRARED SYSTEMS

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OPTI 521

DECEMBER 6, 2010

## ABSTRACT

A major area of concern when designing infrared systems is the defocus with temperature change due to the nature of lens materials. This tutorial describes how this defocus affects the system performance and discusses some techniques for solving this problem. The key advantages and disadvantages of each technique are identified.

## INTRODUCTION

There is continued interest in developing high performance infrared (IR) systems which are capable of operating in harsh environments with extreme temperatures. The technique for maintaining focus of an IR system over an extended temperature range is called athermalization. The problem is quite challenging as most commonly used IR materials exhibit very large changes in refractive index with temperature, which inherently leads to changes in focal length of the system. Several techniques exist to control this effect and maintain acceptable focus over wide temperature ranges.

## EFFECT OF TEMPERATURE ON FOCUS

Considering the simple case of a single element thin lens, the change in focal length of the lens with temperature is given by

$$\Delta f = -\gamma f \Delta T = -\left(\frac{dn/dT}{n-1} - \alpha_L\right) f \Delta T$$

Where:

$\gamma$ = thermo-optical coefficient of the lens

dn/dT = refractive index change with temperature

n = refractive index of the lens

$\alpha_L$= thermal expansion coefficient (TCE) of the lens f = focal length of the lens

$\Delta T$ = temperature change

Further considering the simple case of this lens housing, the expansion of the housing with temperature is given by

$$\Delta L = \alpha_H L \Delta T$$

Where

$\alpha_H$= thermal expansion coefficient (TCE) of the housing

L = length of the housing

In the case of most IR materials $\gamma$ is positive and indicates a negative change in focal length with increasing temperature, while the housing expands, giving the total amount of defocus as

$$\Delta z = \Delta L - \Delta f$$

From aberration theory, the depth of focus for a diffraction limited imaging system ($\lambda/4$) is given by

$$\Delta z = \pm 2\lambda (F/\#)^2$$

Where

F/# = f/D (focal length/clear aperture diameter)

Combining the above gives the tolerable temperature change for a single element thin lens

$$\Delta T = \pm \frac{2\lambda (F/\#)}{D(\alpha_H + \gamma)}$$

As an example, consider a 200mm F/2 Germanium lens in an aluminum housing operating at $\lambda = 10$ microns. With $\gamma = 130$E-06, and $\alpha_H$= 23E-06, the tolerable temperature difference before the thermal defocus becomes unacceptable is only 2.6°C. Clearly this severely limits the applications for which the system can be used. Figure 1 quantifies this relationship further.

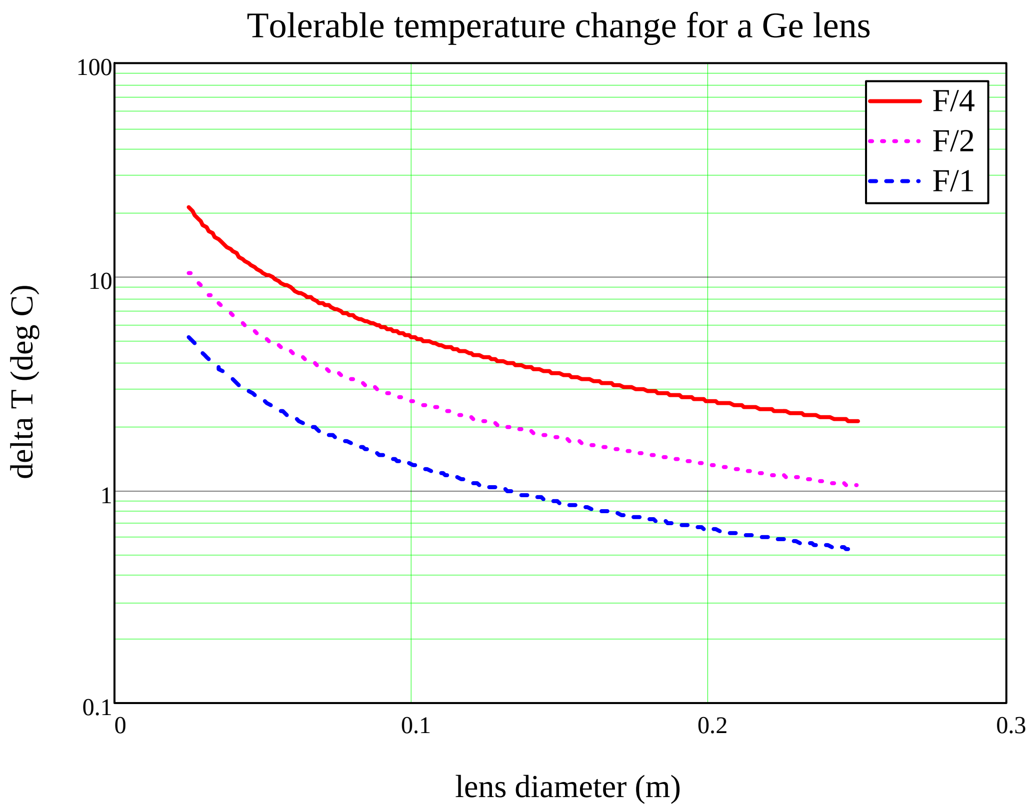



FIGURE 1 TOLERABLE TEMPERATURE CHANGE FOR A GERMANIUM LENS OPERATING AT 10 MICRONS

## ATHERMALIZATION OF FOCUS – TECHNIQUES

As it is often not possible to hold the IR system within tolerable temperature limits, some method which compensates for the change in focus with temperature must be employed. This is known as athermalization and the choice of technique ultimately depends on the application for which the IR system is to be used.

The techniques for athermalization fall into three main categories:

1. Optically passive
2. Mechanically passive
3. Electromechanically active

Each option must be appropriately weighed with respect to the cost, performance, etc. for the system under consideration. Many systems incorporating a variety of techniques have been designed, built, and tested. Some of these techniques are briefly described here, and their respective advantages and disadvantages are discussed.

## PASSIVE ATHERMALIZATION – OPTICAL

Optically passive athermalization eliminates the thermally induced defocus in the system by combining suitably chosen lens materials which together compensate for thermal focus shift.

This form of athermalization has significant advantages to other techniques as it requires no moving parts, hence increasing reliability, and can be very simple in construction leading to compact, lightweight designs. One major disadvantage is that these systems must inherently contain many elements of expensive lens materials, which is further compounded in systems with high magnification where even more elements are required.

### ATHERMAL ACHROMAT

Three conditions must be satisfied in order for an objective lens ($j$ thin lens elements in contact) to be achromatic and athermal: total power, achromatism, and athermalization:

$$\sum_{i=1}^{j} \phi_i = \phi$$

$$\sum_{i=1}^{j} \frac{\phi_i}{\nu_i} = 0$$

$$\sum_{i=1}^{j} \phi_i \gamma_i = -\phi \alpha_H$$

By employing three materials, it is always possible to achromatize and athermalize to the expansion of the housing. A method of identifying viable solutions uses a systematic evaluation of all possible combinations of three materials selected from a short list, with each combination being given a risk factor based on material characteristics and solution sensitivity. Table 1 provides a selection of three-material athermal achromatic solutions in order of increasing risk.

| 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 |

TABLE 1 UNITY FOCAL LENGTH THREE-MATERIAL ATHERMAL ACHROMATIC COMBINATIONS FOR THE 3-5 MICRON WAVEBAND

The first solution from Table 1 is illustrated in Figure 2, with the lens layout and expected blur sizes at -20°C, +20°C, and +60°C (from left to right). Note the diffraction blur size of the Airy disc.

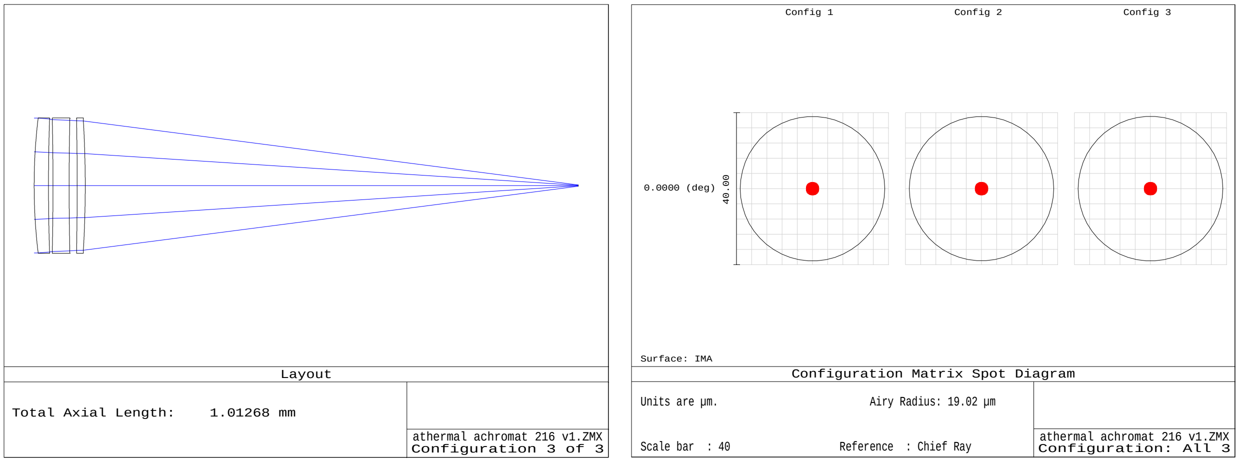


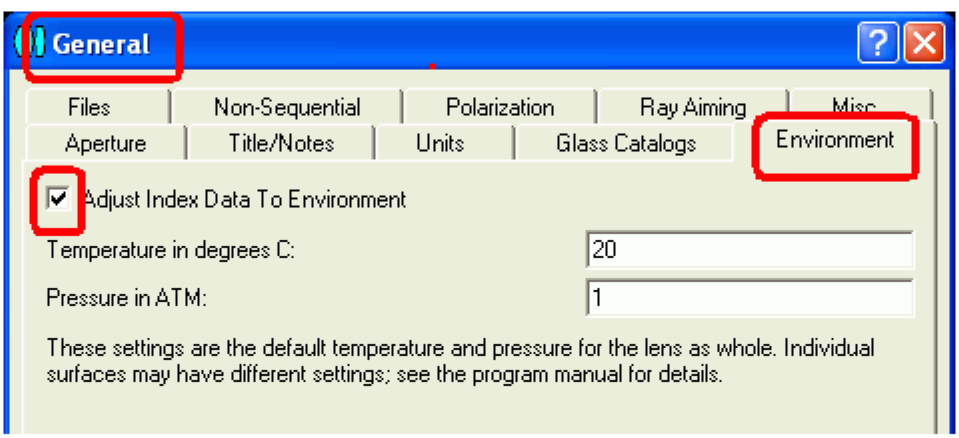

FIGURE 2 ATHERMAL ACHROMAT

## MULTIPLE LENS SYSTEMS

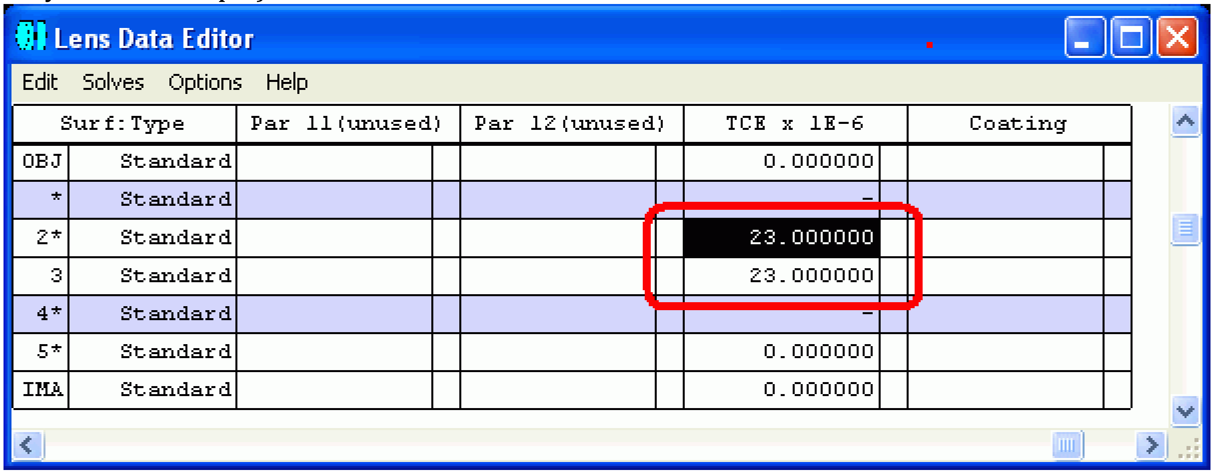
A general expression for the thermal defocus of a system of separated lenses is very complex. In practice, optical design software may be used to aid the designer in developing such an athermal system. While athermal solutions for design problems may be realized with this approach, there is no guarantee these solutions are global optimums and are likely not so. The designer should consider the theory developed for the athermal achromat above as well as other design practices, experiences, and resources to avoid arriving at poor local optimums.

The thermal modelling capabilities in ZEMAX optical design software can model changes in refractive indices due to temperature changes and also the expansion/contraction of components.

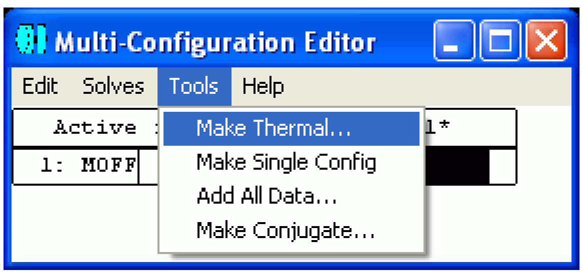
Before doing any thermal modelling, make sure that the “Adjust Index Data to Environment” option is checked:



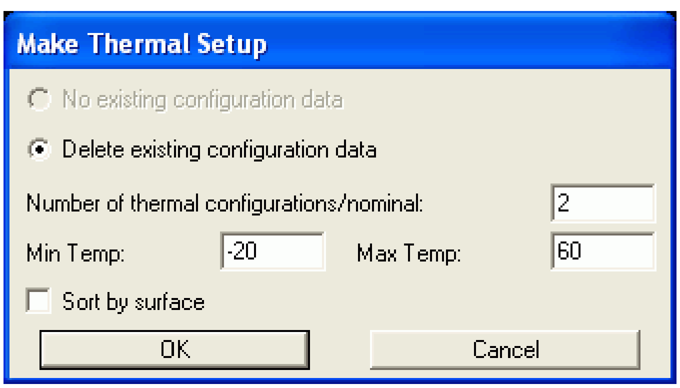
The thermal coefficients of expansion (TCE) of the air spaces between the lenses should be set the appropriate value based on the effective material of the effective spacer in question (aluminium alloy in this example):



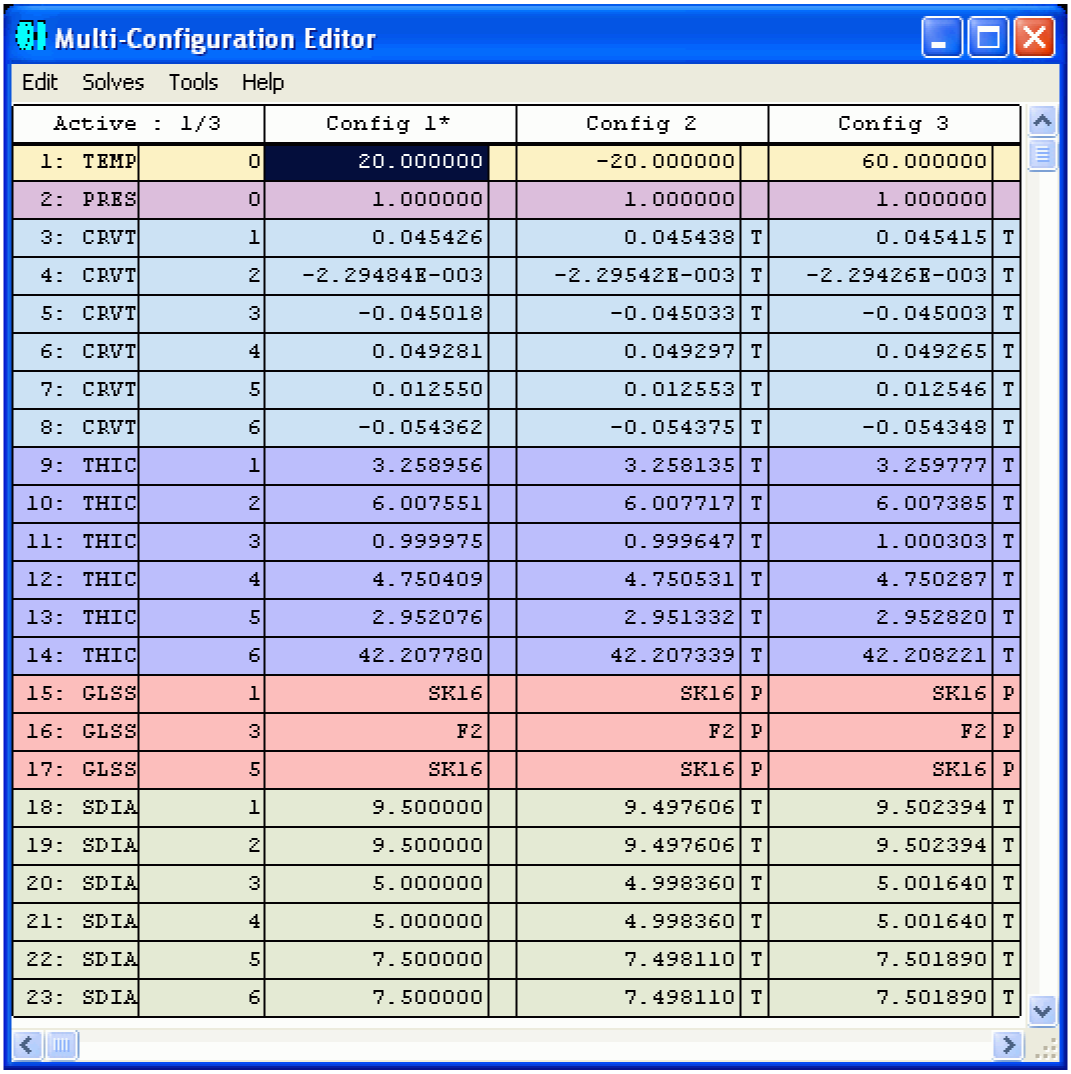

ZEMAX has a built-in tool that inserts all necessary operands affected by temperature change in the Multi-Configuration Editor (MCE):




Beside the nominal temperature, the user can add multiple configurations at different temperatures in the tool window (-20°C and +60°C in this example):



Click OK and the MCE should look something like this (Cooke Triplet sample in this example):




| Active : 1/3 | | Config 1* | | Config 2 | | Config 3 | |
|---|---|---|---|---|---|---|---|
| 1: TEMP | 0 | 20.000000 | | -20.000000 | | 60.000000 | |
| 2: PRES | 0 | 1.000000 | | 1.000000 | | 1.000000 | |
| 3: CRVT | 1 | 0.045426 | | 0.045438 | T | 0.045415 | T |
| 4: CRVT | 2 | -2.29484E-003 | | -2.29542E-003 | T | -2.29426E-003 | T |
| 5: CRVT | 3 | -0.045018 | | -0.045033 | T | -0.045003 | T |
| 6: CRVT | 4 | 0.049281 | | 0.049297 | T | 0.049265 | T |
| 7: CRVT | 5 | 0.012550 | | 0.012553 | T | 0.012546 | T |
| 8: CRVT | 6 | -0.054362 | | -0.054375 | T | -0.054348 | T |
| 9: THIC | 1 | 3.258956 | | 3.258135 | T | 3.259777 | T |
| 10: THIC | 2 | 6.007551 | | 6.007717 | T | 6.007385 | T |
| 11: THIC | 3 | 0.999975 | | 0.999647 | T | 1.000303 | T |
| 12: THIC | 4 | 4.750409 | | 4.750531 | T | 4.750287 | T |
| 13: THIC | 5 | 2.952076 | | 2.951332 | T | 2.952820 | T |
| 14: THIC | 6 | 42.207780 | | 42.207339 | T | 42.208221 | T |
| 15: GLSS | 1 | SK16 | | SK16 | P | SK16 | P |
| 16: GLSS | 3 | F2 | | F2 | P | F2 | P |
| 17: GLSS | 5 | SK16 | | SK16 | P | SK16 | P |
| 18: SDIA | 1 | 9.500000 | | 9.497606 | T | 9.502394 | T |
| 19: SDIA | 2 | 9.500000 | | 9.497606 | T | 9.502394 | T |
| 20: SDIA | 3 | 5.000000 | | 4.998360 | T | 5.001640 | T |
| 21: SDIA | 4 | 5.000000 | | 4.998360 | T | 5.001640 | T |
| 22: SDIA | 5 | 7.500000 | | 7.498110 | T | 7.501890 | T |
| 23: SDIA | 6 | 7.500000 | | 7.498110 | T | 7.501890 | T |

The user can toggle between the configurations (CTRL-A) and observe the analysis windows display the effect of temperature change.

The thermal modelling capability also allows athermalization of a design. The user must carefully construct the appropriate merit function for optimization. For example, the user might choose to minimize the RMS wavefront effort difference between two temperatures. Optimization using glass substitution can be done manually or automatically via the Hammer or Global Search routines. The user may consider creating a glass catalog of lens materials selected from a short list, such as those listed in Table 1 for the 3-5 micron waveband, for a more efficient approach at optimization.

Zoom lenses are extreme cases of multi-lens systems and completely passive athermalization techniques are generally not possible in this type of system.

## PASSIVE ATHERMALIZATION – MECHANICAL

Mechanical athermalization essentially involves some method of moving a lens element or elements by an amount that compensates for thermal defocus. A large number of materials can be utilized as spacers or structural elements, with a correspondingly wide range of expansion coefficients.

The variety of methods which can be used provide certain advantages which make them an attractive solution to the problems of thermal defocus. They are relatively simple, potentially very high accuracy, easy to assemble and service, and can be adapted to cope with reasonable non-linearity of movement.

However for certain applications this technique of athermalization has significant disadvantages. They are usually bulky and heavy, can cause serious sealing problems, often include a great deal of thermal inertia, and are mechanically unreliable (low mean-time between failure MTBF).

## DIFFERENTIAL EXPANSION

By using two different materials with very different thermal expansions arranged as either differential expansion cylinders or rods, it is possible to move the compensating element directly. The rods or cylinders must be of sufficient length to give the required differential movement.

Consider combining spacers of length $L_1$ and $L_2$ of materials with thermal coefficients of expansion $\alpha_1$ and $\alpha_2$ respectively, then to athermalize over a distance $L$ requires that

$$\alpha_1 L_1 + \alpha_2 L_2 = 0$$

$$L_1 + L_2 = L$$

Using materials with $\alpha > 0$ requires L < 0, that is

$$\alpha_1 L_1 - \alpha_2 L_2 = 0$$

$$L_1 - L_2 = L$$

This concept is illustrated in Figure 3

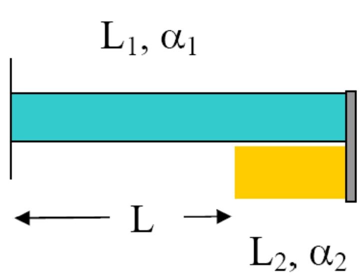



FIGURE 3 DIFFERENTIAL EXPANSION

## ACTIVE ATHERMALIZATION – ELECTROMECHANICAL

Electomechanical athermalization relies on compensator elements driven in a temperature controlled manner using information from separate temperature sensors. This is properly a subject for servo mechanism design and is a brute force solution to athermalization. It is most suitable in complex optical systems such as zoom lenses in which an electromechanical focus mechanism already exists.

The main advantages is using this method are they can cope with thermal gradients through the system, easily cope with non-linear effects, and there is no thermal inertia (temperature sensors can be placed at the compensator elements).

Disadvantages in using this technique of athermalization are complexity, unreliable, bulky and heavy, and requires power.

## AVOIDANCE OF THE PROBLEM

Engineering wisdom suggests that the best way of solving a problem may be to avoid it altogether. This option is limited but possible in the case of athermalization. An all-reflective system consisting of aluminium mirrors in an aluminium housing being one example. Reflective systems typically have limited FOV but catadioptric (reflective/refractive hybrid) lenses can offer some advantage.

# CONCLUSION

There are numerous factors and design constraints which must be considered when selecting the most effective athermalization technique for a particular application. The trade matrix in Table 2 considers many of the parameters and acts as a useful guide.

| | **Optically passive** | **Mechanically passive** | **Electromechanically active** |
|---|---|---|---|
| **Single FOV** | X | X | X |
| **Dual FOV** | | | X |
| **Zoom** | | | X |
| **Performance** | Very good | Good | Depends on technique |
| **Reliability** | Very good | Fair to good | Depends on components |
| **Weight** | Very light | Can be heavy and bulky | Heavy |
| **Power requirements** | | | X |
| **Environmental stability** | Very good | Good | Concerns under vibration |
| **Ease of maintenance** | Excellent | Good | Fair to good |
| **Cost** | Cheap | Fairly cheap | Expensive |

TABLE 2 ATHERMALIZATION TECHNIQUES TRADE MATRIX

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