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The design of athermal infrared optical systems

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ABSTRACT

This paper will discuss the design techniques to athermalize infrared optical systems. The discussion will focus on specific state-of-the-art tactical weapon applications for thermally compensated optical imaging systems. The main objective is to athermalize the system by choosing the correct mounting materials without the use of active mechanisms such as electronic motor or liquid bellows lens focus drives. Two specific designs with their advantages and disadvantages will be discussed -- a catadioptric imaging system and an all refractive imaging system.

1. INTRODUCTION

Focus errors induced by ambient temperature changes is a problem that designers must address in most tactical weapon systems. Optics in these types of systems must remain in focus throughout a wide range of temperatures. A typical temperature range may be -20C to +60C. Although the thermal problem exists for both visible and infrared systems, the problem is usually worse in the infrared spectral region. The high thermal coefficients of refraction (dn/dt) of the infrared materials are usually the main cause of the problem. For example, a single germanium element ($n = 4.02$, $dn/dt = 400 \times 10^{-6}/°C$) of effective focal length 3.000 inches (measured at 4.5 microns and at 20C) has a focal length of +3.015 inches at +60C and +2.985 inches at -20C. A 30 mil defocus is generated by this single element when in most tactical systems only a very small amount of defocus is allowed. Two or more field-of-view (FOV) systems complicate the thermal problem even more. Because of the difference in objective focal lengths and optical configurations each FOV has with respect to the other, the more one FOV is corrected for thermally induced defocus, the worse the other FOV(s) become. The traditional solution to the thermal problem is to actively move a lens group to maintain focus. Some methods that exist include lens group movement by the use of a fluid filled bellows and temperature sensors coupled with a motor driven mechanism.

Many state-of-the-art tactical systems are required to be light weight, compact and user non-interactive. With this in mind the active solutions are undesirable because of their complexity and added weight. An ideal solution would be a passive system consisting of no focus drive electronics, no motors, and no complex or added focus mechanisms. The ideal solution can sometimes be achieved through careful selection of lens materials and mounting materials that keep the optical system in focus throughout the desired temperature range.

2. THE DESIGN PROCESS

In choosing the best solution to meet the needs of the system, either active or passive, the designer must be aware of some trades. Even though the passive system can consist of strong, low density, light weight materials (such as composites or plastics), these materials are sometimes expensive in low quantities and difficult to work. The designer must also be aware of the time consuming design process which involves interactive design efforts from both the optical and mechanical engineers. Both disciplines of engineers must work together in deciding upon the optimum mounting material(s). The best mounting solution for the optical design is not necessarily the best for the mechanical design. In order to achieve a well performing, passively compensated, athermal optical system, design time for this interaction and iteration between the optical and the mechanical engineers must be included when scheduling and planning the design effort.

3. EXAMPLES OF PASSIVE SYSTEMS

Two 3 to 5 micron passive athermalized design solutions are discussed below. The athermal design solutions include a catadioptric dual FOV imaging system and an all refractive dual FOV imaging system. Each design uses a different optical mounting technique to achieve an athermal system. Common to these designs are negative germanium elements and positive silicon elements. The germanium element is used both for color correction and for decreasing the system thermal sensitivity. Because of the high dn/dt of germanium relative to silicon, the powers of the negative germanium and positive silicon elements can usually be balanced to keep focus shifts small over a wide temperature range while retaining the desired optical performance for the system.

3.1 Catadioptric imaging design

The dual FOV catadioptric imaging design consists of a narrow-field-of-view (NFOV) Cassegrain objective and several refractive imaging optics. In wide-field-of-view (WFOV) the secondary mirror is removed from the optical path. Light can then pass through the WFOV objective and into the same imaging optics. (See Figure 1.)

The following philosophy was used in designing the system. The system was to be corrected for thermal defocussing in NFOV while letting the WFOV performance degrade. The assumption here was that a sharp NFOV image was necessary in order to achieve the maximum acquisition range. Generally, since WFOV in tactical systems is used for surveillance (as is the case here) a slight degradation in its performance is usually tolerable. If system requirements were such that all FOVs were required to maintain good focus over the desired temperature range, separate compensating systems would be required for each FOV.

In this design, invar metering rods were used in the primary and secondary mirror mounting structure (see Figure 2). Invar, having a thermal expansion essentially of zero, was chosen as part of the mounting material in conjunction with an all aluminum mirror spider assembly. Precise thermal analysis was conducted to determine the length of the rods needed to compensate for the thermally induced defocus caused by the imaging optics. By using the invar rods, the entire mounting structure was allowed to be made of aluminum, an easily worked and inexpensive material. Calculated performance data showed that the NFOV system stayed in focus throughout the entire temperature range. In addition, the system was fielded in very warm and very cold weather and maintained good focus throughout.

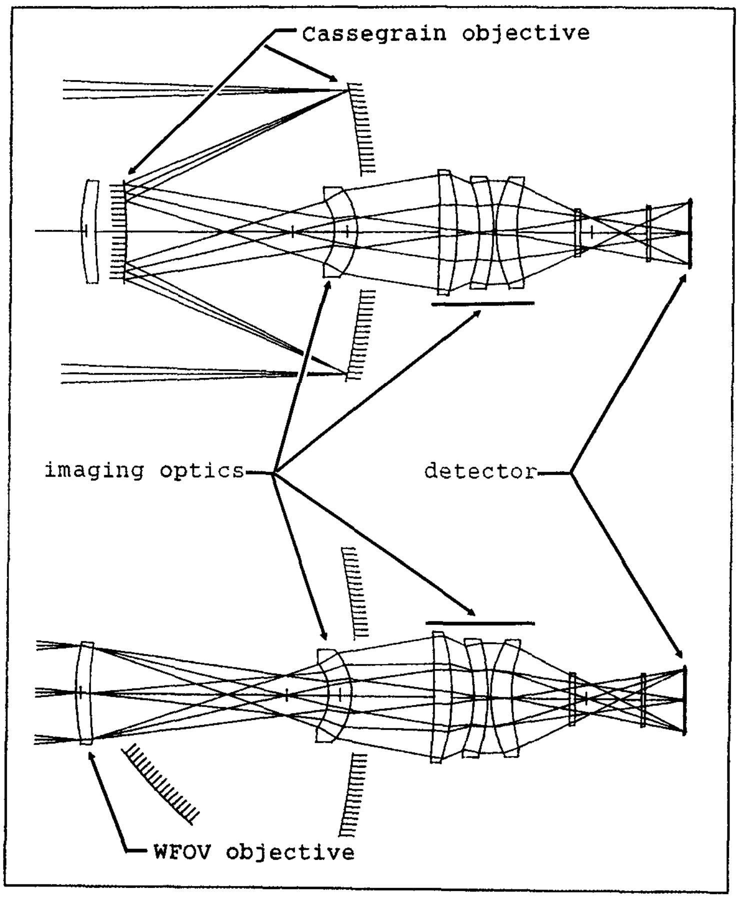

Figure 1. Catadioptric dual FOV imaging system

3.2 All refractive imaging system

The dual FOV all refractive design consisted of NFOV and WFOV imaging optics mounted on a turret with a common objective as shown in Figure 3. Again the same design philosophy was used: the system was thermally corrected in NFOV while the WFOV was allowed to degrade.

Three different lens mounting techniques were analyzed for the best thermal compensation: an all composite mounting structure, an all plastic mounting structure, and a combination part composite part plastic mounting structure (see Figure 4). The all composite mounting technique was initially thought to be the best solution as the selected composite material has an expansion

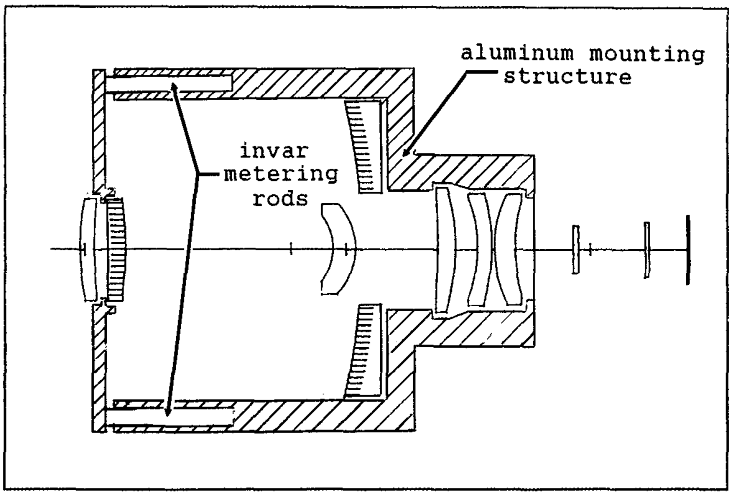

Figure 2. Invar rods were used as compensators to athermalize narrow-field-of-view.

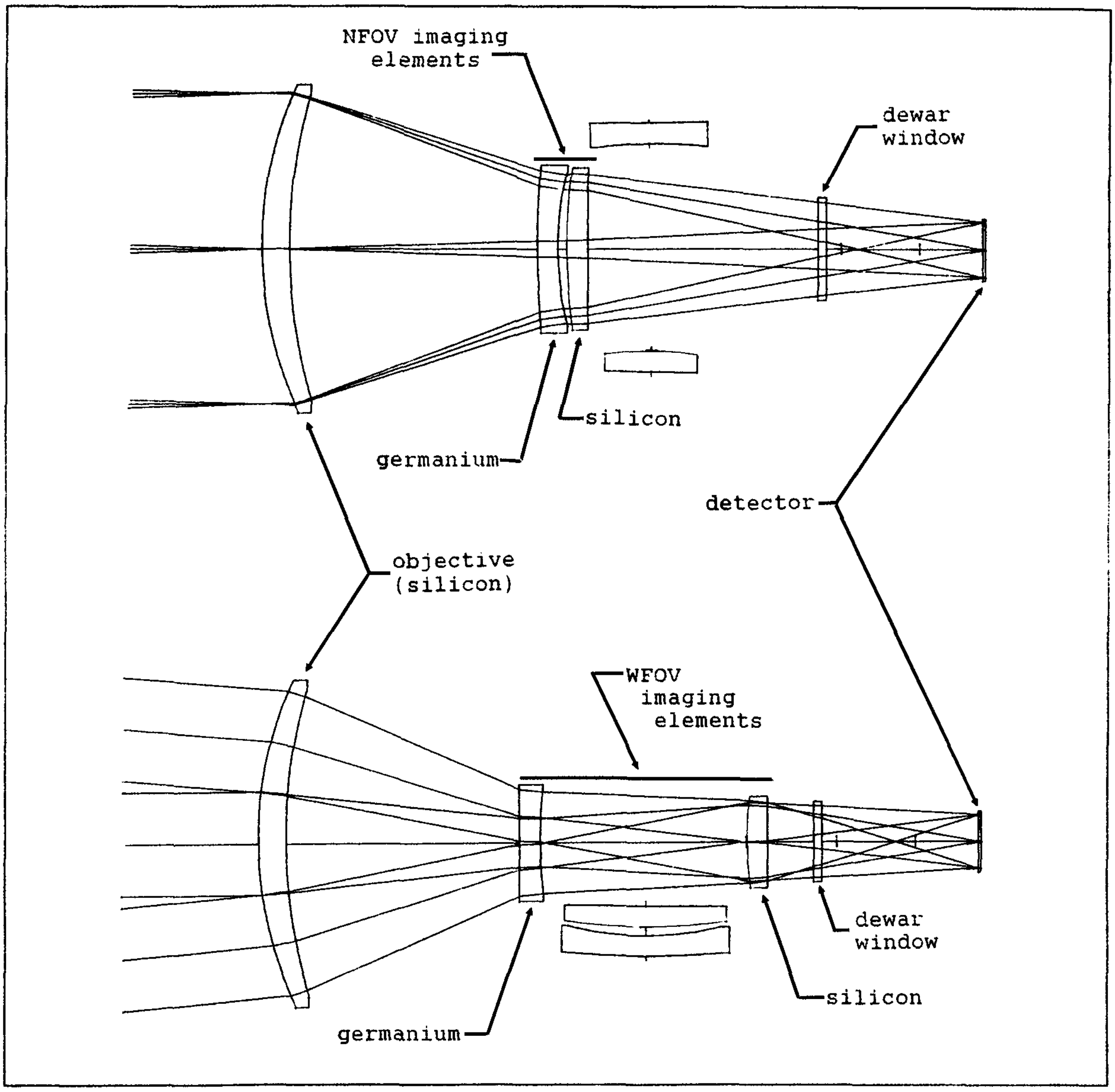

Figure 3. All refractive dual FOV imaging system.

coefficient near zero. But thermal analysis showed that the all composite mounting technique had an unacceptable amount of thermally induced defocus. Next, an all plastic design was analyzed (expansion coefficient = 22.5 x 10^{-6}/°C). Again, thermal analysis of the design showed an unacceptable amount of thermally induced defocus. Compromises had to be made with the mechanical engineers and the choice of material. All plastic would be ideal for mechanical purposes since all the parts could be injection molded and very easy to produce whereas, composite structures had to be laid-up by hand and were therefore very expensive in production.

The design was optimized for best over-all optical performance. The powers of the germanium and silicon elements were balanced to give the least thermal defocus for the system. Thermal analysis showed that the best structural solution to the thermal problem was to make this structure out of part composite and part plastic. Since the lens FOV change mechanism and the dewar/detector mount were complex parts, it was decided to make these pieces of injection molded plastic. Because composite was so expensive to work, its use was limited to simple piece parts. Through careful thermal analysis, the precise amount of composite that was needed to thermally compensate NFOV was calculated. The composite mounted objective was held in the same location throughout the temperature range of the system, while the plastic turret mounted FOV lenses moved relative to the objective with a change in temperature. The plastic mounted FOV lenses actually helped reduce the thermal sensitivity problem. As the FOV lenses moved with the structure with an increase in

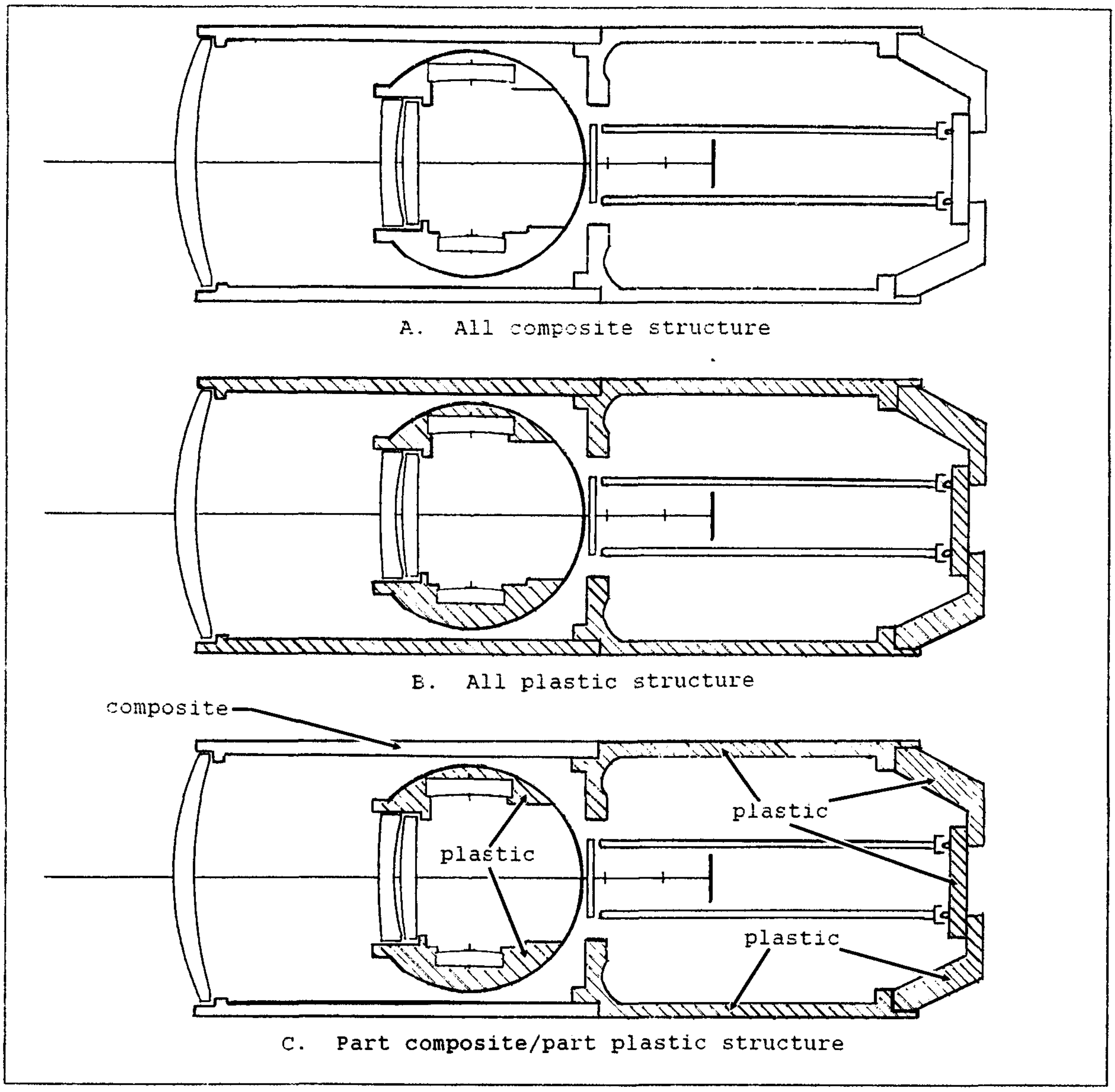

Figure 4. Three different optical mounting techniques were analyzed for thermal stability. A part composite/part plastic mounting structure was used to athermalized narrow-field-of-view.

temperature, the image plane was moved back towards the detector thus creating smaller amounts of thermal defocus. By changing the amount of composite in the structure, NFOV was perfectly athermalized and performed well throughout the entire temperature range.

4. CONCLUSION

Passive athermalized optical systems can be achieved by the careful choice of mounting materials, the design technique used, and through the integrated efforts of both the optical and mechanical engineers. Careful attention must be paid to dual FOV systems. NFOV is of most importance in most tactical weapon systems. In many tactical weapon systems, NFOV needs to be athermalized in order to meet the maximum acquisition range requirements of the system in all environments. WFOV, on the other hand, is usually used for surveillance purposes and target detection and can often be allowed to degrade with temperature changes. Through balancing of power of the germanium and silicon elements, the thermal sensitivity problem can be lessened without degrading the over-all optical performance. In current state-of-the-art tactical systems, the passive athermal design solution is often a more desirable choice than active athermal design solutions. The ability of the optics to remain in focus through all specified temperature ranges without the use of motors and/or complex focus drives enable the system to be light weight, compact, and non-user interactive.