

ATHERMALIZATION OF IR OPTICAL SYSTEMS

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ABSTRACT

Infrared optics defocus with temperature change due to the nature of the optical materials employed in their design. Methods of eliminating this defocus - mechanical, electro-mechanical and optical - are discussed and evaluated in detail.

1. INTRODUCTION

The optical materials detailed in this paper are those that transmit satisfactorily in the 8-12 micron atmospheric window. All of the athermalization methods described are, however, also applicable to the 3-5 micron bandwidth: indeed all the 8-12 micron bandwidth optical materials transmit very successfully in the lower band. The principal differences between optics designed to operate specifically in one band (other than those defined by system configuration i.e., scanned or staring) are the greater variety of optical material available in the lower band but the inability of any single material to operate alone due to chromatic aberration. The paper will concentrate primarily on the 8-12 micron band and limit itself to quantification of the thermal defocus problem for the most common 3-5 micron achromatic pair, that is silicon and germanium.

2. THE THERMAL DEFOCUS PROBLEM

2.1. Simple Lens

The rate of change of power of an optical element with change of temperature $(\frac{dk}{dt})_k$ is defined by its power K and the characteristics of the material of which it is formed - specifically, change of refractive index $\frac{dn}{dt}$ and thermal expansion coefficient - Figure 1. This power change is most conveniently defined for a power of unity and it is this quantity, designated simply as $\frac{dk}{dt}$, that will be used henceforward in this paper. The defocus with respect to temperature $\frac{df}{dt}$ for unity focal length can be found simply by changing the sign of $\frac{dk}{dt}$ and subtracting the thermal

expansion coefficient of the housing. The thermal defocus for an optic of focal length F over a temperature range Δt is then the product of $\frac{dF}{dt}$, F and Δt.

$$\left(\frac{dk}{dt}\right)_k = k \left(\frac{\frac{dn}{dt}}{n-1} - \frac{dl}{dt} \right)$$

- $\left(\frac{dk}{dt}\right)_k$ = change of lens power with temperature
- K = lens power
- n = refractive index
- $\frac{dn}{dt}$ = change of refractive index with temperature
- $\frac{dl}{dt}$ = coefficient of linear expansion

Defining $\frac{dk}{dt}$ as being for K = unity, then the defocus with respect to temperature for a unity focal length lens in a housing with a linear expansion coefficient of $\left(\frac{dl}{dt}\right)_H$ is:-

$$\frac{dF}{dt} = - \left[\frac{dk}{dt} + \left(\frac{dl}{dt}\right)_H \right]$$

Figure 1. Thermal effects in a thin lens element

All of the common infrared optical materials suffer from a high value of $\frac{dn}{dt}$ by comparison with typical optical glass, the most common - germanium - also being the worst with a value some 100 times greater. The resultant thermal power change $\frac{dk}{dt}$ is similarly much larger for germanium than for BK7 (Figure 2) although the gap is apparently narrowed when the effect of an aluminum housing is taken into account. The latter is a little misleading in that, due to the longer wavelength and consequent increase in diffraction effects, germanium optics are usually larger than glass optics for a given application.

MATERIAL	$\frac{\frac{dn}{dt}}{n-1}$	$\frac{dl}{dt}$	$\frac{dk}{dt}$	$\left(\frac{dl}{dt}\right)_H$ for aluminum	$\left(\frac{dF}{dt}\right)_{F=1}$
BK7	6×10^{-6}	7×10^{-6}	-1×10^{-6}	$+22 \times 10^{-6}$	-21×10^{-6}
Ge	132×10^{-6}	6×10^{-6}	$+126 \times 10^{-6}$	$+22 \times 10^{-6}$	-148×10^{-6}

For k and F = unity

Figure 2. Comparison between optical glass and germanium

The effect of the thermal defocus $\frac{dF}{dt}$ due to a germanium lens in an aluminum housing is that a simple infrared optic of this type will rapidly defocus as temperature changes. Figure 3 quantifies, on the basis of a quarter-wave error introduced into a theoretically perfect optic, the temperature range that can be tolerated before the consequent thermal defocus becomes unacceptable: for an 8-12 micron germanium optic of 100 millimeters diameter and an aperture of F/1, this corresponds to a change of only ± 1.4 degrees celsius.

Thermal defocus:-

$$\Delta F = \left(\frac{dF}{dt}\right)_{r=1} \cdot F \cdot \Delta t$$

Depth of focus ($\lambda/4$ error):-

$$\Delta F = \pm 2\lambda (F. \text{number})^2$$

Combining the above, and given:- $\left(\frac{dF}{dt}\right)_{r=1} = -1.48 \times 10^{-4}$

$$\lambda = 0.01 \text{ mm}$$

$$\therefore \Delta t = \frac{\pm 135 \cdot F. \text{No.}}{\text{Diameter in mm}}$$

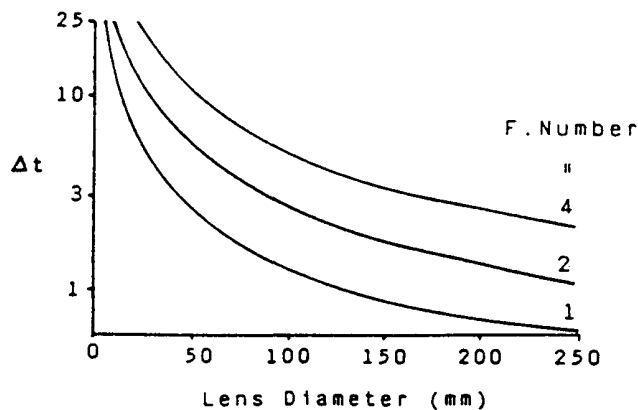


Figure 3. Tolerable temperature change for a Ge lens

The above worrying example may even be optimistic as can be seen from Figure 4 which shows the effect on the MTF of a perfect optic of varying amounts of thermal defocus (specified as a wavefront error). For a typical system cut-off frequency of V (defined by the size of the detectors), the usable performance of the optic, represented by the area under the MTF curve up to a spatial frequency of V , is degraded quite badly by even a quarter-wave of defocus.

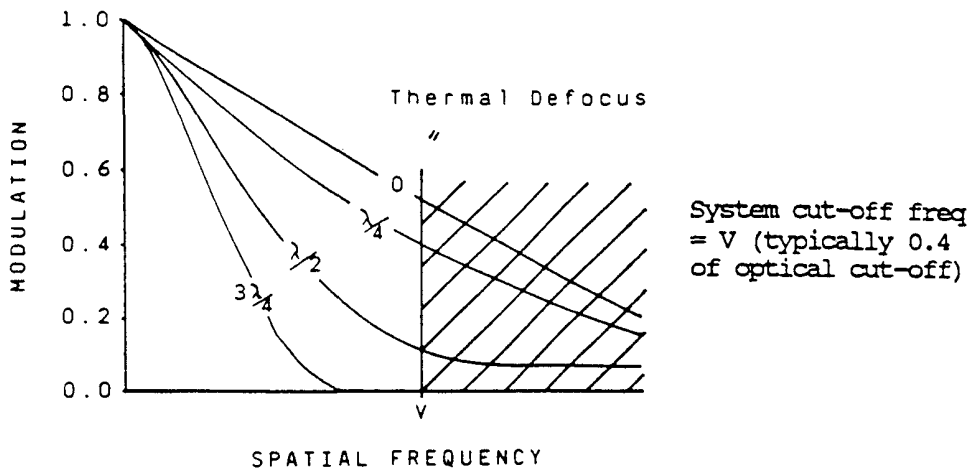


Figure 4. Thermal defocus effect on MTF of a perfect lens

The tolerable temperature change defined in Figure 3 is limited to the case of a single thin lens germanium optic operating in the 8-12 micron bandwidth. What about the more realistic situation of compound optics or, alternatively, optics operating in the 3-5 micron band?

Considering firstly thin-lens 3-5 micron optics and assuming an achromatized silicon/germanium pair, then substituting a value of 245 instead of 135 in the equation for Δt given in Figure 3 defines the temperature change limit for a quarter-wave of thermal defocus. Note, that in this case much of the thermal defocus is due to the aluminum housing, a zero expansion link (such as invar rods) between optic and image plane would increase the factor from 245 to 790. The slightly improved situation with regard to thermal defocus in the 3-5 micron band increases the possibilities of athermalization simply by choice of housing materials¹.

The situation with regard to compound rather than simple optics is a little difficult to quantify but can be tackled in the manner described in the next subsection. Note that this method is equally applicable to single thick lenses having strong surface curvatures.

2.2. Compound Optics

Consider an optic that comprises two thin lens groups separated from each other, the relative thermal power change being the same in each group. Taking the thermal defocus of a single thin lens as unity, then that due to a compound optic of the same overall power can be established from the graph in Figure 5. The latter relates scaling of thermal defocus, with respect to a single lens, relative to front lens to image plane distance (overall length) for 3 different positions of the second lens group. The graph can be conveniently divided into 3 basic lens type areas defined by the relative overall length and the sign of the power of the front lens group. These 3 areas are respectively:-

$$R_T = \frac{\text{Overall Length}}{\text{EFL}}$$

$$x = \frac{d}{\text{Overall Length}}$$

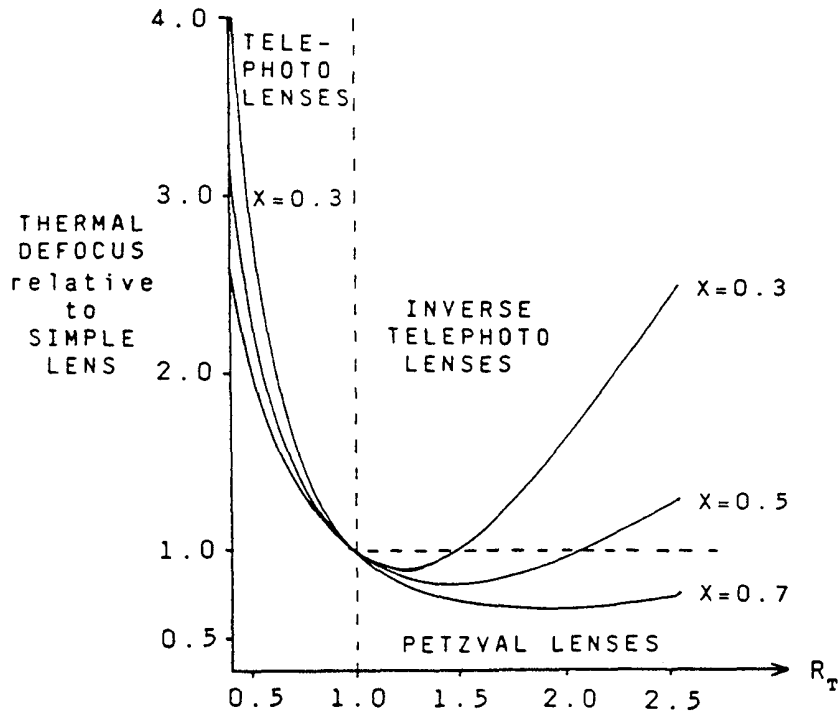
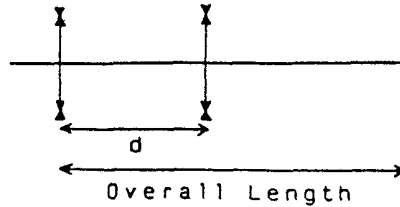


Figure 5. Effect of lens construction on thermal defocus

- a) telephoto lenses - overall length <1.0 , front lens power positive;
- b) petzval lenses - overall length >1.0 , front lens power positive;
- c) inverse telephoto lenses - overall length >1.0 , front lens power negative.

Several conclusions can be drawn from Figure 5:-

1. The intersections of any of the curves with the Scale $=1.0$ line represents the situation whether either one of the group powers is zero i.e., the simple lens case;
2. Telephoto and inverse telephoto constructions always give more thermal defocus than an equivalent power simple lens;
3. Petzval lenses always give less thermal defocus than an equivalent power simple lens;
4. For a given overall length, the lowest thermal defocus is given by positioning the second lens group well back towards the image plane (up to a limit set by the power required of the second lens group), irrespective of lens construction.

Note the universal nature of Murphy's law in the last conclusion. A long relative air-gap in each construction leads to unbalanced lens powers and a high Petzval sum: additionally, in an inverse telephoto this destroys one of the major advantages of this construction, namely a relatively long back focal length.

Note also that the tolerable temperature change as derived from Figure 3 should be divided by the scaling factor obtained from Figure 5 for the specific lens construction.

2.3.Cascaded Optics

Thus far the thermal defocus has been established for single stage optics, that is for a system which only involves a single object/image pair. For a cascaded optical

system where the image from the first optic is relayed one or more times, the tolerable temperature change for the overall system can be established by calculating that due to each stage in the system (applying the appropriate factor dependent on its compound lens construction). The value of Δt_T for the total system is then:-

$$\Delta t_T = (\Delta t_1^{-1} + \Delta t_2^{-1} + \dots)^{-1}$$

3.AVOIDANCE OF THE PROBLEM

Engineering wisdom suggests that the best way of tackling a problem is not to devise a clever solution but to avoid the problem in the first place - Figure 6. This option is limited but possible in the case of athermalized IR optics, an all-reflective system comprising aluminum mirrors in an aluminum housing being the obvious example - Figure 7 (a). Reflective systems are usually (but not necessarily) limited in field of view but athermalized catadioptric optics of moderate field of view are a practical proposition. Figure 7 (b) shows a system that comprises a glass primary and a Mangin secondary plus a positive rear lens which together can be both athermal and (nearly) self-achromatized using only one refractive material (germanium)².

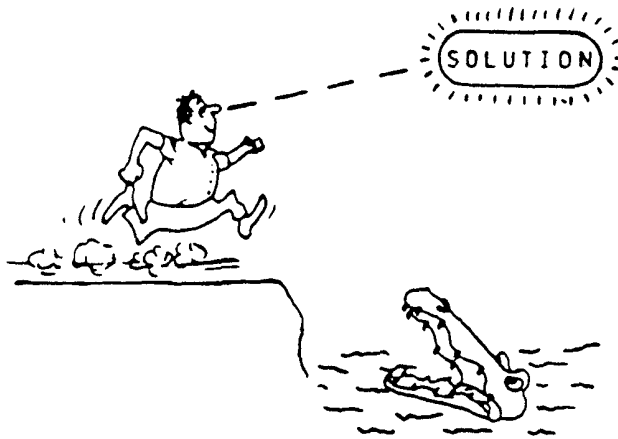


Figure 6. Don't solve it, avoid it !

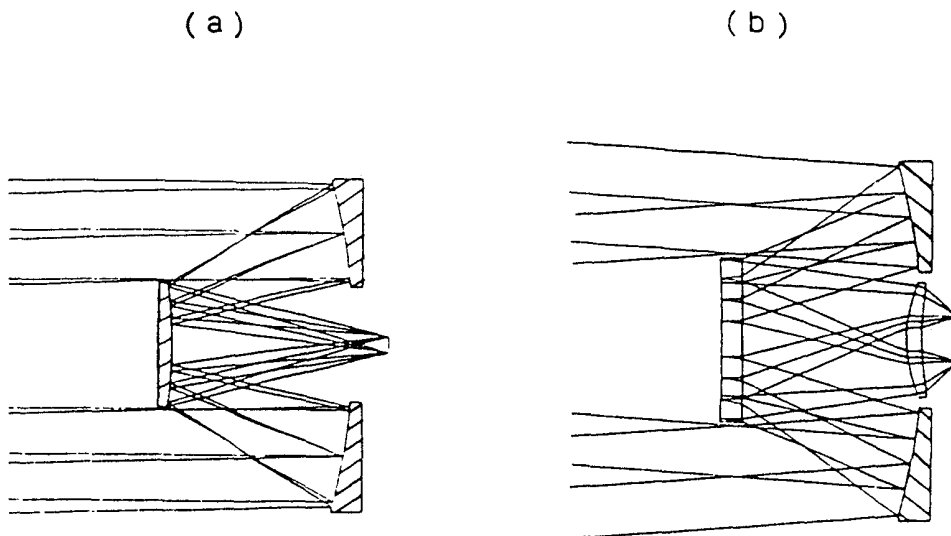


Figure 7. Self-athermal reflective/catadioptric optics

Figures 7(a) and (b) illustrate the advantages of the catadioptric optic over the purely reflective: for a diameter of 100 millimeters the limiting aperture and field angle, set by a maximum aberration level of a quarter wave, increase from $F/2$ to $F/1$ and 1.5 to 8 degrees respectively. Aspherics, or which two are required in the reflective system, are not necessary in the catadioptric: the latter does, however, have a larger obscuration which has a more deleterious effect on the MTF at the lower-middle spatial frequencies.

The obscuration in the catadioptric need not necessarily be large, however, provided that the onus of correcting for the thermal effects of the entire system is not laid solely on the germanium margin secondary. Where this is not the case, or the amount of thermal defocus to be corrected is significantly lowered, then the diameter of the margin secondary relative to that of the primary mirror can be considerably reduced³. This is the situation when the primary mirror is constructed of aluminum (and thus self-athermalized in an aluminum body) and the field angle is relatively small. Such a situation is illustrated in Figure 8 where a high magnification catadioptric afocal achieves complete athermalization.

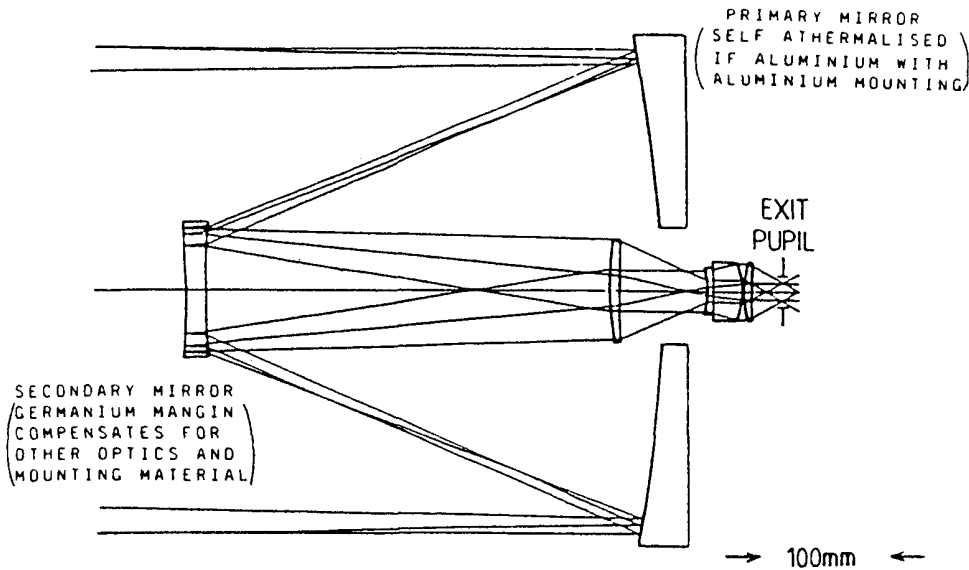


Figure 8. Small obscuration athermal catadioptric afocal

Partial avoidance of the thermal defocus problem may be achieved in refractive optics by eliminating germanium, an action that may be desirable anyway to lessen high temperature absorption, and substituting other IR optical materials that have lower dn/dt values. This, however, leads to greater optical complexity due to the lower refractive indices and necessity to achromatize: the tolerable temperature range is only increased by a factor of up to about four times unless optical athermalization is attempted (see Section 5).

4. MECHANICAL ATHERMALIZATION

4.1. General

Mechanical athermalization essentially involves some agency moving a lens element, or lens elements, - preferably internal to avoid sealing problems - by an amount that compensates for the thermal defocus. It can be subdivided into manual, passive or active:-

Manual involves simple defocusing and is an inexpensive but doubtful option in that thermal images can differ substantially in appearance from visual images and in some situations can be of rather indistinct outline. In these circumstances, it can be quite difficult to establish the correct focus position.

Passive uses an agency, usually involving high thermal expansion, to achieve the necessary refocusing automatically.

Active employs some form of active focus compensation which is computed (usually electronically) and then implemented by a powered agency such as an electric motor.

The following describes some of the ways in which passive or active mechanical athermalization can be achieved although the list is by no means exhaustive - for further examples, see refs 1,5,8.

4.2. Passive Mechanical Athermalization

4.2.1. High expansion rods:- The upper picture in Figure 9 shows a schematic of a high expansion rod system. With rise of temperature the focus of the optic will fall progressively short of the nominal image plane but this is compensated by the rod which moves the rear lens backwards, thus refocusing. The problem is that the required movement (typically greater than 20 microns per degree celsius) is greater than that which can be provided even by a high expansion material like nylon. More than one rod is therefore required and this, plus the major disadvantage that as a compensating material nylon is unreliable, makes this method useful only for relatively crude compensation.

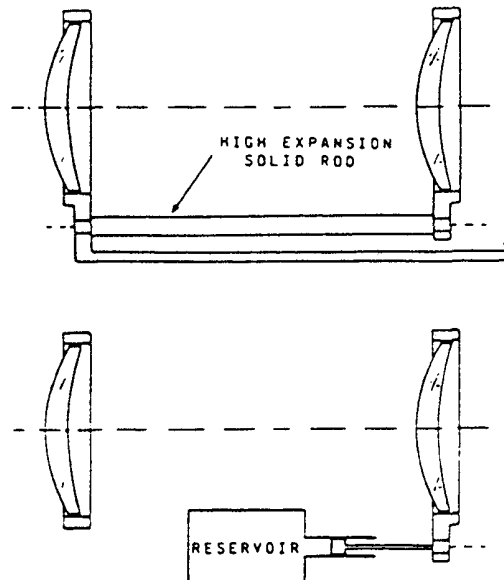


Figure 9. Some passive mechanical athermalization methods

The method can have potential, however, if the required movement can be reduced significantly (see Section 6) in which case more reliable expansion materials can be employed, albeit in a rather complex form.

4.2.2. Hydraulics:- The lower picture in Figure 9 shows a simplistic version of hydraulic athermalization where, with increasing temperature, the fluid in the reservoir expands into the narrow cylinder and moves the piston - thus giving a compensatory lens movement. Basically this method should work quite well but lens designers instinctively shy away (perhaps wrongly) from the idea of hydraulic fluids in optical devices.

4.2.3. Shape memory effect metal :- Shape memory effect elements possess the property of 'remembering' their original shape and dimensions and, on heating, returning to this original stage ⁴.

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 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 (Figure 10) can be used in a variety of ways for the passive athermalization of telescopes. The SME coil actuator can rotate a ring carrying three cam followers: each follower then engages a ramp-cam mounted upon the moving element cell. There is a good resulting mechanical advantage between actuator and lens element movement.

Another passive method of athermalization using SME coils is where they are 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.

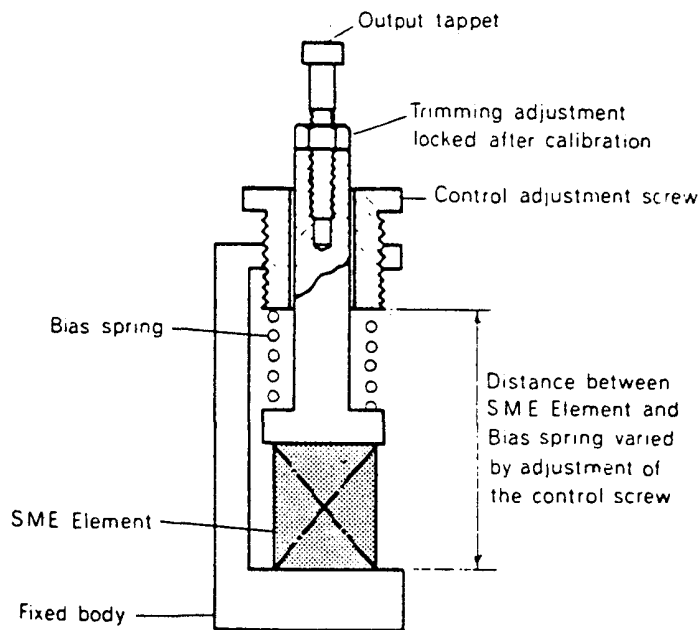
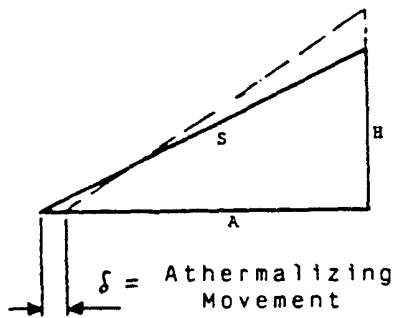
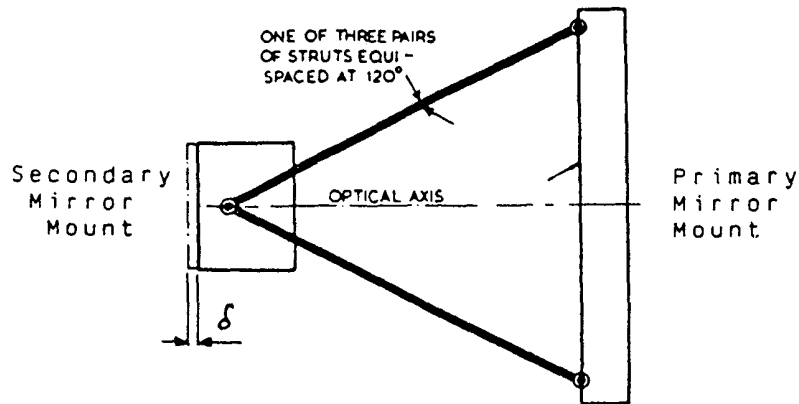


Figure 10. Shape Memory Effect (SME) actuator

4.2.4. Geodetic mechanical athermalization:- A rather neat method of passive mechanical athermalization applicable specifically to catadioptric (or reflective) optics - Figure 11. In this method an athermalizing adjustment of the air-gap between primary and secondary mirrors is produced by the use of materials having different expansion materials for the primary mirror mount and the secondary mirror struts. A higher expansion material for the struts produces a movement of the secondary mirror away from the primary and vice-versa.

4.3. Active Mechanical Athermalization

The automatic version of this method (as opposed to simple manual refocusing) is illustrated in schematic form in Figure 12 for a single field of view optic. A number of temperature sensors along the body of the optic feed their signals into a pre-programmed algorithm that calculates the required movement of a compensating lens and then initiates the motion. This method copes well with longitudinal temperature gradients but requires electronics and a motor and is rather complex relative to other single field of view athermalization options.



$$S_T = S \left(1 + \left(\frac{dl}{dt} \right)_S \Delta t \right)$$

$$H_T = S \left(1 + \left(\frac{dl}{dt} \right)_H \Delta t \right)$$

$$\delta = \sqrt{(S_T^2 - H_T^2)} - A$$

Figure 11. Geodetic passive mechanical athermalization

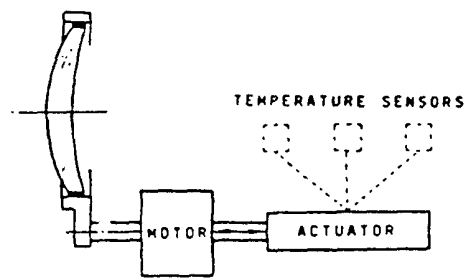


Figure 12. Electro-mechanical athermalization schematic

Where active mechanical athermalization comes into its own is for multi-field-of-view optics where thermal defocus is field-of-view dependent. Figure 13 shows a 6:1 dual field of view infrared afocal telescope which is athermalized for both collimation and magnification by the controlled movement of two internal lens groups.⁶ The electronic software contains two 10 term polynomials that enable positions of the two lens groups to be computed such that collimation and desired magnification are attained for a specific set of inputs from the temperature sensors.

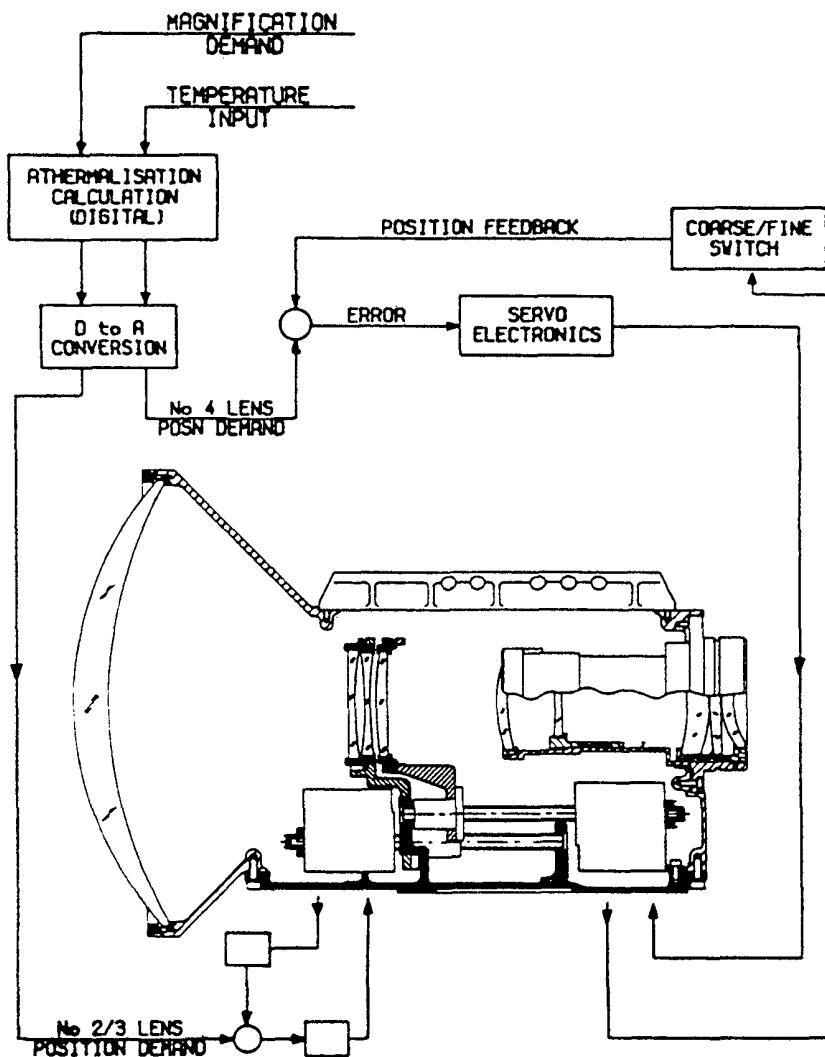


Figure 13. Actively athermalized dual FOV telescope

The compact nature of the telescope means that considerable accuracy in lens group positions (a 4 micron error in the negative moving group longitudinal position is equivalent to a 1% drop in MTF at the spatial frequency of interest) is required.

The lens design described in the previous paragraph is dual field of view but the same essential design could be used as a continuous zoom athermalized for all magnifications: this could be achieved by an extensive algorithm that recalculated the zoom group positions for each set of temperature inputs. Eventually, however, the two moving lens group method becomes inadequate in that, over a sufficiently large zoom range (greater than about 10) or over a very wide range of temperatures or temperature gradients, it is difficult to control aberrations to an adequate level. In these circumstances it may be necessary to resort to the considerable complication of three moving lens groups each controlled electronically⁷.

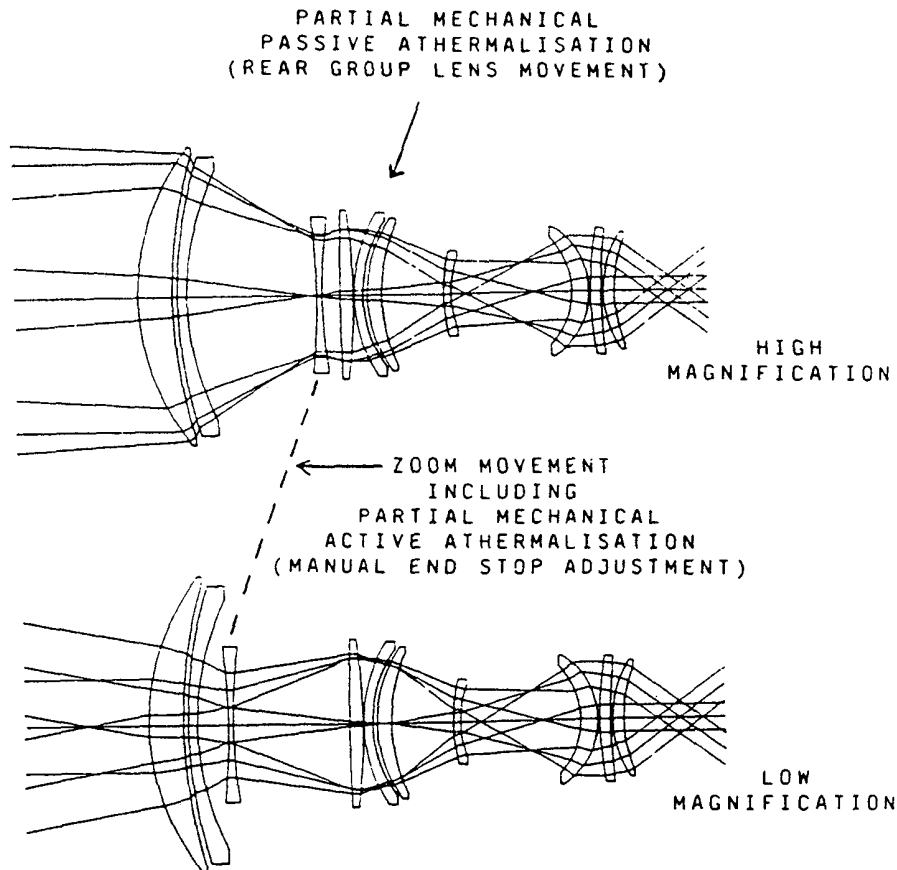


Figure 14. Passive-active mech. athermalised telescope

4.4. Passive-Active mechanical athermalization

This technique is essentially a relatively inexpensive version of that described in the previous section and is best suited to optics which already include axially moving components. Figure 14 shows a dual field of view infrared telescope the construction of which is predominantly germanium⁸. The majority of the athermalization is provided by a mechanically passive device which adjusts the positions of a rear group lens. The residual focus error is then corrected by small manual adjustments to the magnification change lens element. In this way, the change of magnification and aberrations with temperature can be minimised. The problem with this particular method is that mentioned in Section 4.1., namely the difficulty in determining exact focus : it is, however, a reasonable compromise between the inexpensive but crude (magnification and MTF likely to change) all-manual focus method and the precise but expensive electronic active technique.

5. OPTICAL ATHERMALIZATION

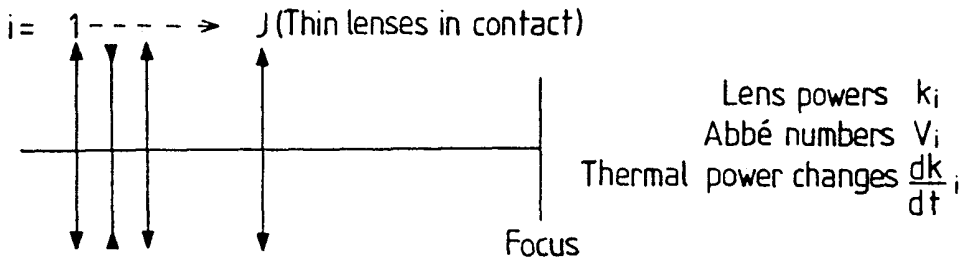
5.1. Background

Athermalization of the focus position of an optical system by choice of refractive materials has been described quite extensively in the literature - Ref 9 is a good example. Figure 15 summarises the three conditions that need to be satisfied, namely:- overall optical power, achromatism and athermalism¹⁰. An obvious conclusion from the number of these conditions is that, unless fortune smiles, a minimum of three different optical materials is usually required for successful optical athermalization.

A condition has been derived¹¹ that, if satisfied by a pair of optical materials can result in an achromatized, athermalized optic. This condition can be written as:-

$$v_1 \left[\left(\frac{dk}{dt} \right)_1 + \left(\frac{dl}{dt} \right)_H \right] - v_2 \left[\left(\frac{dk}{dt} \right)_2 + \left(\frac{dl}{dt} \right)_H \right] = 0$$

Reference to the short list of 8-12 micron bandwidth materials shown in Figure 16 shows the no pair of materials from this list satisfies this condition by some margin : this simply proves what every designer of IR optics knows, which is that it is Murphy rather than fortune that prevails in this region of the spectrum. No realistic athermalized two material solution exists in the 8-12 micron band, unless one of the three basic conditions in Figure 15 can be ignored - see for example Section 5.4.



Conditions to satisfy (power, achromatism, zero thermal focus shift)

1. Total power:-
$$\sum_{i=1}^J k_i = k$$

2. Achromatism:-
$$\sum_{i=1}^J \frac{k_i}{V_i} = 0$$

3. Athermalisation:-
$$\left(1 + \frac{dV}{dt} \cdot \Delta t\right) \sum_{i=1}^J \left(\frac{dk}{dt}\right)_i + \frac{dV}{dt} \cdot k = 0$$

Where $\frac{dV}{dt}$ = exp coeff of mounting material

Figure 15. Optical athermalization conditions

One odd point in the athermalism equation in Figure 15 is that theoretically it gives a different answer dependent on the value of Δt , the temperature increment, as the latter appears in the multiplier outside of the summation. The implication of this is that a particular athermal solution is only valid over a specific temperature range. In reality, this is unimportant as, for any reasonable housing material, the multiplier has a value close to unity even for a large temperature change. Additionally, there is a far greater potential error in that each value of $\frac{dk}{dt}$ is not constant as the $\frac{dn}{dt}$ value for most IR materials varies with temperature range.

5.2. Optical Materials

A short list of 'reasonable' optical materials for use in lenses for the 8-12 micron spectral band is indeed short. Elimination of materials having inadequate transmission, particularly undesirable properties, or for which there are better alternatives leads to a list of only a dozen or so of which Figure 16 lists the 'best' ten (note, however, that only one chalcogenide - IRG 100¹² is quoted although there are other equally applicable alternatives, (for example AMTIR 1 and 3 from Amorphous Materials Inc.)

The materials in Figure 16 have been subdivided into four groups although there is a certain amount of semantic argument about which material belongs to which group : for example, some authorities refer to ZnS and ZnSe as semiconductors, although their electrical resistivity is very high, while others call them chalcogenides because they contain sulfur or selenium.

TYPE	MATERIAL	$V_{8-12\mu}$	$\frac{dk}{dt} \times 10^6$ (k=1)
Alkali Halide	NaCl	19	-95
	CsI	234	-172
Semiconductors	GaAs	107	+60
	Ge	864	+126
	CdTe	150	+53
Dielectrics	ZnS Multispectral	23	+31
	ZnSe	58	+34
	AgCl	54	-92
	KRS-5	165	-229
Chalcogenide	IRG 100	105	+20

Figure 16. Short list of 8-12 um optical materials

Which role is played by a particular material in an achromatized, optically-athermalized lens design is not obvious: simple logic suggests that materials having a high absolute value of $\frac{dk}{dt}$ will tend to form the athermalizing element while materials having high dispersion (low V) will tend to form the achromatizing element. This refers to their major role, in reality all materials in a design contribute to, or partially correct for, the thermal and chromatic effects.

5.3. Optically athermalized material combinations

A computer program was written to investigate 'mindlessly' all possible combinations of three of the ten materials in Figure 16 - remembering that material order is irrelevant¹³. The program calculated the in-contact thin lens total curvatures (rather than powers in order to give an idea of lens bulk) for a unity focal length and assuming an aluminum housing - Figure 17.

NUM	MATERIALS			CURVATURES			RISK	MASS	PETZ
1	ZNSE	ZNS	GE	1.889	-0.853	-0.211	1.0	2.3	0.48
2	KRS-5	ZNSE	GE	0.346	-0.153	0.247	1.0	1.0	0.30
3	KRS-5	ZNS	GE	0.320	-0.064	0.213	1.0	1.0	0.31
4	KRS-5	GAAS	GE	0.364	-0.193	0.313	1.3	1.1	0.31
5	KRS-5	NACL	GE	0.334	-0.133	0.202	1.3	1.0	0.30
6	ZNSE	ZNS	KRS-5	0.949	-0.461	0.159	1.4	1.5	0.40
7	GAAS	ZNS	KRS-5	0.409	-0.200	0.225	1.4	1.0	0.31
8	GAAS	ZNS	GE	1.383	-0.524	-0.506	1.5	1.9	0.30
9	IRG100	ZNS	GE	1.070	-0.290	-0.122	1.5	1.1	0.41
10	CDTE	ZNS	KRS-5	0.534	-0.145	0.204	1.6	1.2	0.37
.
12	IRG100	ZNS	KRS-5	0.681	-0.208	0.116	1.8	<u>1.0</u>	0.37
.
14	KRS-5	CDTE	GE	0.412	-0.424	0.382	1.9	1.4	<u>0.26</u>
.
17	CSI	ZNS	GE	0.703	-0.054	0.182	2.0	1.2	0.41
.
80	CSI	AGCL	CDTE	0.834	-0.445	0.489	5.7	1.7	0.44

Figure 17. Optically-athermal combinations in risk order

Each solution was assigned a risk factor calculated from the sensitivity of the solution to material data errors, the credibility of the data, the availability and difficulty of processing the material, plus a bogy factor for poor transmission (where relevant). Figure 17 highlights the ten lowest risk, the lowest normalised mass, the lowest Petzval sum and another 'interesting' solution.

Also highlighted is my favorite (!) combination of cesium iodide, silver chloride and cadmium telluride - known to connoisseurs of IR optical materials as impractium solutoxide, photo-sensitive lead and unobtainium respectively. Predictably, a conventional combination of ZnSe/ZnS/Ge comes out as just the lowest risk but is very closely followed by KRS-5/ZnSe/Ge : this latter combination, while using a difficult material (KRS-5), has low optical powers/mass and is relatively insensitive to material data errors.

Two final points on Figure 17 - the materials have been printed out in such an order that they approximately represent principal positive power, achromatizing and athermalizing materials respectively; also, the factors used in the risk calculation are my own estimation and therefore open to challenge.

5.4.Athermalized laser beam expanders

Clearly a two material athermalized optic is possible if one of the conditions in Figure 15 can be ignored : logically the only one that can be ignored if an athermalized system is required is that of achromatism. This is the case for an optic to be used solely with a laser, for example, a 10.6 micron laser beam expander. In this case, a simple athermal condition can be derived by making the rate of change of focus with temperature cancel for the 2 simple lenses in the afocal expander:-

$$\left(\frac{dF}{dt}\right)_1 = -F_1 \left[\left(\frac{dk}{dt}\right)_1 + \left(\frac{dl}{dt}\right)_H \right]$$

$$\left(\frac{dF}{dt}\right)_2 = -F_2 \left[\left(\frac{dk}{dt}\right)_2 + \left(\frac{dl}{dt}\right)_H \right]$$

$$\text{Magnification} = -F_2 / F_1 \quad \text{and} \quad \left(\frac{dF}{dt}\right)_1 = -\left(\frac{dF}{dt}\right)_2$$

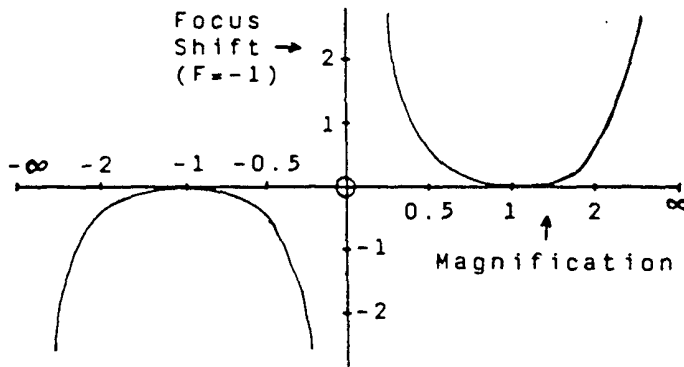
$$\therefore \text{Magnification} = \frac{\left[\left(\frac{dk}{dt}\right)_1 + \left(\frac{dl}{dt}\right)_H \right]}{\left[\left(\frac{dk}{dt}\right)_2 + \left(\frac{dl}{dt}\right)_H \right]}$$

Taking the value of $(dl/dt)_H$ for an aluminum housing as 22.6×10^{-6} leads to various values of magnification for different optical material pairings. The highest magnification for an athermalized Galilean expander is given by Ge/IRG100 at x3.5, although a Keplerian expander (with intermediate image - not feasible for a high power laser system) is possible at x4.8 using KRS5/IRG100.

6. IMPROVED MECHANICAL ATHERMALIZATION

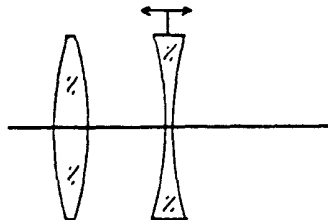
6.1. Background

The major problems with respect to conventional mechanical athermalization are the magnitude of the lens movement that is required and the undesirability/complexity of the mechanisms necessary to achieve that movement. It is worthwhile therefore to consider the lens movement problem on a first order basis.

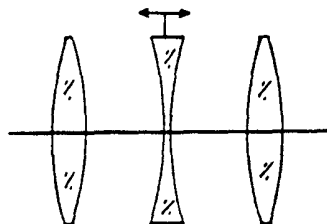


To get large focus shift for small mag. change (and \therefore small lens movement), must be well away from $M = \pm 1$.

This can be achieved using 2 lenses, but EFL changes as lens moves:-



HOWEVER, 3 lenses can be used to maintain EFL during lens movement:-

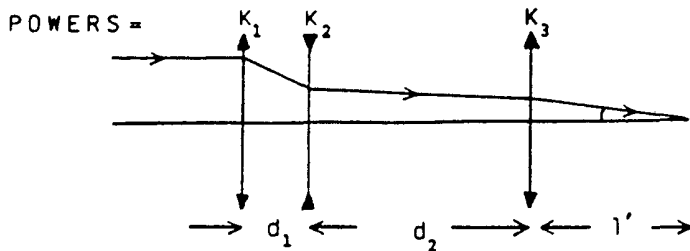


AND, if correct 1st order layout chosen, focusing action can be very rapid.

Figure 18. Focus shift relative to lens movement

Figure 18 shows a graph of image shift relative to the unity magnification (plus or minus) image position for a finite

conjugate negative lens system having a fixed object point : it demonstrates the well-known fact that minimum image shift with respect to lens movement is attained at a magnification of ± 1 . Conversely, a large image shift relative to lens movement will be obtained well away from unity magnification. Use can be made of the latter in a simple lens system where the finite distanced, fixed object is provided by a positive lens which is followed by a moving negative lens operating well away from $\text{magn} = \pm 1$. In this case, however, lens movement also causes a large change of focal length. Provision of a fixed rear positive lens enables a solution to be found where a rapid focusing effect is accompanied by little change of focal length.



CONDITIONS:-

(1) Overall power = unity

(2) Large shift of focus w.r.t. lens movement:-

$$\frac{\delta l'}{\delta d_1} = K_2 + K_1 K_2 (d_2 - d_1) \quad \therefore \quad K_2 = \frac{\delta l' / \delta d_1}{1 + K_1 (d_2 - d_1)}$$

for low K_2 :- high +ive K_1 ; moving lens as near front as possible

(3) Constant EFL during lens movement

$$\frac{\delta U_3}{\delta d_1} = K_3 - K_1 + K_1 K_3 (d_2 - d_1) = 0 \quad \therefore \quad K_3 = \frac{-K_1 K_2}{\delta l' / \delta d_1}$$

Figure 19. Small movement athermalization conditions

6.2.Small movement athermalization

Figure 19 derives the three conditions that need to be satisfied for a small movement mechanically-athermalized system¹³. Note, however, that a small departure from the third condition is preferable in that there is usually a small thermally-induced change of focal length as well as a defocus : ideally the former should be at least partially corrected by the athermalizing movement. The second condition very clearly indicates that, for a given focus shift relative to lens movement, the lowest moving lens power - and therefore lowest aberration/boresight variation - is achieved when :- a) first lens power is positive and high; b) the moving lens nominal position is as far forward as possible. For greatest simplicity of lens construction, the three conditions can be arranged to give the first order layout of a Petzval lens thus making it possible to correct all Seidel aberrations (except SIV which is low anyway).

A thin lens example of a small movement athermalized layout calculated using the equations in Figure 19 is shown in Figure 20. To reduce the thermally-induced change of focal length, the rear lens has been made into a ZnSe/ZnS pair: change of focal length is then only 0.2% for a temperature change of 50 degrees celsius.

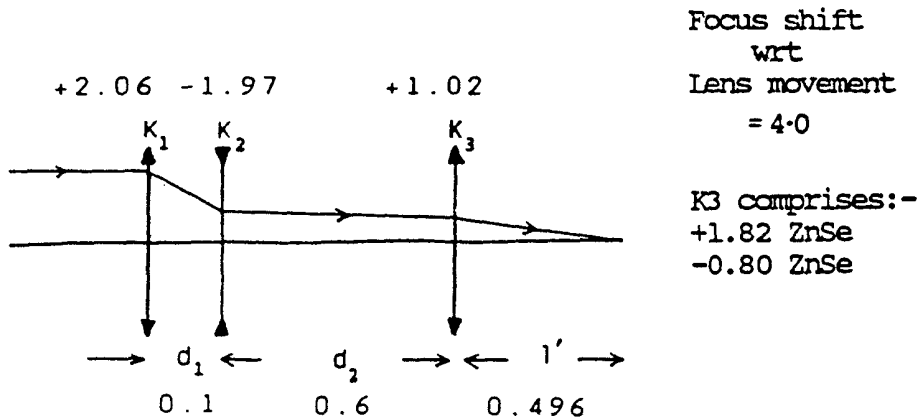


Figure 20. Thin lens small movement solution

The relatively small mechanical movement required by the solution shown in Figure 20 can be achieved by a combination of high/low expansion metal rods such as that shown in Figure 21.

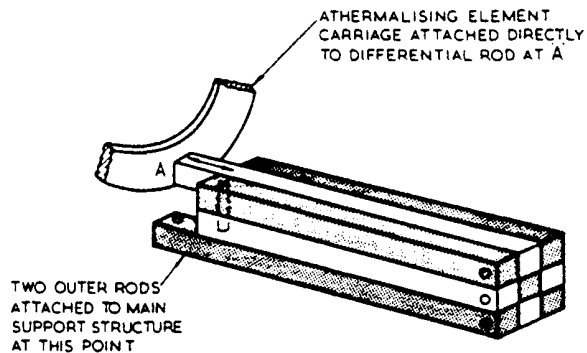


Figure 21. Lens movement from differential expansion

7. SUMMARY

The problem of defocus with temperature in an infrared optic can be avoided but the options to do so are limited to systems involving mirrors and usually therefore obscuration of the aperture (for other than a strip field of view). The table below summarises the various athermalization methods described in the paper. There is no really clear winner, optical athermalization is the most elegant, the mechanical methods demonstrate the trade-off between complexity, athermalizing movement and potential for more than one field of view. The method to be preferred in a particular case depends on the requirement : a simple rule-of-thumb is that optical is best for small systems, passive/active mechanical for large. Of the mechanical methods, active is most suitable for multi field of view and small movement passive where unreliable mechanisms or motors are best avoided.

The basic alternatives and their relevant features are summarised in Table 1. Three specific options are illustrated in Figure 22 which shows alternative designs for a 90 mm focal length, F/1.5, 5 degree field of view diffraction-limited optic.

8. ACKNOWLEDGEMENTS

Thanks to Phil Copeman for the drawings, Sue Pilkington for typing the manuscript and the directors of Pilkington Optonics for permission to publish.

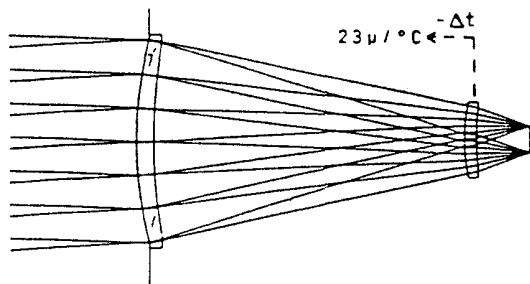
<u>Method</u>	<u>Single Multi FOV</u>	<u>Refl. Cat. Refr.</u>	<u>MTF over Temp</u>	<u>Cost</u>	<u>Power</u>	<u>Relia- bility</u>
Avoid	S	R/C	H	L	NO	H
Mech. Manual	S	R/C/Rr	M	L/M	?	M
Mech. Passive	S/M?	R/C/Rr	M	L/M	?	M
Mech. Active	S/M	R/C/Rr	M	M/H	Yes	M
Optical *	S	C/Rr	H	M	No	H
Mech. Sm. Movement	S	Rr	M/H	M	No	H

* Potential size limitation

Table 1. Summary of IR athermalizing methods

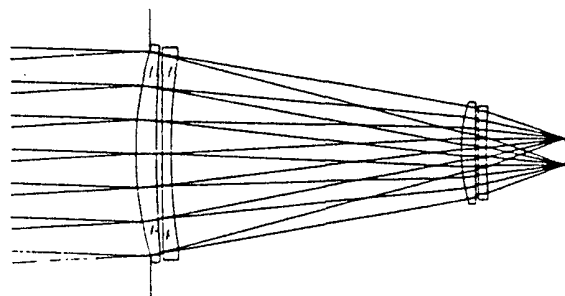
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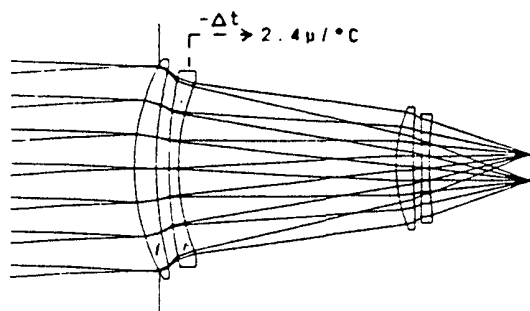
Mechanical

- Simple/OK materials
- Large movement
10μ/°C whole lens)
- $\Delta F = 2.3 \times 10^{-4} \Delta t \cdot F$



Optical

- Nothing moves
- $\Delta F = 0.7 \times 10^{-4} \Delta t \cdot F$
- Nasty materials



Improved Mechanical

- Small movement
- OK materials
- $\Delta F = 0.4 \times 10^{-4} \Delta t \cdot F$
- Boresight?

Figure 22. Examples of 3 methods of IR athermalization

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