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Athermalisation Techniques in Infra Red Systems

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Abstract

A major area of concern when designing infra red systems is the defocus effect caused by the variation in temperature of the system from ambient. This paper outlines how this defocus affects the performance of the system and discusses in some detail techniques for overcoming this problem. The advantages and disadvantages of each technique are identified and a trade-off matrix shows the relative merits of each.

Introduction

With the increased interest shown in infra red systems over the last decade it has become necessary to design high performance systems which are capable of functioning in harsh environmental conditions. One such capability is the systems ability to operate at either high or low temperatures and this poses a serious problem for the optical and mechanical designer.

The technique for maintaining focus over a large temperature range for any infra-red system is known as athermalisation. This becomes a significant problem in that germanium, the most commonly used optical material in the infra red has a very large coefficient of refractive index change with temperature. Table 1 shows the variation in this coefficient for a range of materials and it can be seen that the value for germanium is about two orders of magnitude higher than for conventional glass.

MATERIAL	TEMP COEFF OF REFRACTIVE INDEX x10^{-4}	REFRACTIVE INDEX 10 MICRONS
GLASS BK7	+0.025	1.51
GERMANIUM	+3.96	4.003
SILICON	+1.62	2.38
ZINC SULPHIDE	+0.50	2.20
ZINC SELENIDE	+0.60	2.40
KRS-5	-2.35	2.37

Table 1 - Optical Materials Summary

It is this very high coefficient of refractive index with temperature of germanium which dictates the need for a technique to maintain focus over large temperature ranges. This is because any change in temperature of the infra-red system significantly alters the refractive index of each germanium element leading to changes in the focal length of the system (Fig 1). This gives rise to a large amount of defocus in the system and in some cases can lead to a variation in magnification.

Effect of Temperature on I.R. Lens Focus Position

The effect on the focus position of a lens can be easily derived by considering the formula for the power of a thin lens.

The power, K, is given by $(n_1-1)(C_1-C_2)$ where n_1 is the refractive index of the material at a temperature T_1, and C_1 and C_2 are the curvatures of each side of the lens.

Let the new refractive index after a temperature rise of Δt be n_2 such that

$$n_2 = n_1 + \frac{dn}{dt} \Delta t$$

Where dn/dt is the coefficient of refractive index change with temperature.

The change in focus ΔF is then simply

$$\Delta F = \frac{1}{K_{t1}} - \frac{1}{K_{t2}}$$

which after substitution gives

$$\Delta F = \frac{1}{(C_1 - C_2)} \frac{\Delta n}{(n_1 - 1)^2 + n\Delta n - \Delta n}$$

where $\Delta n = dn/dt\, \Delta t$

The change in index is then

$$\Delta n = \frac{A(n-1)^2}{1 - A(n-1)}$$

Where $A = (C_1 - C_2)\, \Delta F$ --- (i)

This gives Δt, the change in temperature to be

$$\Delta t = \frac{A(n-1)^2}{dn/dt(1 - A(n-1))} \quad \text{--- (ii)}$$

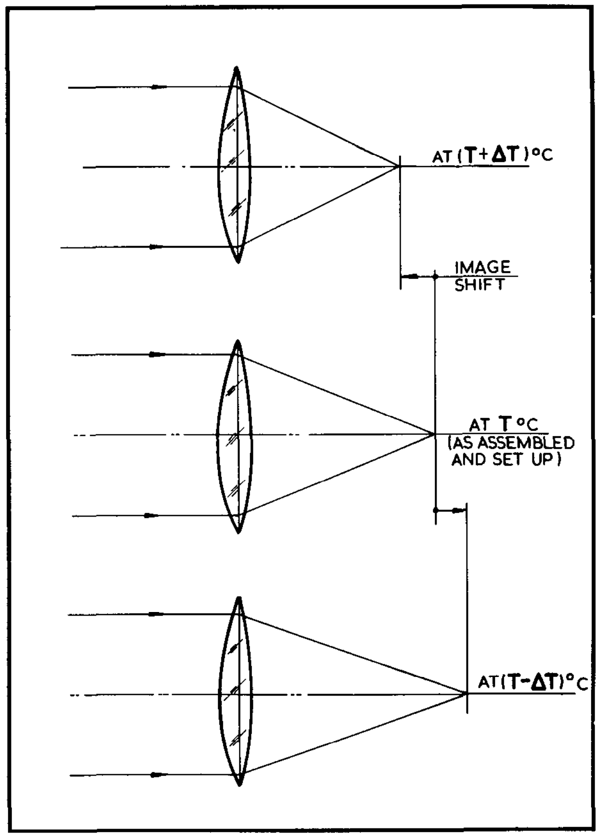

Figure 1 - Effect of temperature on Image Position in Germanium Systems

Now, in order for the lens to show no appreciable change in performance we need to apply the Marechal Tolerance Criteria[1]. This tolerance criterion uses the diffraction based Strehl Intensity Ratio (S.I.R.) with the normalised intensity put equal to or greater than 0.8. Marechal found that this was equivalent to the variance of the wavefront aberration being $< \lambda^2/180$. For defocus this condition gives rise to the tolerance on defocus of:

$$\frac{\Delta W_{20}^2}{12} < \frac{\lambda^2}{180}$$

$$\text{or} \quad \Delta W_{20} \leq \lambda/4$$

where ΔW_{20} is the change in focus or change in curvature of the emerging wavefront measured at the exit pupil. It can be shown that

$$\Delta W_{20} = 1/2 \sin^2\alpha \, \Delta F$$

The focus change ΔF can be written in terms of the wave aberration by writing

$$\Delta F = \frac{2\Delta W_{20}}{\sin^2\alpha}$$

where $\sin^2\alpha$ is the numerical aperture and ΔW_{20} is the corresponding wave defocus at the pupil.

Now from Equation (i) $A = (C_1 - C_2)\Delta F$ therefore

$$A = \frac{2(C_1 - C2)\, \Delta W_{20}}{\sin^2\alpha}$$

We will make the approximation that

$$\sin^2\alpha = \frac{1}{4(FNo.)^2}$$

Where FNo. is the F number of the system

We can write

$$(C_1 - C_2) = \frac{K}{(n-1)} = \frac{1}{F(n-1)}$$

Where F is the focal length

$$A = \frac{8\Delta W_{20}(FNo.)^2}{F(n-1)}$$

Now the Marechal tolerance requires

$$\Delta W_{20} \leqslant \lambda/4$$

So for a diffraction limited lens

$$A = \frac{2\lambda(FNo.)^2}{F(n-1)}$$

Substituting into equation (ii) gives

$$\Delta t = \frac{2\lambda(FNo)^2(n-1)}{dn/dt(D - 2\lambda\, FNo.)}$$

Where D is the diameter of the lens.

This can be further reduced as $2\lambda FNo. << D$

$$\Delta t = \frac{2\lambda FNo.(n-1)}{dn/dt\; D}$$

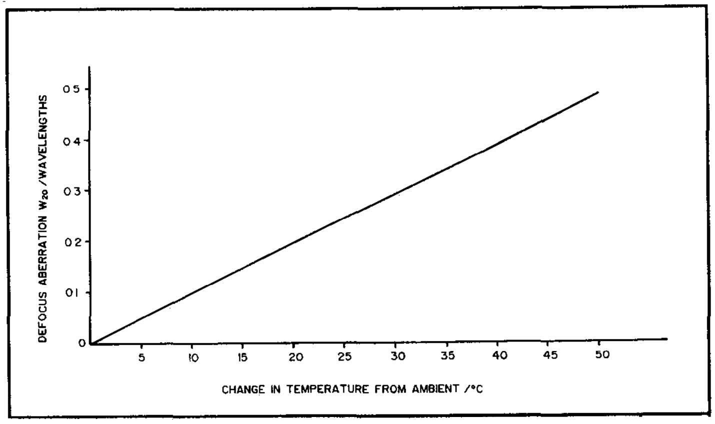

Figure 2 - Defocus Aberration vs Temperature Variation

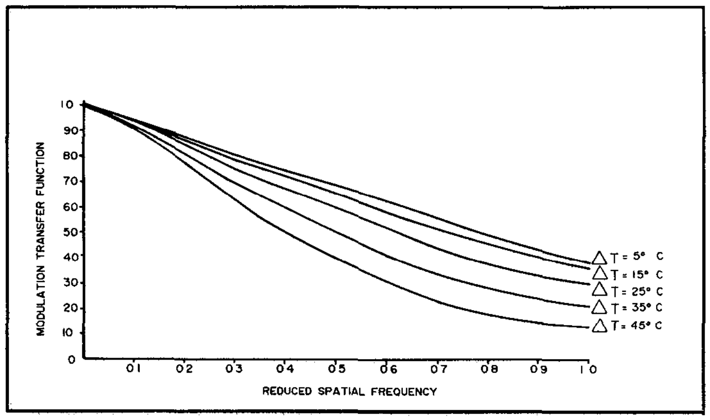

Figure 3 - Performance vs Spatial Frequency

For an F/4 I.R. lens of 100mm aperture the allowed temperature difference is approximately 6°C. It can be seen that this can severely limit the applications for which the system can be used as it dictates that it must be used in a temperature controlled environment.

It is instructive to see how the wave defocus varies with temperature and Figure 2 shows a plot of W_{20} for a range of temperature variations.

Figure 3 shows how the actual performance or modulation transfer function (MTF) of the system drops with increasing temperature. This gives a good indication of the temperature variation which is tolerable for a particular application.

Techniques

If it is not possible to hold the infra-red system at a constant temperature or even within tolerable limits some method which compensates for the change in focus with temperature must be utilised. This is known as athermalisation and the choice of athermalisation technique is often directly controlled by the type of application for which the infra-red system is to be used.

There are a number of options available that might provide compensation of focus and possibly magnification. These systems are generally concerned with the physical movement of one or more lens elements to compensate for its change in focus with temperature. One technique is more sophisticated in that it uses inherent optical properties of materials to give compensation.

The techniques for athermalisation fall into three main areas, these being:

a) Mechanically passive systems
b) Mechanically (Electronically) Active Systems
c) Optically passive systems

Each option must be judged upon its merits with respect to performance, cost etc for the system under consideration. Some of the techniques will be rejected for optical performance reasons while others might provide an acceptable optical solution but prove to be mechanically unattractive.

PPE have gained considerable experience in this field over the past ten years. Systems incorporating a variety of techniques have been designed, manufactured and tested. Some of these techniques are described in detail here and the advantages and disadvantages are discussed.

a) Mechanically Passive Athermalisation

There are a number of methods for athermalisation via mechanically passive means. These are as follows:

1. High or low expansion solid materials
2. High expansion waxes and fluids
3. Differential expansion with direct or lever actuation
4. Shape memory effect (SME) coils

The above methods all involve either direct movement of the lens element(s) or indirect movement via cams, levers, screwthreads etc. and are discussed in more detail here.

1. <u>High or low expansion solid materials</u>

Various methods can be utilised either direct displacement via a single high expansion rod or indirect displacement via circumferential expansion.

The first method (Fig 4) supports the athermalising element in a suitably guided carriage which is connected to the outer housing via a length of high expansion solid rod. This rod is chosen to have a suitable coefficient of expansion and length.

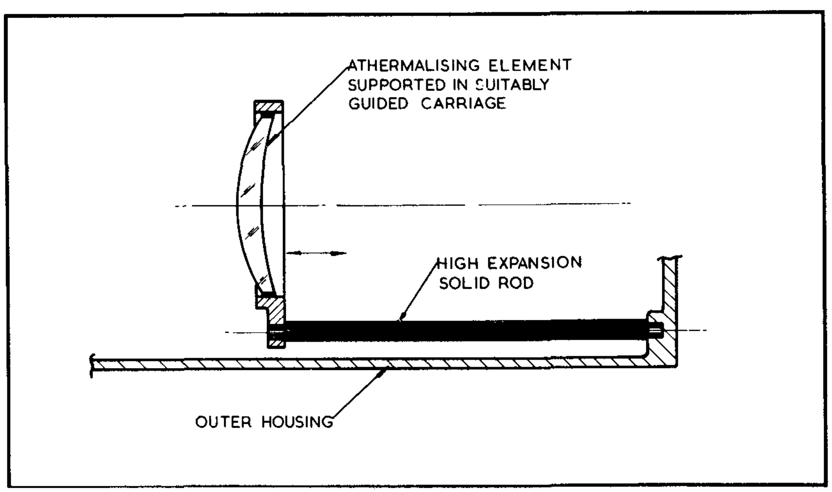

Figure 4 - Direct Displacement - Single High Expansion Rod

The second method (Fig 5) utilises three separate thermal expansion rings, usually plastic, of suitable length to give the required displacement. One end of these rings is fixed so that expansion causes a displacement at the other end. This displacement generates rotation along the axis and this rotation is used to drive the focussing element.

Another means of athermalising via mechanically passive means which is very successful is the use of a geodetic support structure for positive or negative displacement in catadioptric systems. Three pairs of struts equispaced at 120^{o} are used to join the primary mirror cell to the secondary mirror cell. Fig. 6 shows how movement of the athermalisation element is achieved.

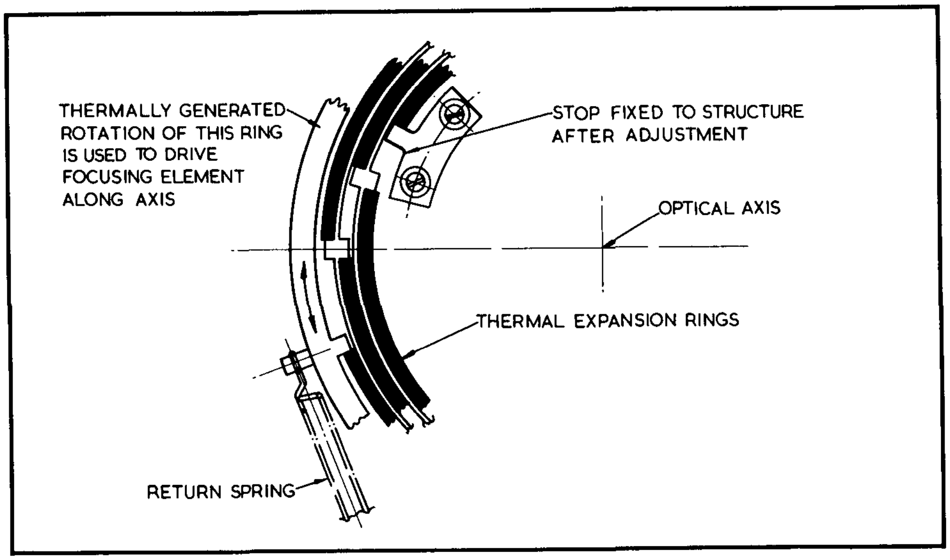

Figure 5 - Indirect Displacement via Circumferential Expansion

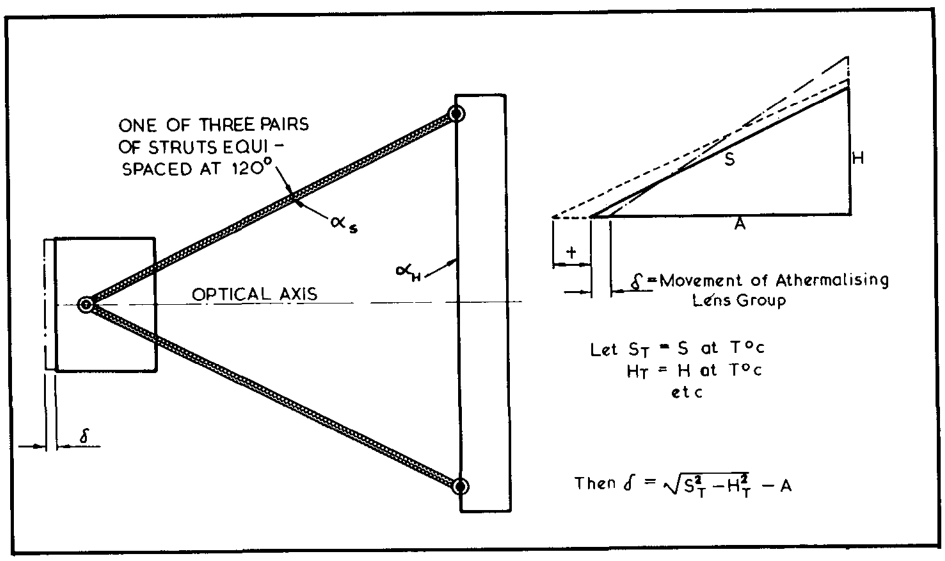

Figure 6 - Geodetic Support Structure for
+ve or -ve Direct Displacement

2. <u>High Expansion Waxes and Fluids</u>

By using a high expansion fluid or wax in a cylindrically shaped bore the athermalising element can be directly moved by pressure exerted from the expanding fluid/wax onto a "piston" connected to a suitably guided carriage (Fig. 7). By introducing a change in the cross-sectional area of the bore the rate of displacement and errors in positioning can be reduced.

An athermalising element can be displaced indirectly using a high expansion fluid which displaces the athermalising element via a low expansion fluid (Fig 8). The high expansion fluid is contained in a cylinder which is finned for fast response via convection.

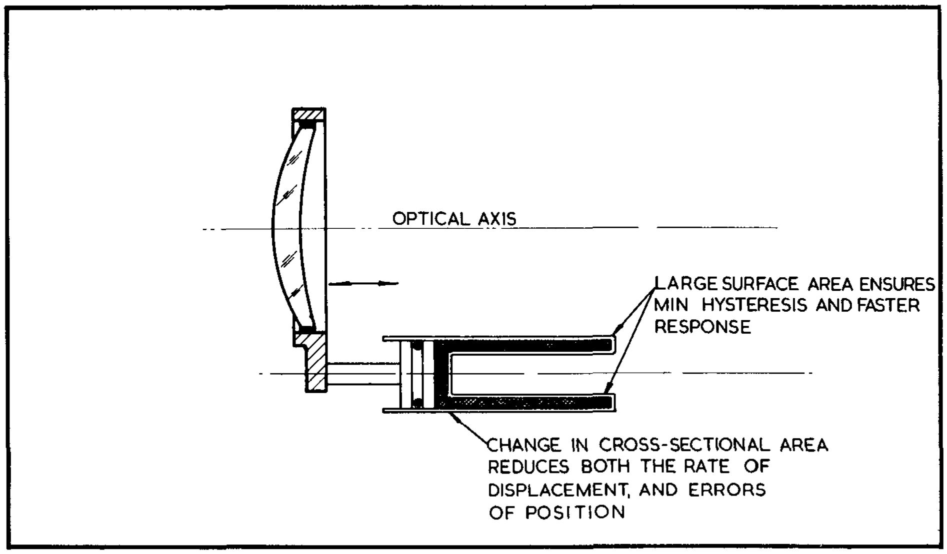

Figure 7 - Direct Displacement from High Expansion Fluid

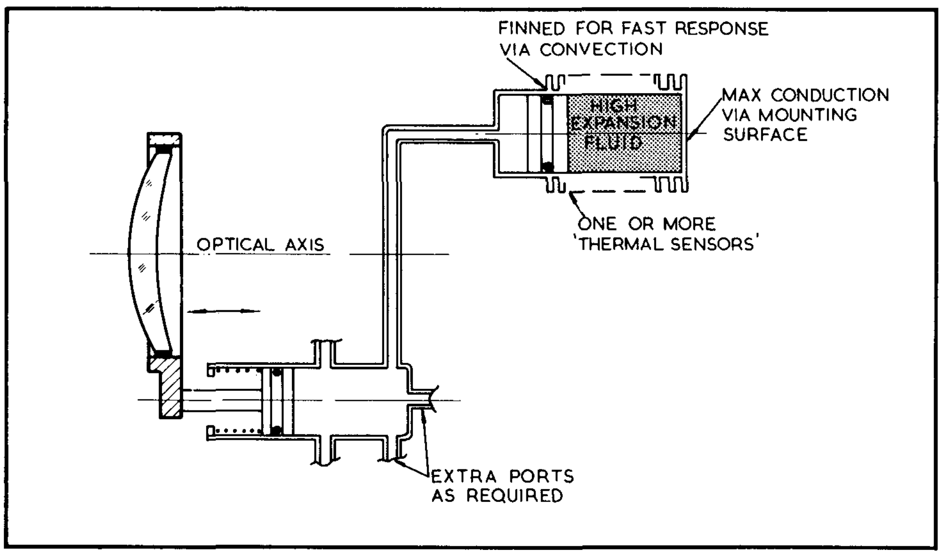

Figure 8 - Indirect Displacement from High Expansion Fluid Thermal Sensors

3. Differential Expansion with direct or lever activation

By using two materials with very different thermal expansions arranged as either differential expansion cylinders or differential expansion rods (Figs. 9, 10) it is possible to move the athermalising element directly. The rods or cylinders must be of sufficient length to give the required differential movement.

The athermalising element can be moved via a lever attached to a short length of the material or via a longer length attached directly to the moving element.

4. Shape Memory Effect (SME) Coils

Shape memory effect elements possess the property of "remembering" there original shape and dimensions and, on heating, returning to this original state[2].

The behaviour of S.M.E. elements may be likened to that of non-linear mechanical springs in which the instantaneous stiffness of the spring and its strain energy content are dependent on both the temperature and the deflection from its unloaded

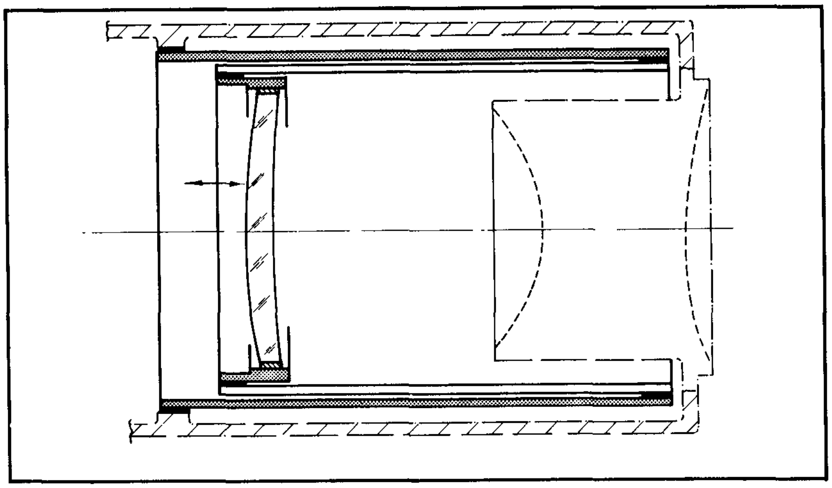

Figure 9 - Direct Displacement using Differential Expansion Cyclinders

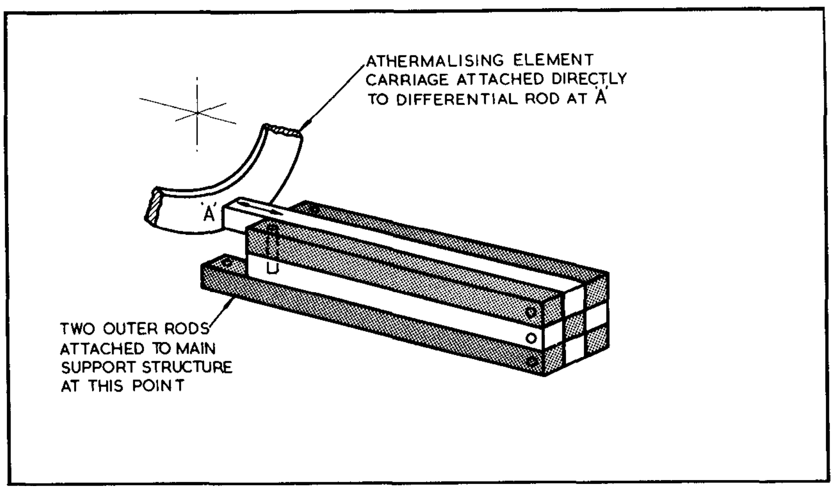

Figure 10 - Direct Displacement using Differential Expansion Rods

position. The analogy can be taken further by imagining that the non-linear mechanical spring is reversible within narrow limits. This means that it will adopt certain deflections repeatedly for the same load and temperature. Restoring the load and temperature to their initial conditions restores the spring to its initial dimensions.

Shape Memory Effect Actuators (Fig 11) can be used in a variety of ways for passive athermalisation of telescopes. The SME Coil Actuator can rotate a ring carrying three cam followers. Each follower engages a ramp-cam mounted upon the moving element cell. A good mechanical advantage of actuator/lens element movement prevails.

Another passive method of athermalisation using SME coils to be used in conjunction with a piston which is hydraulically connected to a common master (averaging) cylinder. This master cylinder drives the lens element cell. In this system the SME coil/piston assemblies can be positioned as required except for space limitations.

It can be seen that there are a variety of methods which can be used for athermalisation via mechanically passive means. These systems have certain advantages which make them an attractive solution to the problems of defocus discussed earlier.

i) Relatively simple
ii) Potentially very high accuracy
iii) Reliably carry out the athermalisation
iv) Easy to assemble and service
v) Can be adapted to cope with any "reasonable" non linearity of movement

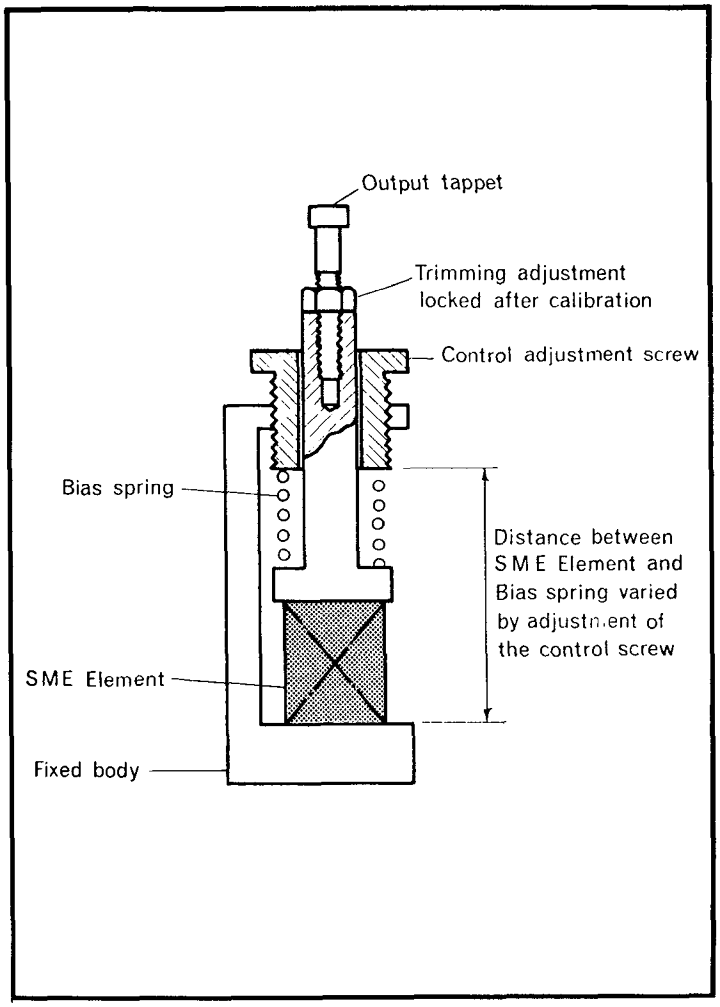

Figure 11 - Simple Shape Memory Effect (SME) Actuator

It can be noted however, that for certain applications the mechanically passive method of athermalisation has significant disadvantages, these being:

i) Usually bulky
ii) Heavy
iii) Can cause serious sealing problems
iv) Cannot cope with large non-linearity of movement
v) Subject to hygroscopic effects
vi) Often include a great deal of thermal inertia (i.e. actuator is at different temperature to athermalising element)
vii) Mechanically unreliable (i.e. high MTBF (meantime between failures))

b) Mechanically Active Athermalisation

The actively athermalised system seems, at first glance, to be relatively straight forward in that the athermalising elements are moved directly via a drive motor.

The system contains one or more temperature sensors, an electric motor, a look-up table and a servo circuit. It is essentially the classical servo/control loop used in many applications. Temperature sensors actuate motors which drive the athermalising element to its correct position via feedback mechanisms and servos. Essentially mechancially active athermalisation is electronic athermalisation.

In electronic athermalisation a distinction needs to be made between two types, namely, digital or microprocessor based control systems and analogue control systems.

Although a microprocessor based system requires a significant amount of skill, design and investment it is considered to be a more flexible and more suitable approach. The analogue control system may be considered an easier option but it does suffer from technical and system disadvantages. However, as mentioned earlier the use of either of these electronic systems must be dictated by system requirements. If the law relating lens movement to temperature is very simple and straightforward it would be unnecessary to use sophisticated microprocessor control, analogue methods would be just as effective and less costly. If, however, the law relating lens movement to temperature is a very complex polynomial it would not be practical to use analogue methods and microprocessor control would be more effective.

The main advantages in using electronic methods of athermalisation are as follows:-
i) By using a number of temperature sensors they can cope with thermal gradients through the system.
ii) Easily cope with any non-linear effects.
iii) Temperature sensors can be placed at the point of lens movement so there is no thermal inertia.

Disadvantages in using electronic techniques for athermalisation are:-
i) Complexity of electronics associated with this technique.
ii) Motors, encoders etc are unreliable.
iii) Heavy due to weight of motors etc.
iv) Must have separate electronic control box.
v) Bulky.
vi) Need for power supplies.

c) <u>Optically Passive Athermalisation</u>

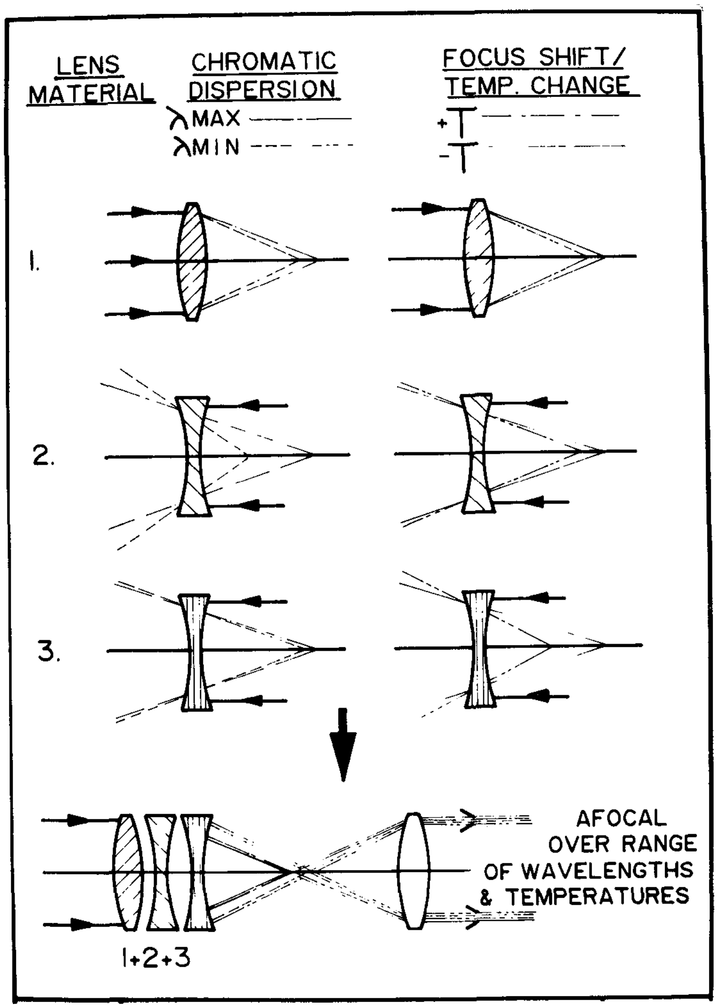

Figure 12 - Optical Athermalisation - 3 Materials

The concept of optically passive athermalisation is essentially an ideal one in that the change in focus of the system is dealt with at the point of temperature rise i.e. there is a form of compensation within the materials of the system. Optical athermalisation is the process of substantially reducing the thermal focus shift of a lens by utilising differences in the thermal properties of optical materials.

There are a number of infra-red transmitting materials with a wide variation in thermooptic coefficients i.e. temperature coefficients of refractive index, dn/dt. This temperature coefficient of refractive index, different for every material may be either positive or negative and may vary with wavelength and with temperature.

Optically passive athermalisation eliminates the thermal focus shift in the system by combining suitably chosen optical materials which together compensate for thermal focus shift (Fig 12). It can be considered analogous to chromatic correction i.e. optically passive athermalisation is to temperature changes what achromatization is to wavelength changes. Straw[3] has introduced this concept in a simplistic form using combinations of glass and plastic materials.

This form of athermalisation has significant advantages to the previously described systems in that they involve no moving parts, hence increasing reliability, and they can be of very simple construction leading to a compact, lightweight design. One major disadvantage is that these systems must inherently contain many elements of expensive infra-red materials and therefore this technique is economically restricted to systems with low magnification. In systems of relatively high magnification (typically greater than x7) where one has a tripling of the optical elements there is the associated increase in mass, and cost and a decrease in transmission.

Design Considerations

The choice of athermalisation technique is often directly controlled by the type of application for which the infra-red system is to be used. In certain circumstances it may not be possible to use an actively compensating mechanism. For reasons of either space limitations, reliability, weight etc a passive system may be the only solution. However, if the optical characteristics are such that the focus is not a simple linear relationship with temperature or if the change in focus is also a complex function of magnification it may not be possible to use passive means. In this case there must be a direct trade of between mechanical and/or electronic complexity and the need to compensate for all the variables.

Before this trade-off can be considered the optical design constraints for the systems must be studied.

(i) When a telescope is athermalised for focus only the magnification variation is uncontrolled. In some instances this may not be satisfactory and it is a prerequisite of the application that the telescope must remain in focus and with the correct magnification over a certain temperature range. The main areas which require this accurate control of both focus and magnification are in avionic use where the optical system is being used for very accurate gun aiming or sighting. This criteria may not be of particular benefit if the optical system is to be used for surveillance or target acquisition.

(ii) In a system which utilises an athermalisation technique involving physical movement of a lens element there is always a tendency for some residual spherical aberration to be introduced. This is due to the fact that the spherical aberration of a lens is directly related to its power and the power balance of a lens system is dictated by the separation between each lens. By altering the separation this power balance changes hence altering the spherical aberration. This spherical aberration inbalance can lead to a reduction in performance and must be taken into account in the early design stages.

(iii) It has been mentioned earlier in the paper that passive optical athermalisation, by choosing suitably compensating materials is analogous to chromatic correction. A severe design constraint when using this particular athermalisation technique is the difficulty in balancing the chromatic aberration, caused by the varying dispersion characterics of the materials, with the athermalising technique, using varying thermal characteristics of the materials. Other factors which must be taken into account when athermalising via passive optical methods are the environmental conditions which the sytem must withstand and the suitability of the optical materials in this environment.

(iv) In systems that exhibit more than one magnification the change in focus is both a complex function of temperature and a complex function of magnification. This complex polynomial can be represented in graphical form and Fig 13 shows focus movement as a function of magnification for various temperatures. One important point to note here is that at the extremes of the temperature range the distance moved by the athermalising element whilst the lens is zooming from one end of its magnification range to the other can be an order of magnitude higher than the distance that is required for focussing the lens from 100m to ∞ . These commments are typical of zoom systems in the 8-12 micron waveband.

(v) If a dual field of view system is required a switching method can be used to switch in extra elements to alter from one field of view to another. There must be the facility to refocus these elements if they are switched in at temperatures other than ambient.

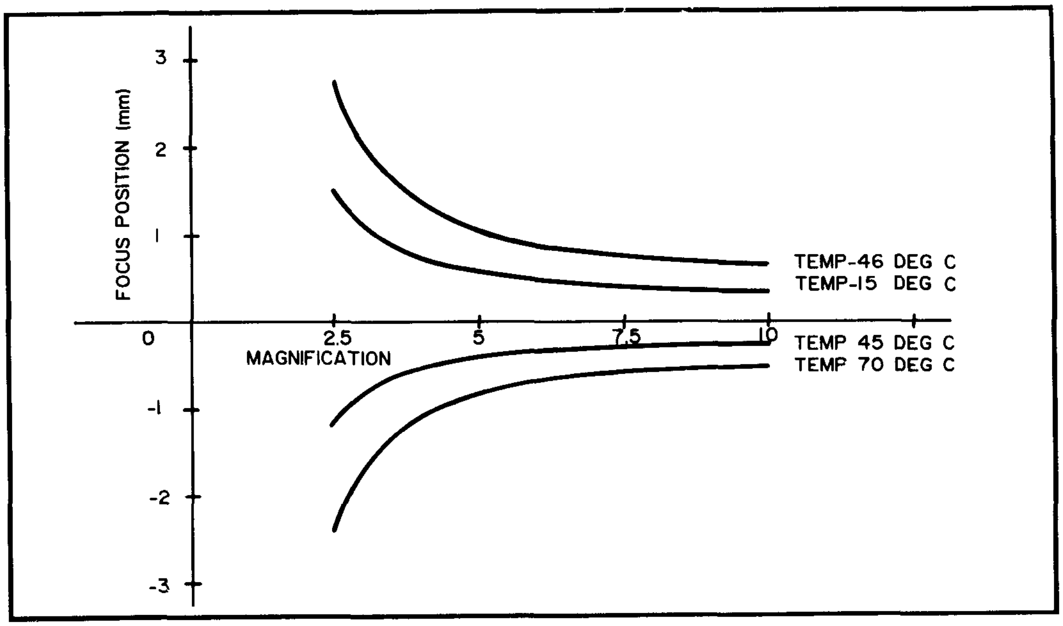

Figure 13 - Athermalisation Curve for Zoom Telescope

(vi) When dealing with changes in temperature only the longitudinal changes through the telescope have been considered. It is not easy to compensate for transverse variation of temperature across the lens elements. Any transverse variation will give rise to an increase in path length across the lens element causing it to behave more as if the lens was decentred. This transverse variation with temperature has not been considered in this paper.

It can be seen that there are numerous factors and design constraints which must be taken into account and considered when choosing the most effective athermalisation technqiue for a particular application. In summing up and presenting the various techniques a trade-off matrix has been prepared. This trade-off matrix (Fig 14) considers all the parameters discussed and although not exhaustive it acts as a useful guide. Obviously each technique must be considered separately with respect to environmental conditions, performance criteria, maintenance etc for a particular application.

Conclusion

It seems clear from the optical performance viewpoint that ideally all infra-red optics should be maintained at a constant temperature which effectively eliminates any defocus problems. In the majority of cases, however, this ideal situation cannot be maintained and some technique for athermalisation must be utilised. Three techniques have been dealt with here,namely, mechanically passive, mechanically/electronically active and optically passive methods and a trade-off matrix has been drawn up showing the relative merits of each. It is important to stress, once again that the choice of athermalisation technique is usually directly controlled by the application for which the infra-red system is to be used. Each technique must be judged with respect to the total system under consideration.

	SINGLE F.O.V.	DUAL F.O.V.	ZOOM	PERFORMANCE	RELIABILITY	WEIGHT	COST	POWER REQMT'S.	ENVIRONMENTAL STABILITY	EASE OF MAINTENANCE
MECHANICALLY PASSIVE	✓			GOOD	FAIR TO GOOD	CAN BE HEAVY AND BULKY	FAIRLY CHEAP	NONE	GOOD	GOOD
MECHANICALLY OR ELECTRONICALLY ACTIVE	✓	✓	✓	ATHERMALISATION TECHNIQUE CAN COMPROMISE PERFORMANCE	DEPENDENT ON ELECTRONIC COMPONENTS	HEAVY DUE TO MOTOR ETC	EXPENSIVE	✓	CANNOT WITHSTAND HARSH ENVIRONMENTAL CONDITIONS eg. VIBRATION	FAIR TO GOOD DEPENDENT ON COMPLEXITY OF ELECTRONICS etc
OPTICALLY PASSIVE	✓			GOOD (DIFFRACTION LIMITED)	VERY GOOD	VERY LIGHT	CHEAP	NONE	DEPENDENT ON CHOICE OF OPTICAL MATERIALS USUALLY VERY GOOD	EXCELLENT

Figure 14 - Trade Off Matrix

Acknowledgements

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