Critical Review Vol. CR43, Optomechanical Design, ed. P.R. Yoder, Jr. (July 1992) Copyright SPIE

Athermalization of optical instruments from the optomechanical viewpoint.

Thomas H. Jamieson
Lockheed Missiles and Space Co., Palo Alto, California.

ABSTRACT

The refractive properties and physical dimensions of optical components change with temperature, and hence also do the characteristics of optical systems. Athermalization is the principle of stabilizing the optical performance with respect to temperature, either by designing the optical elements and mounts to be mutually compensating, or by including movable corrective mechanisms. For refractive materials, two coefficients can be defined which characterize the thermo-optical sensitivity, one applicable to uniform temperature changes, and the other to spatial temperature gradients. For normal optical glasses, the effects are small, but for plastics, infrared materials, and liquids, the thermal effects can be so great as to limit their usefulness. Passive athermalization is analogous to achromatism and optical systems can be designed simultaneously achromatic and athermal. The use of composite, and high expansion mounts employing plastics or fluids, gives greater control of thermo-optical effects. Active athermalization uses auxiliary power to drive compensating elements to maintain optical performance. Commercial optical design programs can be used to model and analyze thermally perturbed systems accurately.

1. INTRODUCTION

The theme of this session is stability, and in fact thermal stability is only one more requirement imposed upon the opto-mechanical design of imaging systems. The aim of the optical designer is to ensure that the geometrical aberrations are small and stable over the entrance aperture, over the required field of view, over the waveband of interest, over the range of magnifications in the case of zoom systems and, in addition, over the required range of environmental temperature.

The temperatures that optical instruments (even those produced for the consumer market) experience can be extreme. A furnace camera must endure several hundred degrees, while others operate near the absolute zero of outer space. At such temperature extremes, mere survival of the optics may be as important as maintenance of image quality. All optical instruments are designed to operate satisfactorily over some specified range of temperature, which in the case of military systems is typically from $-40^{o}C$ to $+70^{o}C$, and even commercial cameras and binoculars can be used in Arizona in summer and in Alaska in winter.

The temperature changes experienced by optics may be with respect to time, in which case the temperature is uniform throughout the optical system, or with respect to space, if there are temperature gradients over the optical elements. In general there is a combination of both. Temperature variations cause changes in the dimensions of the elements, mount and support structures, and in the refractive properties of the optical materials. The actual changes which can occur with increasing temperature, include:-

1) surface radii increase,
2) spherical surfaces become aspheric,
3) inter surface separations normally increase,
4) refractive indices of optical materials increase or decrease,
5) refractive index of air decreases,
6) strain on the optical elements causes warping and bi-refringence.

1.1 Physical Constants

The basic physical coefficients of the materials which control the magnitude of temperature effects are the **linear coefficient of thermal expansion** α defined as:-

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

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

$$\beta = dN/dT$$

where N is the refractive index of the transmitting material.

The values of α for virtually all optical materials are positive, vary considerably in magnitude, and for a given material are fairly constant over a wide temperature range. The values of β vary in sign and magnitude for different materials and vary considerably with temperature and wavelength. Care should be taken to distinguish between the value of β relative to air and relative to vacuum (absolute), which can differ significantly due to the large change in the index of air. For any refracting material the index relative to vacuum N(abs) is related to that relative to air N(rel) by:-

$$N(abs) = N(rel) \times N(air)$$

where N(air) is the index of air relative to vacuum. Differentiating gives:-

$$dN/dT(abs) = dN/dT(rel)\ N(air) + N(rel)\ dN(air)/dT$$

Since N(rel) is very close to unity we have:-

$$\beta(abs) = \beta(rel) + dN(air)/dT$$

The value of N(air,T) varies with temperature T according to Penndorf (1957) as follows:-

$$N(air,T) = 1.0549\ (N_{15} - 1)/(1 + 0.00366T).$$

Differentiating with respect T gives dN(air,T)/dT as:-

$$dN(air,T)/dT = -0.003861(N_{15} - 1)/(1 + 0.00366T)^2$$

where N_{15} is the index of air at 15°C, and this according to Edlen (1957) varies with wavelength as:-

$$(N_{15} - 1)x10^8 = 6432.8 + 2949810/(146 - \nu^2) + 25540/(41 - \nu^2)$$

where $\nu = 1/\lambda$, and λ the wavelength is in μ and T in centigrade. The value of dN(air,T)/dT at 15°C and pressure 760 mm is $-0.964x10^{-6}$ for the wavelength 0.55μ.

2. SPATIAL TEMPERATURE DISTRIBUTION

All portions of an optical system may not be at identical temperatures. Change of ambient conditions, varying solar load, removal of the optics to different environments etc., lead to quasi-stationary temperature differences between elements, and over the element surfaces themselves. An example is that of the optical mount at a different temperature from the optical element and the environment, which occurs frequently in both military and commercial instruments. It has been shown that, for the ideal case of a plate held in a circular mount of infinite extent and conductivity at elevated temperature, a radial quadratic thermal gradient exists over the surface of the plate. This is approximately true for finite mounts, finite conductivities and for lenses as well plates.

Most optical systems only have to endure changing environments but in a few, the elements are deliberately cooled. In high sensitivity longwave infrared sensors some optical elements as well as the detectors are cooled to cryogenic temperatures to increase the signal to noise, and in some cases this cooling must be effected within an few minutes. Mirror surfaces are cooled from the rear, whereas, lenses can only be cooled from the periphery. Athermalization in these cases corresponds to minimizing the magnitude, duration, and effects of thermal gradients.

2.1 Refractors

Consider the effects of temperature change on an optical element of thickness S, small compared to its diameter. This implies that longitudinal temperature gradients are being neglected. The change in optical path difference dW along a reference ray through the center of the element at temperature T, and that along an arbitrary ray through a part of the element of thickness S+dS at temperature T+dT, is:-

$$dW = (N - 1)\ S - (N + dN - 1)\ (S + dS)$$

Now since $dS = \alpha\ S\ dT$ we may rewrite this as:-

$$dW = S\,(N-1)\,\gamma$$

where:- $\gamma \doteq \beta/(N-1) + \alpha$

is a thermo-optical coefficient, which depends only upon the physical properties, and describes the sensitivity to spatial temperature distributions. Thus the magnitude of wave aberration dW for a plate or thin lens due to a temperature gradient depends only upon the maximum temperature difference, the element thickness and the optical material, and to this approximation is independent lens diameter and shape.

The majority of optical glasses have values of γ in the range 5 to 25×10^{-6}, except the special fluor crown (FK) and phosphate crown (PK) glasses from Schott and Ohara and the ATF glasses from Hoya. For the common optical glass BK7 (N =1.518 and $\gamma = 9.9 \times 10^{-6}$), of thickness S=10mm, and dT = 10^{o}C, the wave aberration induced is 1.25λ (λ = .546 μ). This is a significant aberration! Figure 1A shows the wave aberration calculated by finite raytrace of a simulated quadratic thermal gradient of 10^{o}C between center and edge of a 10mm thick lens of BK7. This result is typical of standard glasses. A few special glasses, however, have been developed with small and even negative values of γ to desensitize them to gradients, such as FK51, PK51, and FK03 from Ohara. Figure 1B shows the corresponding wave aberration for a lens of FK03 of the same thickness, with the same thermal gradient. Those glasses with small values of γ are those whose increase in physical path length is balanced by the decrease in refractive index.

For optical plastics the γ values are much greater, in the range -100 to -200×10^{-6}, and since the heat capacities and thermal conductivities of plastics are low, the probability and magnitude of potential temperature gradients are high. Figure 1C shows the corresponding wave aberration for the same gradient applied to a polycarbonate lens ($\gamma = -117 \times 10^{-6}$) of the same dimensions. Note the scale on the wave aberration curve in this case is greater by a factor of 10.

For optical materials in wavebands other than the visible, the effects are also large. Section 4.1.2 gives a fuller description of infrared materials, but for typical materials such as germanium and chalcogenide glasses (AMTIR1, ZnS etc.) in the infrared, the γ values range from 50 to 150×10^{-6}, and for the alkali metal halides such as NaCl, KBr etc., the values are mostly negative from -10 to -120×10^{-6}. The wave aberration (for λ = 10 μ) of a 10mm thick germanium singlet subject to the above gradient, is illustrated in Figure 1D. The very large value of

γ for germanium creates a significant aberration, but the combination of thermal capacity, conductivity, and long infrared wavelength, means that thermal gradients are generally not so serious in germanium systems.

The negative values of γ give rise to the possibility of balancing positive and negative γ materials together, to produce a resultant zero effect. As stated above, only a few catalog optical glasses have negative γ values, one such being FK03. To illustrate the technique of desensitizing designs, we compare the effects of the above thermal gradient on a common BK7/SF2 doublet, to that of a doublet of FK03/SF2, in Figures 2A and 2B. In the latter example the relative thickness of either element is varied to achieve the balance, and the thermal changes to the wavefronts are greatly reduced, but some higher order effects are becoming evident.

We have noted the deleterious effect of thermal gradients on the optical performance, but an equally important aspect of athermalization is the prevention of gradients in the first place. Gradients are minimized in magnitude and duration by selecting materials which can absorb large amounts of heat with small resulting temperature rise, and conduct this heat away rapidly. A measure of this ability is the quantity, the thermal diffusivity, defined as:-

$$k/(\rho\, c)$$

where k is the thermal conductivity, ρ is the density, and c is the specific heat.

The values of the diffusivity for a material give a comparative indication of its tendency to create and sustain temperature gradients, and this value can be easily calculated from glass catalog data. Optical glasses have quite high values, optical plastics are low, and germanium is high compared to other infrared materials.

2.2 Reflectors

The thermal properties of pure mirror systems are determined by their expansion coefficients, since their dN/dT values are zero. Modern mirrors, especially those for large aperture, astronomical, or space applications, are complex structures, and their thermal design and analysis is beyond the scope of this paper, except for a few general comments. Solid monolithic construction for mirrors becomes increasingly impossible as their diameter increases. The weight and rigidity of mirror materials cause them to deform under their own weight. Lightweighting is achieved by, say, molding or machining recesses in the mirror rear surface, or by employing a composite structure, of a thin mirror face and rear sheet, fused to a ribbed or "egg-

crate" type support structure. This technique simultaneously reduces the mirror weight and by reducing the heat capacity, improves the temperature uniformity across the surface. Thermal analysis is further complicated by the fact that the cross section of the support structure may vary in thickness between the mirror center and edge, in the shape of a single or double "arch", to increase the mirror rigidity.

As stated in Section 2, in sensitive infrared systems, the optical elements both refractive and reflective, are often cooled to prevent the thermal background radiation from swamping the sensor signal. The elimination of surface temperature gradients depends upon material choice, and additionally, upon the design of the cooling system, which may simply be radiation cooling to vacuum in space applications, or mechanical refrigerators or fluid transfer cooling for rapid cooldown applications. Uneven mirror cooling results in surface deformations, and athermalization may be a very involved procedure. The choice of the face sheet and support structure materials is particular important, with beryllium being particularly advantageous. The method and area of attachment of face sheet to support structure can greatly affect thermal uniformity of the mirror surface and the consequent wave aberrations.

Modern mirror optical designs often employ a high degree of decentering to avoid central obscuration problems, and in this case thermal gradients or even uniform temperature change, cause deviations of the line of sight, which have to be taken into account at the design satage. For fast cooldown mirrors, note that the mirror surfaces only are cooled, and the mount and spacer remain at ambient temperature.

3. TEMPERATURE CHANGE WITH RESPECT TO TIME

Different considerations apply in the case of thermal "soak", where the complete optical system is at a uniform temperature, but this varies with time. The primary effect is to produce a change in focus position, and to a lesser extent, to change the magnification and upset the balance between geometrical aberrations, all of which cause serious degradations in image quality.

It is instructive to calculate the individual contributions to focus shift for a typical single lens, due to radius change, thickness change, and index change. We shall consider three materials, namely, BK7, polycarbonate, and germanium, since they span the range of available thermo-optical constants. The results, as a percentage of focal length, calculated from simple first order ray tracing, are given below:-

	radius	thickness	index	total
BK7	.0143	-.00045	-.0114	.00238
polycarbonate	.1399	-.00983	.4746	.6056
germanium	.0118	-.00059	-.2644	-.2532

We see that the effects are additive; the radius effect is always positive; the index effect can be of either sign and is usually the greatest in magnitude; and the thickness effect is an order of magnitude smaller. Consequently, we can consider, without large error, only "thin" lenses.

Each lens has two radii R_1 and R_2, refractive index N, spectral dispersion ν, linear expansion coefficient α, and temperature coefficient of index β. As a general rule, the optical designer chooses the values of R_1, R_2, and N to permit the lens to operate over a finite aperture and field, ν for operation over a finite waveband, and α and β for operation over a finite temperature range. The converging power K of a thin lens is given by the well known expression:-

$$K = (N-1)(1/R_1 - 1/R_2)$$

Differentiating with respect to temperature we have:-

$$dK/dT = (1/R_1 - 1/R_2)\, dN/dT - (N-1)(1/R_1^2 dR_1/dT - 1/R_2^2 dR_2/dT)$$

Since $\alpha = 1/R\ dR/dT$ we can rewrite this as:-

$$dK/dT = (N-1)(1/R_1 - 1/R_2)(\beta/(N-1) - \alpha)$$

Thus:- $$dK/dT = K\,\delta$$

where:- $$\delta = \beta/(N-1) - \alpha$$

is a second thermo-optical coefficient which characterizes the change of converging power of the lens with respect to temperature. We can write this relationship in terms of the lens focal length f, which is equal to 1/K, as:-

$$df = -\delta f\, dT$$

and thus $-\delta$ is analogous to a "focal length expansion coefficient", namely the fractional change in focal length per degree of temperature change.

The value of α is positive for all refracting materials, and the value of δ for optical glasses range from -32×10^{-6} to 22×10^{-6}. Those optical glasses with small δ values, are those for which the increase in focal length, due to expansion of surface radii, is balanced by a corresponding decrease, due to higher index. The δ values of optical plastics and infrared materials are (similar to γ), more extreme than optical glasses.

We see that there are two coefficients, γ and δ, both functions of α and dN/dT, which are useful in describing optical temperature effects.

Note the relationship between them, namely, that $\delta = 2\alpha + \gamma$. Thus glasses with small values of γ, have large values of δ, and we have the somewhat paradoxical situation that those glasses which are insensitive to temporal thermal gradients are highly sensitive to spatial thermal gradients. For example the Schott glass FK51, which has the one of the smallest numerical values of γ in the catalog, has one of the largest values for δ. For plastic and infrared materials the values of dN/dT dominate, and there is little difference between γ and δ.

4. ATHERMALIZATION OF FOCUS - TECHNIQUES

Uniform temperature change causes optical performance degradation, primarily through image defocus. The means employed to counteract the effect come under three general principles.

Passive Athermalization - Optical
No moving parts are employed, and the onus is on the optical designer to choose appropriate optical materials to follow the mechanical expansion.

Passive Athermalization - Mechanical
Moving parts may be employed, but the energy required for motion comes from the thermal expansion itself, and the onus is on the mechanical designer to choose the structure to match the focus shift.

Active Athermalization - Electromechanical
No optomechanical compensation is attempted and supplied energy provides motion by means of an electromechanical servo system, to track the focus change.

The necessity and/or choice of athermalization method depends upon the application of the optical instrument, its size, weight, cost, required performance, and environmental specification.

4.1 Passive Athermalization - Optical

The concept of designing optics to be insensitive to temperature change is not new. A paper of Perry dates from 1943, and Grey applied the ideas to military optical plastic designs as early as 1948. Volosov dealt with thermal soak in 1958, and Kohler and Strahle(1968) describe various lens designs, some athermal with respect to soak and others with respect to spatial gradients. The results of these investigations, indeed, were probably behind the development of some special glasses types at Schott Glaswerk. Straw and Estelle (1980) in separate papers investigated the plastic/glass Cooke triplet system used in inexpensive commercial cameras. Several review papers have appeared, Jamieson (1981), and, devoted to the infrared Roberts (1989) and Povey (1986), who emphasizes active techniques.

The goal of athermalization is that the focus position should remain fixed with respect to the mount structure, not necessarily fixed with respect to the lens, i.e. we match the focus change of the optical system to the thermal expansion of the mount. To achieve this in single lens systems, we choose a glass with the same value of δ as the value of $-\alpha$ for the support structure. The expansion coefficients of metal optical mount materials range from almost zero for invar steel to 26×10^{-6} for magnesium. Modern construction plastics have much larger coefficients, and although they have undesirable properties such as hysteresis, and moisture absorption, they are increasingly employed in medium quality optics because of low cost, and ease of fabrication.

Aluminum is probably the most common prototype mount material, and the value of α (23.6×10^{-6}) is large compared to the δ value of common optical glasses except for the special FK and PK glasses. Note that these glass types (say FK51) have two useful thermal properties, namely values of γ close to zero making them insensitive to spatial thermal gradients, and values of δ, which closely match the properties of aluminum. The use of optics of a single optical material, however, is normally permissible only where chromatic aberration is unimportant, such as laser optics.

4.1.1 Doublets

Achromatic operation (i.e. over a finite range of wavelengths) demands that refractive systems employ multiple materials of differing dispersive powers. The powers K_1 and K_2 of the individual elements of an achromatic doublet of total power K, are given by the well known relations:-

$$K_1 = \nu_1 K/(\nu_1 - \nu_2) \quad \text{and} \quad K_2 = -\nu_2 K/(\nu_1 - \nu_2)$$

where ν_1, ν_2 are the Abbe dispersion coefficients of the doublet materials. We can define δ_D, as the thermo-optical coefficient for the achromatic doublet by:-

$$K \delta_D = K_1 \delta_2 + K_2 \delta_2$$

where δ_1, δ_2 are the individual thermal- optical coefficients, which gives:-

$$\delta_D = (\nu_1 \delta_1 - \nu_2 \delta_2)/(\nu_1 - \nu_2)$$

The doublet will be athermal as well as achromatic if the value of δ_D is the same as $-\alpha$ for the mount. A search of the glass catalogs enables

the value of δ_D for achromatic material pairs to be calculated and matched to the mount to some tolerance. Approximately 150 doublet pairs from the Schott catalog, were found with a $-\delta_D$ value within $0.5x10^{-6}$ of aluminum. A requirement, however, on the glass choice is that the individual lens powers be small, otherwise the surface curvatures become impracticably steep, and the high order geometrical aberrations unacceptably large. This secondary requirement in the search reduces the number of solutions. Table 2 shows the individual lens powers for K equal to unity, of glass pairs matched to aluminum to the above tolerance, with the sum of the absolute values of K_1 and K_2 less than 3.5. Figure 3A gives the wave aberrations, at 20°C and 60°C, for one solution, namely the athermal pair FK5/SF14, of 250mm focal length at F/5, compared to a common BK7/SF2 doublet of the same aperture and focal length.

A similar search for solutions can be carried out for any specified mount material. Since there is normally a greater choice of optical glasses than mount materials, it is more reasonable that the optical designer should conform to the mechanical specifications. If, however, the glass choice is restricted by, say, special transmission requirements, the mechanical designer may have to employ unusual materials or even a composite mount of multiple materials (see section 4.2) to achieve the deired expansion.

4.1.2 Infrared Imaging Systems

Probably more effort has been devoted to athermalizing infrared optical systems than to all others, because dN/dT of most materials suitable for use in this waveband, is extremely high, and this type of system frequently must conform to full military environmental temperature range. The materials used fall into three groups, namely semiconductor types (germanium and silicon), chalcogenide glasses (ZnSe,AMTIR1), and crystalline alkali metal halides (NaCl, KBr etc.). Germanium is a most desirable infrared optical material because of its high refractive index and low spectral dispersion, but it has the great disadvantage that its refractive index and even transmission are highly temperature sensitive. To quantify the effect, we compute the temperature range dT over which a germanium lens maintains diffraction limited performance, which by convention implies a defocus aberration of $\lambda/4$. For a lens of focal length f, the focal shift due to a temperature increment dT is -d f dT, and this gives rise to a wave aberration:-

$$dW = - \delta f dT/(2 F\#)^2$$

where F# is the relative aperture (ratio of focal length to entrance aperture) and if $dW = \lambda/4$, then solving for dT, we have:-

$$dT = 2\lambda (F\#)^2 / (f\delta)$$

For a typical infrared lens of germanium of 500mm focal length at F/5, the allowable temperature change is only 8^oC. If we compare this to a similar doublet lens of BK7/F2, the corresponding temperature tolerance in wavfront terms is comparable, and athermalization is important in both types of system. Note that for germanium, the value of $-\delta$ is $-136x10^{-6}$, which implies that as the temperature increases, the focus moves in towards the lens, and thus it will match no ordinary spacer. Table 3 quotes a collection of optical materials and their coefficients, suitable for the 8 μ to 12 μ thermal infrared waveband.

We may add an element of a different material to form a doublet to athermalize the germanium. A suitable material is KRS5, which, although a double halide (thallium bromo-iodide), is insoluble in water and can be optically polished. Figure 3C shows the wave aberrations for a germanium single lens of 400 mm focal length at F/4 at 20^oC and 60^oC contrasted with a similar Ge/KRS5 doublet. We see that the temperature change has added 2λ to the germanium lens, whereas it produces no measurable aberration change in the doublet. The lens powers appropriate for athermalization mean, however, that both elements are of the same sign, so that the chromatic aberration of the doublet is uncorrected and greater than germanium alone.

Reliable data on the thermal coefficients of optical materials is often difficult to obtain. The optical glass manufacturers quote dN/dT values for their products, although not all glasses are included. Schott and Ohara give values for up to six temperature ranges from -40^oC to $+80^oC$, and at five wavelengths in the visible waveband, but Hoya quotes the value at 0.6328μ only. The situation is more unsatisfactory with other materials and wavebands especially at low temperatures. The values for optical plastics are somewhat uncertain due to their variable composition. Although some chalcogenide glasses may be of varying composition, other infrared materials are either simple elements (Ge and Si), or stoichiometric compounds (KBr, ZnSe) with well defined indices. Probably the main reason for the lack of reliable thermo-optical data of infrared materials, is insufficient measurements. This lack of reliable infrared thermal data is especially significant, since cooling is often employed, and the optical properties change considerably on cooling to cryogenic temperatures, and even the expansion coefficients of mount materials decrease significantly, approaching zero at 0^oK.

Because of the importance of germanium as an infrared optical material, we repeat its thermal (from 100 - 293^oK) and spectral variation

(from 1.9 to 18μ) of the index N(λ,T), which according to Li (1980), is as follows:-

$$N^2(\lambda,T) = e(T) + L(T)\,(A_0 + A_1T + A_2T^2)/\lambda^2$$

where $L(T) = \exp(-3\,M(T))$,

$A_0 = 2.5381$, $A_1 = .001826$, and $A_2 = 2.8888\times10^{-6}$,

$e(T) = 15.2892 + 1.4549\times10^{-3}T + 3.5078\times10^{-6}T^2 - 1.2071\times10^{-9}T^3$,

$M(T) = -.00089 + 2.626\times10^{-6}(T-100) + 1.463\times10^{-8}(T-100)^2 - 2.221\times10^{-11}(T-100)^3$,

with λ in μ and T in degrees K . Although this very complicated expression is claimed to be valid only down to 100°K, we have used it at 80°K and 40°K without noticeable error.

4.1.3 Triplets

By employing three materials, it is always possible to achromatize and match exactly the thermal defocus to the expansion of the mount. For three thin elements close together of total power K, the system will be achromatic and athermal if:-

$$K_1 + K_2 + K_3 = K$$

$$K_1/v_1 + K_2/v_2 + K_3/v_3 = 0$$

$$K_1\delta_1 + K_2\delta_2 + K_3\delta_3 = K\alpha$$

For visible waveband systems employing conventional glasses, this degree of athermalization is rarely necessary, but it may be used with advantage in the infrared waveband, where the materials have large values of α and dN/dT. Applying the above equations to the materials in Table 3, generates 364 solutions, from which we select those with the smallest absolute values of lens powers (Σ K), in order that the systems be reasonably practical. A series of achromatic and athermal triplets with small absolute powers, is given in Table 4. The smallest power solution is the triplet Ge/NaCl/CsI with a value for Σ K = 1.11, for a total power of unity. For durable practical solutions, we should probably not use crystalline halides, which are brittle and water soluble, except perhaps KRS5. With this restriction the best solution is Ge/ZnS/KRS5 (Σ K of 1.15), and Figure 4A shows its wave aberrations at 20°C and 60°C. The best non-halide combination is ZnS/AMTIR1/Ge with Σ k of 3.09.

Infrared materials other than germanium and silicon, are expensive and difficult to fabricate, so that if we must use elements of those materials, there is some advantage in keeping their diameters small. We

can achieve this if we use a single germanium lens and a small sub-aperture doublet of the other materials, separated by a distance d from it. The above equations now become:-

$$h_1 K_1 + h_2 K_2 + h_2 K_3 = h_1 K$$

$$h_1^2 K_1/\nu_1 + h_2^2 K_2/\nu_2 + h_2^2 K_3/\nu_3 = 0$$

$$h_1^2 K_1 \delta_1 + h_2^2 K_2 \delta_2 + h_2^2 K_3 \delta_3 = K\alpha$$

where h_1, and h_2 are the ray heights at the single lens and doublet respectively. Taking $h_2/h_1=0.5$ we cut in half the size of the non germanium elements and search for solutions using the above equations. Note that the separation d is given by:-

$$d = (1 - h_2/h_1)/K_1$$

and we choose only those solutions which give rise to positive d values.

Using the 14 materials, there are 91 such systems, 47 of which have a positive d and the solution with the smallest value of Σ k (2.02) is Ge-ZnS/KRS5. The sub-aperture doublet provides three benefits; it balances the chromatic, and the thermal aberrations of the germanium single lens, and corrects the spherical aberration, eliminating the need for aspherizing the germanium. The design is shown in Figure 4B, and although rather long (1.7 times the focal length), shorter systems of this type do exist with higher lens powers.

4.1.4 Multiple Lens Systems

A general expression for the thermal defocus of a system of separated lenses is very complex, but a good approximation can be derived by consideration of the wave aberration dW_i due to a change df_i in the focal length f_i of each lens. The value of dW_i is given by:-

$$dW_i = 0.5 (h_i/f_i)^2 df_i$$

where h_i is the paraxial ray height at each lens, and summing over all lenses, gives the total wave aberration as:-

$$\Sigma dW_i = 0.5 \Sigma (h_i^2 K_i \delta_i) dT$$

Compound lens systems consist of units of single lenses, doublets or triplets and the total thermal defocus can be calculated, by applying this relationship, with the values of δ_i corresponding to each unit. Note that this method takes no account of the changing mechanical spaces between the lenses. In addition, for a general set of lenses the length of the mount is not even approximately equal to the focal length. An improved procedure is to convert the wavefront ΣdW_i to an effective focus shift, and subtract from it, the expansion of the actual lens mount. The mount

length is approximately equal to the overall length of the optics from first element to final focus, and varies with the type of lens design.

As an example, the telephoto lens, commonly used because of its compact nature, has an overall length less than its focal length, and consists basically of two lens groups, with powers K_1 and K_2, which are of opposite sign. For a total power of K, typical values of K_1 and K_2 are K_1=2K and K_2=-K with a separation of 0.25/K, which gives $dW = 0.5(1.75h_1^2K\,\delta)$, where h_1 is the semi-aperture and δ is some approximate average for the glasses in the system. Thus the thermal defocus for a telephoto lens is greater than for the equivalent single lens, while the length of the mount is smaller, and for the above case is 0.75/K. On the other hand, in a Petzval type lens, used for its wide aperture capability, the converging power is shared equally between two groups of the same sign. Typically $K_1 = K/2$ and $K_2 = K$ and in this case the thermal defocus is smaller than the focal length, while the overall length is longer, namely $0.75h_1^2K\delta$ and 1.5/K, respectively.

Zoom lenses are extreme cases of multi-lens systems, consisting of several groups of elements, some of which, move longitudinally to alter the gross focal length and others to re-focus the system for varying conjugate distances. The overall length bears little relationship to focal length and completely passive athermalization techniques are generally not possible in this type of system. Zoom lenses achieve their variable focal length effect by balancing the power of one group of elements against others, and even small thermal changes to the focal lengths or image positions of individual groups can greatly upset the overall zoom effect and the residual balance of chromatic and geometrical aberrations.

4.1.5 Plastic and Liquid lenses

Plastics are becoming increasing popular as optical materials because of the low cost of material and manufacture. The four most common types are acrylic, polystyrene, polycarbonate, and the co-polymer SAN. As was noted in section 2.1, their major disadvantage, is their temperature sensitivity, since both α and dN/dT values are all very large. To demonstrate this sensitivity, an acrylic lens of 100mm focal length has 0.55mm of thermal defocus for 20°C temperature change, and in an aluminum mount at F/5 this corresponds to 2.4 λ aberration. Although only a few materials exist, it is possible to athermalize all-plastic designs, if we employ three different plastics to satisfy the equations of section 4.1.3, and a highly expansive plastic mount. Figure 5A shows a close triplet design of acrylic, polystyrene, and SAN designed for a polycarbonate ($\alpha = 67.5\times10^{-6}$) plastic mount. The

design is achromatic and athermal and although individual lens powers are high, it can operate at F/5 over a large temperature range with respectable performance. The wave aberrations for this design are shown in Figure 5B.

The all-plastic separated (Cooke) triplet has been investigated in considerable detail, because of its importance as a lens for small format cameras. At low relative apertures, say F/8, the thermal defocus can just be tolerated, but wider apertures demand athermalization. According to Estelle, it is not possible to athermalize the all-plastic design. In order to correct the aberrations over a substantial field with three elements, the choice of powers for the elements is severely restricted, and the actual values required are approximately +2, -3, +2 , for a total triplet power of unity. When all elements are plastic, the resulting thermal defocus is of the same magnitude as a single plastic lens of unit focal length. Partial athermalization occurs if we choose plastic for one positive and one negative element, their defocus balances one another, and use ordinary optical glass, typically up front, for the third unbalanced defocus.

Recently, liquids have been proposed as optical elements, sandwiched between the elements of doublet or triplet lenses. The dispersive properties of optical liquids are even more extreme than optical plastics. Liquids of adequate consistency and specification for use in optical design, are manufactured by Cargille for use in refractometry, chemical analysis, engineering and forensic applications. The perceived advantage of optical liquids is that their abnormal optical properties permit their use as substitutes for expensive rare earth glasses, which are necessary in wide spectral waveband apochromatic lens designs. In effect, since these liquids are relatively inexpensive and only small amounts are required, we gain extra optical elements at little cost by filling the air spaces, in doublet and triplet designs, with them. This benefit is partially off-set, when we take into account the extra complexity of mount, required to retain the liquids in the appropriate space. An additional advantage is that coatings are not required on glass to liquid interfaces, which may reduce scatter fron the system.

We propose an additional use for such liquids, namely to athermalize plastic optical designs. An achromatic doublet of acrylic and polycarbonate gives medium quality performance, which degrades rapidly with temperature. If we add a liquid to the air space, we can achromatize and athermalize using the equations of Section 4.1.3. The effective expansion coefficient for the liquid is zero, and the radii and thickness of the liquid element are controlled by the plastics containing it. The doublet becomes a "cemented" triplet, and since we must maintain the individual optical powers, the triplet has only one degree of freedom, and can only be bent to minimize, but not correct, geometrical aberrations. The liquid we have used, has the extreme value of dN/dT -900×10^{-6} , and the wave aberrations of this design are shown in Figure

6A. The optimum bend has larger residual spherical aberration than the equivalent "dry" doublet, but has an order of magnitude higher thermal stability. The spherical aberration can be removed by aspherizing one surface, which may add little to the cost, since plastic is molded rather than ground and polished. In laser diode optics achromatization is not required, so we can maintain the athermalization yet reduce the spherical aberration, by adjusting the power distribution between acrylic and the polycarbonate elements. For a doublet of this type with 10mm focal length at F/3, the r.m.s. aberration is as low as 0.025 λ over a range of plus or minus 20^{o}C. The system and corresponding wave aberrations is illustrated in Figure 6B.

Several hundred of these liquids are available, together their refractive index, dispersions and dN/dT, from their manufacturer, but increased measurement accuracy is necessary, if they are used for crtical designs.

4.1.6 Reflective systems

For pure mirrors, there is no value of dN/dT to consider, and the value of δ for an individual mirror is simply $-\alpha$ of the substrate. In general reflective systems consist of multiple mirrors separated by large separations, and the change of these spaces has a significant effect on the total thermal defocus. Consequently the relationships of Section 4.1.4 are not generally applicable, since they ignore varying separations. If we consider even the simplest multiple mirror system, namely a two surface cassegrain or gregorian separated by a distance d , the expression for the thermal defocus is a complicated function of d , the two radii, and the two expansion coefficients. This expression is of limited value in the choice of mirror substrate materials for athermalization, but we can gain some insight into the possibilities if we consider the particular case of optical surface, spacer or mount material of being identical. All points on the optics and mount expand at the same rate and the system is self-athermalized since the focus remains precisely constant with respect to the mount. A typical example is diamond machined aluminum mirrors supported in an aluminum housing. A more general system is a two element cassegrain, with dissimilar mirror surface materials, held in a mount of a third material. The primary mirror has positive converging power and the secondary is diverging, so that it is somewhat analogous to a telephoto type construction. The mirror substrates might be of lower expansion materials (optical glass, ULE) than the mount (aluminum), or conversely, higher expansive substrates (aluminum) in a mount of lower expansion material (steel). Simple paraxial ray tracing shows that in the former case, the focus moves in towards the mirrors, while in the latter, the movement is away from the mirrors, and the actual movement can be quite large due to the telephoto effect.

If we calculate an actual case, namely, F/4 300mm focal length

cassegrain with a separation and back focus both equal to 75mm, i.e. the image is located at the vertex of the primary mirror. With a steel mount ($\alpha = 17.3 \times 10^{-6}$) a 40^{o}C temperature change produces 0.0519mm change in the length of the mount. With both mirrors of aluminum ($\alpha = 23.6 \times 10^{-6}$) the defocus is 0.248mm, whereas with beryllium mirrors ($\alpha = 11.6 \times 10^{-6}$) the defocus is -0.125mm. The corresponding aberrations are -2.68λ and $+2.44\lambda$ respectively. In principle, an appropriate choice of substrate materials, (the two mirrors need not be identical) and spacer material, allows any cassegrain design to be athermalized. Alternately the focal position can be moved back or forth to a specified position in either direction with respect to the mirrors. In practice the choice of substrate, and spacer materials, is driven by other considerations, and a perfect match may be impossible.

From the above, we see that an effective method of athermalizing an infrared telescope system is to convert a refractive design to reflective! The inverting telescope is a common component in thermal imagery, and is used to magnify (or minify) the system field of view to that of the scanner, typically 30^{o} to 60^{o}. The telescope consists of an objective and "eyepiece", the latter being invariably refractive and often of germanium, because its high refractive index allows the eyepiece to operate over this large field of view. If the objective is also germanium, the total system is very temperature sensitive. From section 4.1.2, the temperature rise causes the focus of germanium lenses to move inwards, while the mount moves outwards, we see that the thermal defocus of objective and eyepiece add to produce a very large effect in the direction opposite to the mount. If the objective is reflective, then as described above, by proper choice of surface and mount materials, the defocus of the objective outwards from the mirrors, can be matched to the eyepiece defocus in towards the germanium lenses.

4.2. Passive Athermalization - Mechanical

The optical materials are fixed and the positions of the optical elements are controlled by choosing the mechanical structure such that its thermal expansion matches the thermal defocus of the optics. A large number of materials can be employed as spacers or structural elements, with a correspondingly wide range of expansion coefficients, from invar steel with α of zero or slightly negative, to plastics such as CR-39 with $\alpha = 138 \times 10^{-6}$. A list of potential structural and spacer materials is given in Table 5A.

A suitable spacer material, with exactly the correct value to match the thermal defocus in any particular case, is not always available. The effective expansion of the spacer can be modified by various techniques.

For example it may be set at an angle to the optical axis, say, by incorporating the expanding member into a strut type arrangement supporting the secondary mirror of a cassegrain telescope. The expansion of the strut is scaled by the cosine of the angle to produce a smaller displacement along the axis.

The expanding element may be in the form of a circumferential ring or series of rings in tandem. Their expansion can be made to drive a screw thread connected to a focusing element. In this arrangement, the effective thermal expansion can be negative, since the distance between element and focus can be decreased with increasing temperature by employing a screw thread of the appropriate direction. If the expansion rings are high expansion material, then considerable focussing movement can be effected.

More than one material may be used to form composite or multiple element structures. By combining spacers of length L_1 and L_2 of materials of expansion coefficients α_1 and α_2, we produce an effective expansion coefficient for the composite spacer of :-

$$(\alpha_1 L_1 + \alpha_2 L_2)/(L_1 + L_2)$$

Note that if L_2 is negative and greater numerically than L_1 then the effective expansion is negative, and corresponds to a re-entrant mount. The lengths L_1 and L_2 are of low and high expansion materials respectively, and if, say $L_2 = -.9\, L_1$, the value of α is $10\,(\alpha_1 - .9\alpha_2)$, based on the net spacing of $.1L_1$, which is of course much smaller than the overall mount length. For L_1 and L_2 of SS304 and Al1100 respectively, using Table 5A gives an effective α value of -39.4×10^{-6}. The lengths L_1 and L_2 of expanding material may be in the form of cylinders, one inside the other, or simple stacked rods. This technique requires an athermalizing mount length much greater than the system focal length. Consequently the method is most suitable for optical designs in which the overall length is considerably longer than the focal length, such as the inverted telephoto.

Another use of the expansion of composite material mounts is to control the position of a compensator element by means of a bi-metal element. Equal lengths of metals of differing expansion coefficients are fused together along their length, and when the temperature changes, the differential expansion of each material causes the device to distort into a circular arc. This distortion can be made to control the optical element position. A suitable bi-metallic arrangement to control a lens position is an annulus, or washer, which distorts from flat to spherical or conical. The outer periphery is fixed to the lens mount and the inner rim of the

annulus drives the focusing element back and forth.

Another effect which has been proposed for mechanical athermalization, is the expansion of fluids such as waxes, liquids or gases contained in a cylinder and piston arrangement or thin metal bellows. The high expansion coefficients of the fluids in this type of arrangement, can provide a great magnification of the focus compensator travel. The reservoir containing the fluid should have a large surface area to ensure fast heat transfer and prompt response.

All mechanical athermalization is passive in the sense that it is automatically controlled by the temperature and requires no power to be supplied. The methods are relatively simple and have high accuracy, but on the other hand, they have disadvantages of extra bulk, weight, cost, and suffer from high hysteresis and often low reliability.

4.3 Active Athermalization - Electromechanical

No attempt is made to thermally desensitize the optomechanical design and relies on compensator element(s) driven in a temperature controlled fashion using information from separate temperature sensors. This is properly a subject for a session on electronic or servo mechanism design, and is a brute force type solution to athermalization, which should be used only when other techniques fail. It is most suitable in complex optical systems such as multi configuration optics or zoom lenses, in which an electromechanical focus mechanism already exists. An electric motor drives the focusing compensator, usually through a servo loop, which receives control signals from temperature sensors, placed in several locations. Positional control can be simple analog direct drive or via digital processor, the latter being a much more flexible approach. In complex systems, the focus position is usually a non-linear function depending on many factors, among which is conjugate distance, and atmospheric pressure, so that the addition of temperature as a variable simply represents a perturbation to the control signals. The increased availability of electronic micro-circuitry renders the use of microprocessors and sophisticated software control, increasingly attractive. The penalty to be paid for this added flexibility, is considerable extra cost and weight, and lower system reliability.

5. THERMAL MODELING IN OPTICAL DESIGN CODES

Whatever method of athermalization is chosen, an accurate assessment of its effect should be performed by geometrical ray tracing. A number of comprehensive optical design programs are available commercially to analyze in detail the performance of optical systems. All such programs are capable of calculating the effects of temperature change (at least temperature soak), but some require considerably more user input than others. The capabilities of the programs vary considerably, and the

procedures described here are based on those available in Optima, the Lockheed in house software, and CodeV from Optical Research Associates. Both programs include comprehensive thermal modeling features, including uniform temperature change and radial gradient modeling. Of equal importance to the user, is the availability of a large number of stored physical constants for optical glasses, mirror substrate, and mount materials.

The detailed changes required to made to the optical system to accurately simulate the effects of temperature, are the following. The refractive index of air is converted to a nominal design temperature (usually 20^{o}C), using equations such as those in Section 1.1. The indices of all refractive materials are converted to absolute values by multiplying them by the air index. The air indices at the new temperature, follow from the above equations and the indices of the refracting materials are calculated using the values of the stored expansion and dN/dT coefficients. The value of dN/dT used, is interpolated according to the actual wavelength and temperature used. Optima stores the coefficients for 5 wavelengths and 6 temperature ranges, while CodeV has 5 wavelengths and a single temperature value.

The radius of each optical surface is increased according to its stored expansion coefficient. The effect of temperature on inter surface distances is less well defined. The elements are usually held in a single tube mount, and kept separated by means of spacers, which may be of a different material from the mount. Thus it may be difficult to determine whether the total mount controls the expansion of the optics and the spacers become loose and/or compressed by this expansion, or whether each lens and spacer expands according to its own coefficient and the mount "stretches" to accommodate their expansion. The mechanical designer may decide which is the more accurate assumption for his particular layout, and either option can be modeled by specifying the surface separations to the program in the appropriate manner.

Radial thermal gradients are modeled in an approximate fashion, by assuming that the refractive index and thickness of a lens element changes as a function of the radial distance from the optical axis. The temperature profile is converted to a thickness increment and fitted to an effective aspheric figuring function, added equally to the sag of both surfaces of the lens. Similarly, the temperature variation is converted into refractive index profile and fitted to a multi-term polynomial, which is used to compute the actual index at any ray height. For reasonably thin lenses, the index is constant along any ray through the lens, and conventional ray trace procedure is approximately valid, but for thick lenses a true gradient index ray trace should be used. Similarly axial thermal gradients may be approximated by dividing the lenses into thin sections by introducing extra dummy surfaces at differing temperatures.

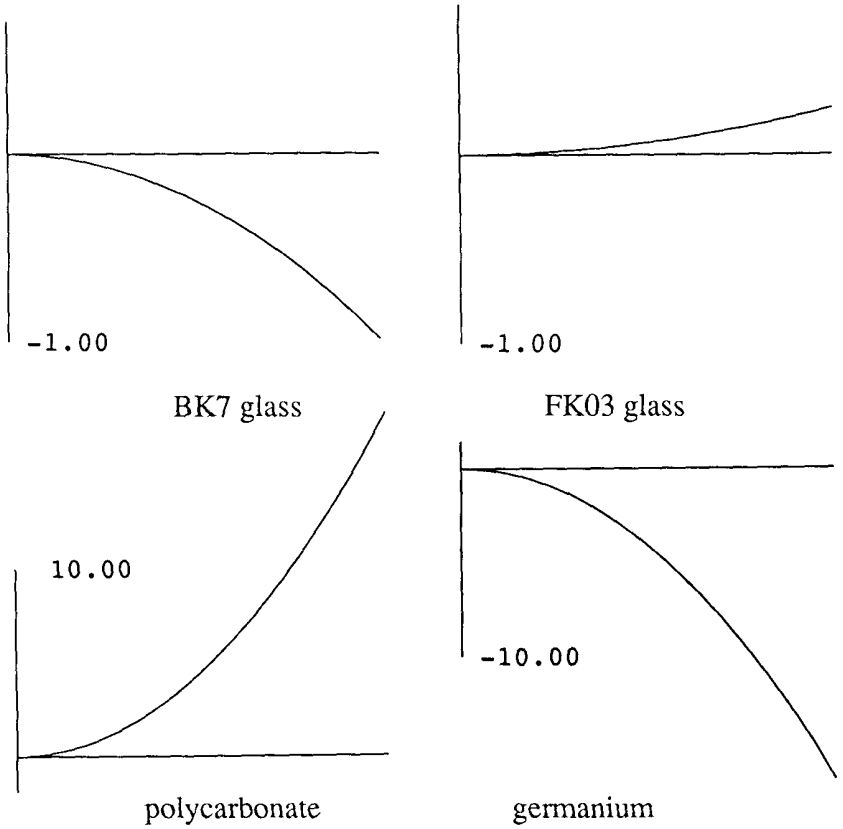
The design examples of thermal soak and thermal gradients, given in this paper were computed according to the above methods.

6. SUMMARY

We have described the effects of spatial and temporal thermal variations on the performance of a broad number of types of optical systems, and the computational procedures required to simulate accurately the performance reduction.. We have described some optical and mechanical design techniques, which we can use to stabilize or desensitize the image quality with respect to temperature. Whether and what type of athermalization is used, depends on a host of factors, including:- relative aperture, waveband, materials employed, single or multi focal length, image quality, environmental specification, and considerations of size, weight, cost, power, and reliability. As a word of warning, it should be remarked that systems can behave in an unpredictable thermal fashion, and some experimental verification may be advisable.

7. REFERENCES

R. Penndorf, J.O.S.A. **47**, 176-182 (1957)
B. Edlen, J.O.S.A. **43**, 339-344 (1953)
J. W. Perry, Proc. Pays. Soc. (London) **55**, 257-285 (1943)
D. S. Grey, J. O. S. A. **38**, 542-546 (1948)
D. S. Volosov, Opt. Spectrosc. **4**, (1958)
H. Kohler and F. Strahle, Proc. I. C. O. **9**, 116-153 (1972)
K. Straw, Proc. S.P.I.E. **237**, 386-391 (1980)
L. R. Estelle, Proc. S.P.I.E. **237**, 392-401 (1980)
T. H. Jamieson, Opt. Eng. **20**, 156-160 (1981)
V. Povey, Proc. S.P.I.E. **655**, 142-153 (1986)
M. Roberts, Proc. S.P.I.E. **1049**, 72-75 (1989)
H. H. Li, J. Pays. and Chem. Ref. Data **9**, 561-658 (1980)



Figures 1A to1D. Wave aberration due to quadratic thermal gradient of 10 ^{o}C in 10mm thick BK7, FK03, polycarbonate and germanium.

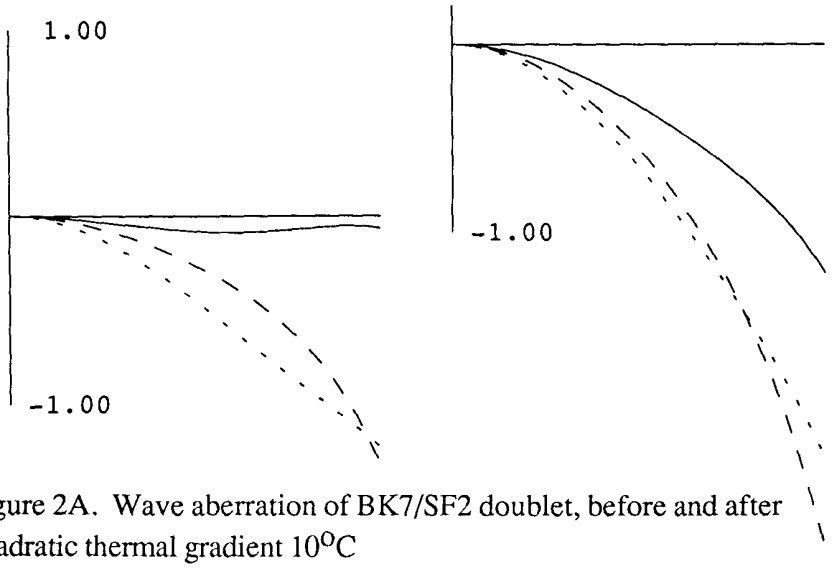


Figure 2A. Wave aberration of BK7/SF2 doublet, before and after quadratic thermal gradient 10^{o}C

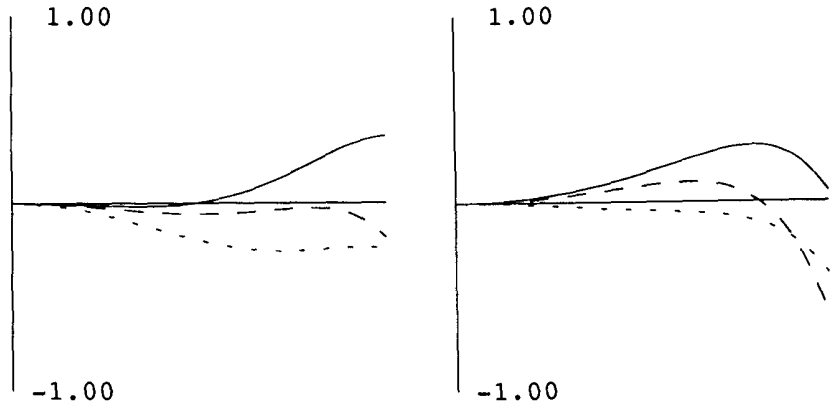


Figure 2B. Wave aberration of FK03/SF2 doublet, at uniform temperature and with quadratic thermal gradient 10°C.

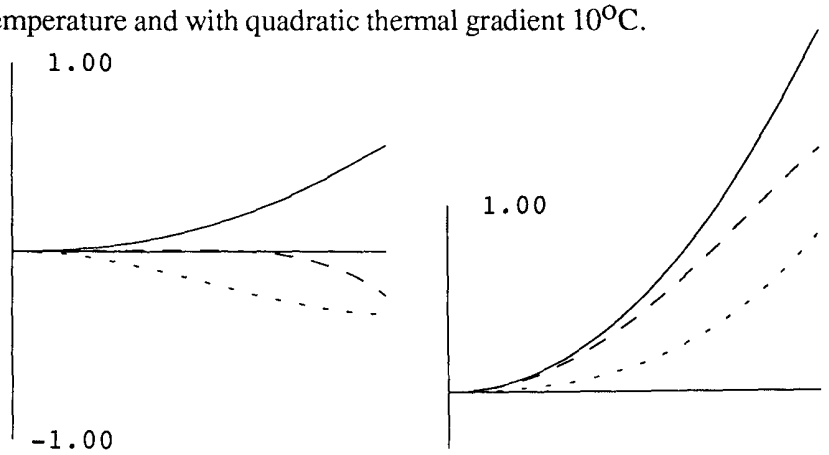


Figure 3A. Wave aberration of BK7/SF2 doublet lens(F/5, 250mm focal length) at 20°C and 60°C.

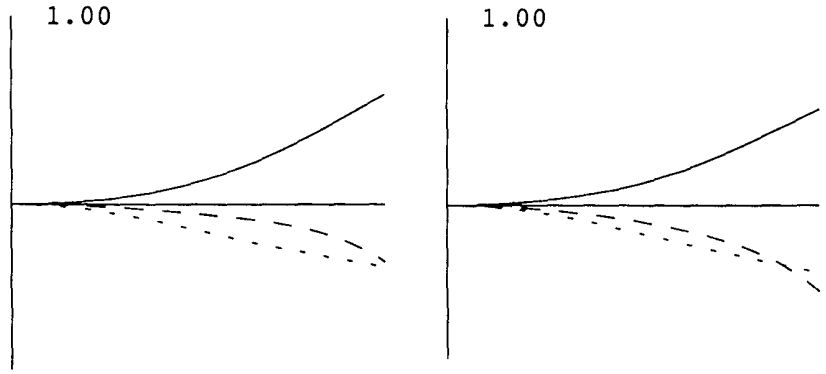


Figure 3B. Wave aberration of FK5/SF14 doublet lens(F/5, 250mm focal length) at 20°C and 60°C.

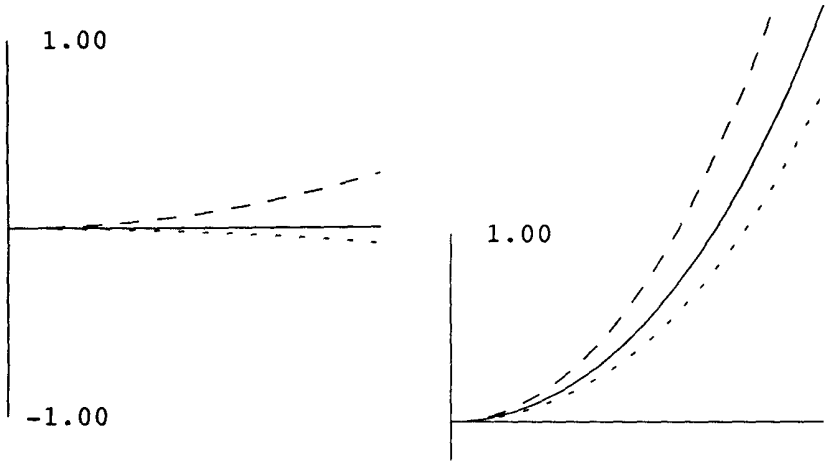


Figure 3C. Wave aberration of germanium single lens, (400mm focal length at F/4) at 20°C and 60°C.

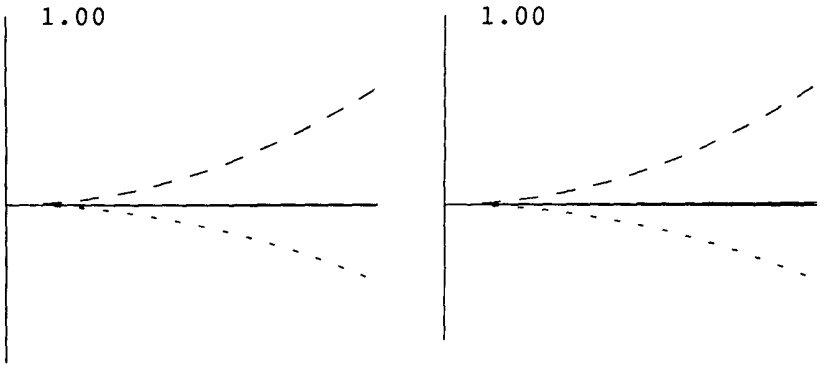


Figure 3D. Wave aberration of athermal, non-achromatic Ge/KRS5 doublet lens, (F/4, 400mm focal length) at 20°C and 60°C.

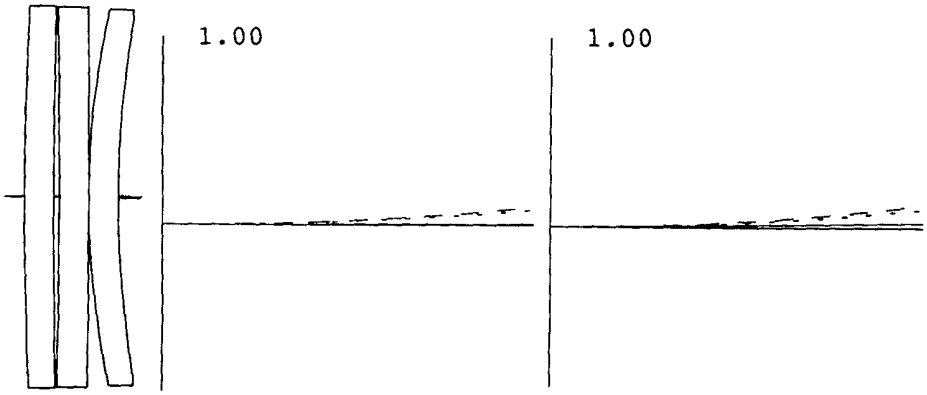


Figure 4A. Wave aberration of Ge/ZnS/KRS5 triplet (F/4, 400mm focal length) at 20°C and 60°C.

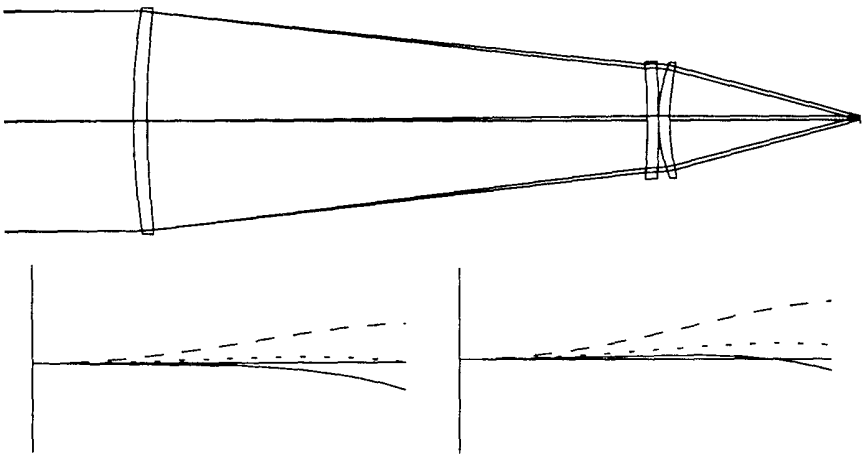


Figure 4B. Ge single lens plus ZnS/KRS5 doublet (F/4, 400mm focal length) at 20°C and 60°C.

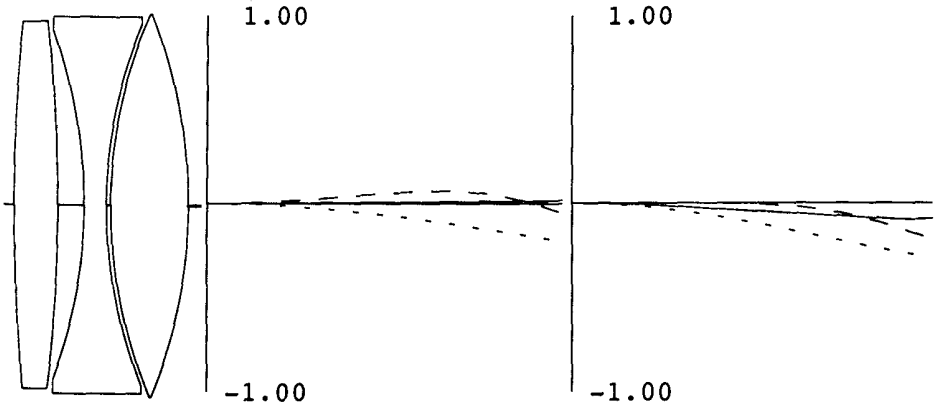


Figure 5A. 100mm F/6.3 all plastic triplet, at 20°C and 40°C

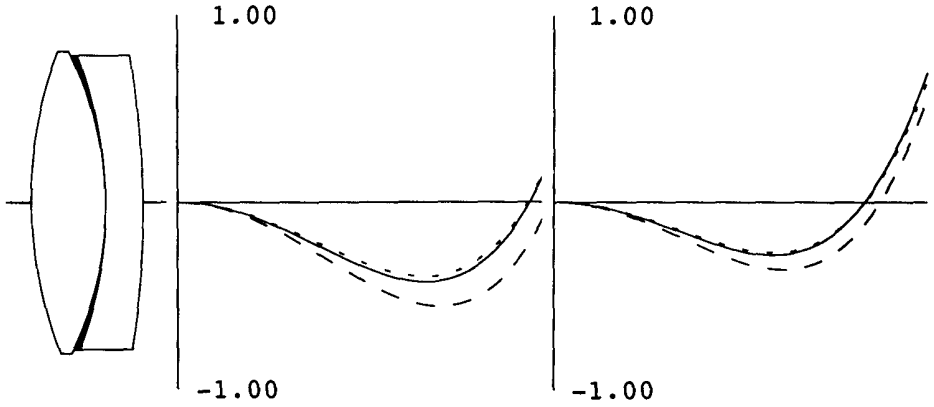


Figure 5B. 100mm focal length F/5 acrylic/liquid/polycarbonate triplet lens at 20°C and40°C

Table 1. Values for absolute thermo-optical coefficients δ and γ ($x10^{-6}$) respectively for Schott glasses.

FK3	-11.66	4.74	FK5	-14.89	3.51	FK51	-29.35	-2.15
FK52	-30.68	-1.88	FK54	-30.66	-1.46	PK2	-3.95	9.85
PK3	-4.58	9.62	PK50	-11.42	6.18	PK51	-31.82	-5.62
PK51A	-28.12	-2.72	PSK2	-3.97	8.83	PSK3	-3.58	8.82
PSK50	-11.64	5.56	PSK52	-11.55	5.45	PSK53	-15.37	3.43
BK1	-6.54	8.86	BK3	1.81	12.41	BK6	-5.88	9.72
BK7	-4.33	9.87	BK10	-1.49	10.11	BALK1	-10.94	7.26
BALKN3	-5.82	9.98	K3	-7.08	9.52	K4	-3.01	11.59
K5	-7.76	8.64	K7	-8.03	8.77	K10	-1.04	11.96
K11	-2.31	10.49	K50	-2.18	11.82	K51	5.75	14.35
ZK5	-6.80	10.60	ZKN7	6.07	15.07	BAK1	-5.72	9.48
BAK2	-6.96	9.04	BAK4	-3.00	11.00	BAK5	-6.73	8.87
BAK6	-4.91	9.69	BAK50	8.99	16.39	SK1	-1.62	10.58
SK2	-0.67	11.33	SK4	-4.22	8.58	SK5	-1.67	9.33
SK6	-0.94	11.46	SK9	-0.26	11.74	SK10	-5.03	8.97
SK11	-3.51	9.49	SK12	-3.54	9.26	SK14	-3.60	8.40
SK15	-5.89	7.91	SK16	-5.68	6.92	SKN18	0.18	12.98
SK19	-4.14	8.66	SK20	-3.38	9.42	SK51	-12.69	5.11
SK52	0.34	12.34	SK55	-3.05	8.95	KF3	-3.96	12.24
KF9	-1.42	12.18	KF50	-1.63	12.97	BALF4	0.26	13.06
BALF5	-7.27	8.93	BALF6	-2.03	11.37	BALF8	-6.50	10.10
BALF50	-8.19	8.41	BALF51	-6.75	9.45	SSK1	-1.40	11.20
SSK2	-1.51	10.89	K3	-1.84	11.36	SSK4	-3.46	8.74
SSKN8	-4.94	9.26	SSK51	-6.86	8.34	SSK52	-3.53	9.87
LAKN7	-7.86	6.34	LAK8	-1.07	10.13	LAK9	-2.89	9.71
LAK10	-1.15	10.25	LAK11	-7.96	6.44	LAKN12	-9.69	5.51
LAKN13	-11.03	5.77	LAKN14	-2.27	8.73	LAKN16	1.25	11.85
LAK21	-7.63	5.97	LAKL21	-3.28	8.92	LAK23	-11.19	4.61
LAK28	-0.73	10.67	LLF1	-5.01	11.19	LLF4	-5.73	10.67
LLF6	-3.53	11.47	BAF3	-4.09	11.51	BAF4	-4.04	11.76
BAF5	-2.74	11.26	BAF8	-1.69	12.31	BAF9	-0.60	12.40
BAF50	-7.17	9.43	BAF52	-8.00	8.80	BAF53	-1.92	11.08
BAF54	-1.96	10.44	LF1	-6.45	10.55	LF3	-5.07	11.13
LF5	-6.75	11.45	LF8	-6.76	10.24	F1	-5.32	12.08
F2	-3.82	12.58	F3	-2.58	13.42	F4	-4.37	12.23
F5	-2.48	13.52	F6	-3.79	13.21	F9	-2.20	13.20
FN11	-3.93	11.07	F14	-2.36	13.44	F15	-3.26	12.94
BASF1	-5.11	11.89	BASF5	6.36	22.16	BASF6	-3.69	11.11
BASF10	-5.38	11.82	BASF13	-2.17	12.03	BASF51	6.32	17.12
BASF52	4.51	14.91	BASF54	-0.06	14.54	BASF55	5.63	15.83
BASF56	-2.36	13.84	BASF57	-2.21	11.99	BASF64	-3.68	10.92
LAF2	-9.02	7.18	LAF3	-7.33	7.87	LAFN7	3.46	14.06
LAF9	3.11	17.51	LAFN10	-0.15	11.25	LAF21	-1.90	9.90
LAF22	-4.24	9.76	LAFN23	-9.08	7.12	LAFN24	0.85	11.65

LAF25	2.79	14.39	LAF26	3.35	14.55	LAFN28	-1.18	10.42
LASF3	0.66	11.66	LASFN9	-3.18	11.62	LASF11	-0.14	11.46
LASF13	3.10	15.50	LASFN15	-2.33	10.67	LASFN30	-2.04	10.36
LASFN31	-2.64	10.96	LASF32	-4.37	11.43	SF1	0.11	16.31
SF2	-3.33	13.47	SF3	0.33	17.13	SF4	2.51	18.51
SF5	-2.18	14.22	SF6	3.72	19.92	SFL6	-9.61	8.39
SF7	-1.82	13.98	SF9	0.97	17.37	SF10	1.05	16.05
SF11	8.01	20.21	SF12	-1.89	13.71	SF13	2.96	17.16
SF14	5.75	18.95	SF15	-1.15	14.65	SF16	-3.01	13.79
SF18	1.02	17.22	SF19	-0.27	15.13	SF50	-8.73	11.47
SF53	0.42	16.82	SF54	1.69	17.09	SF55	0.64	17.04
SF56	-0.10	15.70	SFL56	-8.36	9.04	SF57	4.81	21.41
SF58	4.09	22.09	SF61	1.62	17.42	SF62	-1.17	15.23
SF63	0.82	17.22	SFN64	-7.30	9.70	TIK1	-17.85	2.75
TIF2	-9.87	7.33	KZFN1	-3.39	10.81	KZFN2	-1.54	10.66
KZFS1	-2.01	7.99	KZFSN2	1.82	10.82	KZFSN4	1.89	10.89
KZFSN5	2.04	11.04	KZFS6	-0.96	9.24	KZFSN7	2.61	12.21
KZFS8	3.30	13.90	LGSK2	-20.31	3.89			

Table 2. Achromatic glass pairs of unit power, athermal to aluminum ($\alpha = 23.6 \times 10^{-6}$) to within 0.5×10^{-6}.

FK5	F2	2.059	-1.059	FK5	BASF1	2.226	-1.226
FK5	BASF10	2.240	-1.240	FK5	BASF54	1.832	-0.832
FK5	LAF9	1.670	-0.670	FK5	SF7	1.958	-0.958
FK5	SF9	1.788	-0.788	FK5	SF12	1.917	-0.917
FK5	SF14	1.599	-0.599	PK50	LASF13	2.096	-1.096
PK50	KZFSN7	2.135	-1.135	PSK53	SF56	1.692	-0.692
SK51	FN11	2.489	-1.489	SK51	LAF9	1.885	-0.885
SK51	SF12	2.271	-1.271	LAKN13	SF13	2.067	-1.067
LAKN13	SF18	2.209	-1.209	LAKN13	SF62	2.485	-1.485
LAK23	SF9	2.183	-1.183	LAK23	SF14	1.854	-0.854
LAK23	SF19	2.345	-1.345	BAF50	SF14	2.468	-1.468
BAF52	SF14	2.327	-1.327	LAF2	SF6	2.315	-1.315
LAFN23	SF14	2.138	-1.138	SF6	TIF2	-1.235	2.235
SF61	TIF2	-1.486	2.486				

Table 3. Refractive index N, Abbe ν value, expansion coefficient α, absolute thermo-optical coefficients β, δ, and γ ($\times 10^{-6}$) for infrared, plastic and some liquid optical materials.

Infrared:-	N	ν	α	β	δ	γ
GERM	4.00	861.03	5.70	392.14	124.87	136.27
SILICON	3.43	241.00	2.50	156.69	61.93	66.93
ZNSE	2.41	57.84	7.60	58.68	34.12	49.32

ZNS	2.20	22.76	7.90	40.88	26.17	41.97
CDTE	2.68	148.79	4.50	95.42	52.46	61.46
AMTIR1	2.50	119.97	13.00	69.59	33.47	59.47
GAAS	3.28	107.00	5.90	146.84	58.56	70.36
KRS5	2.37	164.73	61.00	-236.29	-233.22	-111.22
KCL	1.46	30.27	36.00	-28.90	-99.25	-27.25
KBR	1.53	61.45	27.60	-41.47	-106.44	-51.24
KI	1.62	89.26	42.60	-51.56	-125.76	-40.56
NACL	1.49	18.65	44.00	-26.44	-97.44	-9.44
CSBR	1.66	132.30	47.90	77.40	68.84	164.64
CSI	1.74	236.20	50.00	-91.68	-174.05	-74.05

Plastic:-	N	ν	α	β	δ	γ
ACRYLIC	1.4918	57.46	62	-105	-278.4	-154.4
POLYCARB	1.5855	29.91	68	-107	-253.4	-117.4
POLYSTYR	1.5905	30.87	50	-140	-289.7	-189.7
SAN	1.5674	34.81	50	-110	-246.5	-146.5

Liquids:-	N	ν	α	β	δ	γ
CG305974	1.30	97.44	0.00	-328.26	-1076.26	-1076.26
CG505257	1.50	25.80	0.00	-466.45	-923.66	-923.66
CG710209	1.71	20.93	0.00	-657.65	-926.27	-926.27
CG810184	1.81	18.41	0.00	-901.74	-1113.27	-1113.27

Table 4. Achromatic athermal triplets and powers K_1, K_2, K_3 for total power of unity.

			K_1	K_2	K_3
GERM	ZNSE	CSI	0.63	-0.078	0.440
GERM	ZNS	KI	0.497	-0.161	0.664
GERM	ZNS	CSI	0.541	-0.065	0.524
GERM	KRS5	KCL	0.624	0.488	-0.112
GERM	KRS5	NACL	0.606	0.459	-0.065
GERM	KCL	CSI	0.521	-0.091	0.571
GERM	KI	NACL	0.416	0.726	-0.142
GERM	NACL	CSI	0.511	-0.054	0.543
GERM	CSI	AGCL	0.545	0.633	-0.179
ZNS	CDTE	KRS5	-0.176	0.888	0.288
ZNS	CDTE	CSI	-0.156	0.795	0.362
ZNS	KRS5	CSBR	-0.194	0.341	0.853
ZNS	CSBR	CSI	-0.169	0.344	-0.139
CDTE	KI	NACL	0.592	0.590	-0.182
CDTE	NACL	CSI	0.698	-0.121	0.423
AMTIR1	KRS5	NACL	0.867	0.302	-0.169
AMTIR1	NACL	CSI	0.772	-0.150	0.378
GAAS	KRS5	NACL	0.799	0.383	-0.183

GAAS	NACL	CSI	0.692	-0.157	0.465
KRS5	NACL	CSBR	0.396	-0.151	0.755
KI	NACL	CSBR	0.655	-0.196	0.541
NACL	CSBR	CSI	-0.130	0.651	0.479

Table 5A. Coefficients of thermal expansion of common structural materials ($x10^{-6}$), values approximate. From CodeV manual.

ABS (medium impact	86.4	Al 356 (cast)	21.4
Al 713 (Tenzalloy)	24.1	Al 771 (Precedent 71A)	24.7
Al 1100 (wrought)	23.6	Al 2024	23.2
Al 6061	23.4	Al 7075	23.6
Be-Cu 17200	17.8	BeO	6.7
Be S-200F impact ground	11.2	Brass, Cartridge 26000	20.0
Brass, free cutting	20.5	Cordierite (CG4, Ge)	-0.07
CR-39 (Allyl diglycol)	138	Cu 10200	17.6
DUCTILE cast iron nodule	11.9	Granite	8.3
Graphite Epoxy GY70/X30	0.2	Invar 35	0.56
Invar 36	1.5	Kovar	5.5
Polycarbonate 141 grade	67.5	Mg AZ31B-F or H24	25.2
Metal Matrix Gr/Al (40%)	0.4	Moly (Low Carbon Grade)	5.0
Moly TZM w/Ti & Zr	5.2	Nylon (transparent)	77.6
Plexiglass G	83.0	SS303/303Se (Austenitic)	17.3
SS304 (Austenitic)	17.3	SS316 (Austenitic)	16.0
SS416/416Se Martensitic	9.9	SS430 (Ferritic)	10.4
SS440S/B/C Martensitic	10.1	Polystrene, 30% glass fiber	86.4
SiCAl Metal Matrix Bars	14.8	SiCAl Metal Matrix Co	12.4/10.8
Table/Bench, 400 Series	10.0	Table/Bench - (6061T6)	23.0
Table/Bench, Super Invar	-0.18	Table/Bench - Steel	11.0
Titanium	10.8	Ti - 6Al - 4V	9.5

Table 5B. Coefficients of thermal expansion of mirror substrate materials ($x10^{-6}$), values approximate. From CodeV manual.

Cer-Vit (O/I TM) C-101	0.3	Fused Silica CGW 7940	0.52
Fused Silica Amersil Types	0.51	Zerodur	0.05
Be I-70A	11.6	Be I-220	11.6
Be I-400	11.2		