Thermal and structural design constraints for radiometers operating in geostationary orbits

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ABSTRACT

For a radiometer to operate properly in a geostationary (GEO) orbit the thermal and structural design must be made insensitive to the operational environment. The performance of the radiometer is very often limited by the instruments transient thermal excursions. By properly designing the thermal control system along with the proper optical port opening, the performance of the instrument can be optimized. As the pointing and absolute registration requirements become more demanding, it is required that the structure be designed to be insensitive to environmental effects. Design considerations for pointing stability, radiometric calibration, along with assembly and test concerns will be addressed.

Introduction

The purpose of a radiometer is to accurately measure the radiance of a scene in one or more spectral bands. Radiometers typically consist of a scanning system, an optical system, detectors, the electronics necessary to place the measured values into a data stream, and a mechanical structure to hold the instrument together. By placing a radiometer in orbit around the earth the radiance of large areas can be measured quickly. In a geostationary orbit the radiometer is approximately 23,500 miles above the surface of the earth and it remains above the same point on earth at all times. The spacecraft completes one revolution of earth and one revolution about its north-south axis in the same time that the earth completes one revolution on its axis (1 day). This orbit allows the radiometer to view one hemisphere of the earth continuously so the radiance of any point on this hemisphere can be measured at any time.

While operating in this orbit the radiometer must make radiance measurements of the scene (in several wavelength bands) and it must provide calibration information so that the radiance data can be used by the scientific community. In addition to these requirements the instrument must maintain registration (location accuracy) for each of the wavelength bands within specified values. These requirements determine the complexity of the structural design and the materials that can be considered for use in the construction of the instrument.

Limitations Due to Temperature Changes

There are two major impacts on the performance of a radiometer due to temperature changes. These are changes in optical performance (due to thermally induced changes in shape or alignment) and changes in radiometric calibration.

Temperature changes always cause expansions and contractions proportional to the coefficient of expansion (CTE) of the material, the size of the object and the magnitude of the temperature change. Both bulk temperature changes and temperature gradients can cause components to distort resulting in poor overall performance of the radiometer. A good example of this effect can be found on a scan mirror. The bulk temperature of a scan mirror (in a GEO environment) will typically change by at least 40°C during each day. It will also experience widely varying gradient conditions as the

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sun first illuminates one end of the mirror, then the entire mirror face, then the other end of the mirror, and finally none of the mirror. If materials with CTE differences or non-uniform materials are used in the construction of the scan mirror the daily temperature change will cause the mirror to distort. A temperature gradient through the thickness of the mirror will cause similar distortions. Temperature gradients in the plane of the mirror face may also cause distortions of the mirror.

The pointing (location) accuracy of a radiometer is also limited by temperature induced distortions. When the instrument structure changes temperature it expands or contracts causing optical alignments to change which results in changes in pointing. As location accuracy requirements are tightened the engineer is forced to use low CTE materials and to incorporate more complex thermal control systems to minimize thermally induced distortions.

Radiometric calibration errors can be introduced by fast changing temperatures or very high temperatures inside the instrument. Data from a spaceborne radiometer is calibrated by measuring radiance while looking at space and while looking at an internal calibration target (ICT) of a known temperature. These measurements provide two data points relating the indicated (measured) radiance to the true radiance of a scene (see Figure 1). The true radiance of any scene can be found by taking the measured radiance of the scene and linearly interpolating between the ICT data point and space look data point.

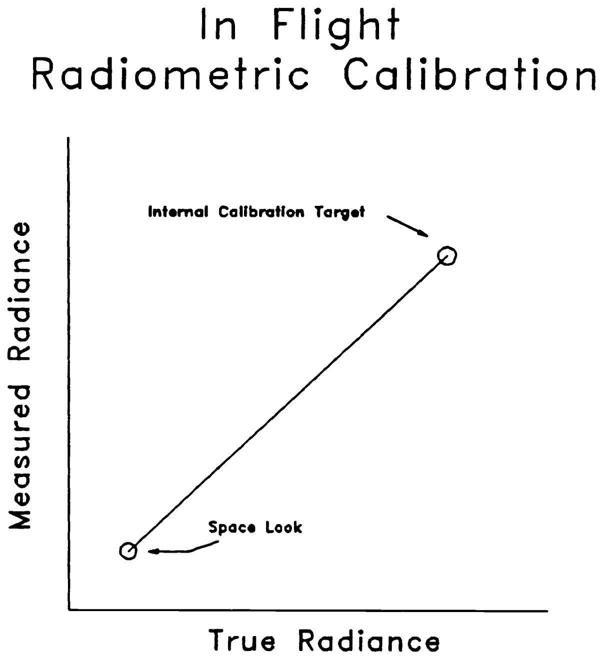

Figure 1

There are two sources of error that the structural/thermal design can introduce into the calibration of the instrument. One error source is an incorrect ICT calibration due to "non-blackness" of the calibration target and temperature differences between the ICT and the interior of the instrument. The radiance measured while looking at the ICT includes the energy emitted from the ICT and the energy emitted from the instrument interior that is reflected from the ICT into the optical system. The engineer needs a method of estimating the magnitude of this error so that a design that minimizes the error can be created.

This error can be estimated by summing the energy emitted by the ICT with the energy reflected by the ICT and determining an equivalent ICT temperature that emits this amount of energy.

$$\epsilon_n\, e_{\lambda b}(\lambda, T_{ICT}) + (1-\epsilon_n)\, \epsilon_{inst}\, e_{\lambda b}(\lambda, T_{inst}) = e_{\lambda b}(\lambda, T_e) \tag{1}$$

where:

$$e_{\lambda b}(\lambda, T) = \int_{\lambda_i}^{\lambda_f} \frac{2\pi C_1}{\lambda^5 (e^{C_2/\lambda T}-1)}\, d\lambda \tag{2}$$

and

ϵ = emittance
λ = wavelength
T = Temperature
C_1 , C_2 = Constants in Planck's spectral distribution of emissive power.

Subscripts:

ICT = Internal Calibration Target
n = direction normal to ICT
inst = instrument interior
e = equivalent
i = initial
f = final

The calibration error is estimated by subtracting the actual ICT temperature from the equivalent ICT temperature. Figure 2 shows the results of this method for a 293 K ICT in the wavelength band of 3.8 to 4.0 micrometers with various ICT emittances and environment temperatures. This figure shows that the calibration error increases significantly as the temperature of the instrument interior increases and as the emittance of the ICT decreases. If the instrument interior is held at the ICT temperature, or if the ICT is "black" (emittance is 1.0) no calibration error occurs. An engineer can use this method of evaluating temperature effects on calibration error to set design limits for the instrument interior temperatures or to determine if time and effort should be spent in designing a "blacker" ICT.

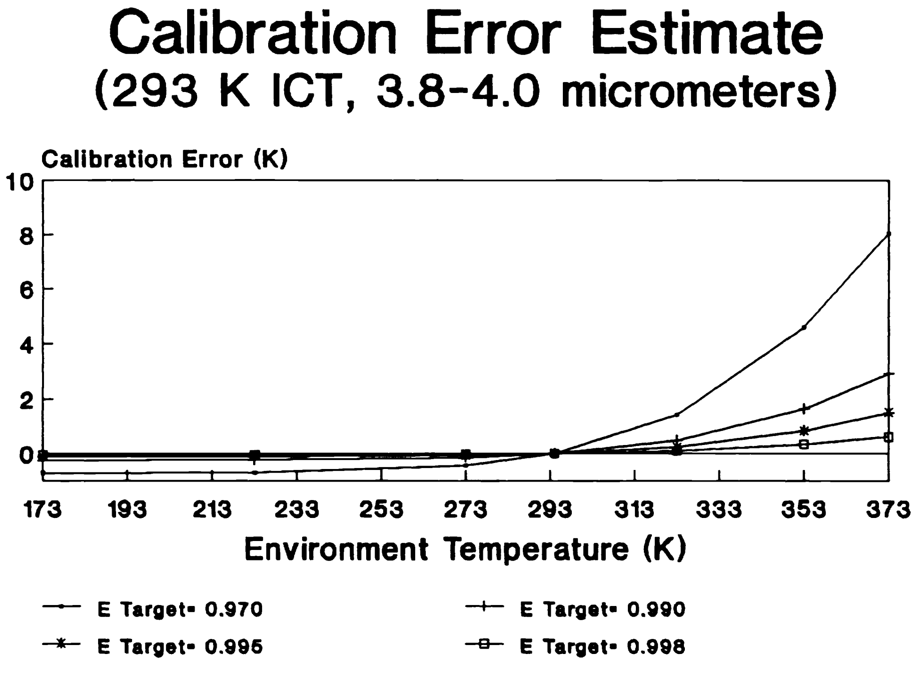

Figure 2

The other source of calibration error that the structural/thermal design can influence is due to optical elements changing temperature between space look calibrations. The energy emitted by the optical elements (into the optical system) is always measured by the instrument. If the magnitude of this energy changes, the calibration of the instrument changes. The calibration error due to this effect can be lowered by decreasing the rate of temperature change of the optical elements or by more frequent space look calibrations. The most active (thermally) optical element of a radiometer in a GEO environment will be the scan mirror. As part of the design of a scan mirror the engineer must evaluate the impact of scan mirror temperature change on the calibration error. The calibration error due to changes in scan mirror temperature can be estimated by summing the energy (from the scene) reflected by the scan mirror with the energy emitted by the scan mirror and equating this with the energy that a blackbody at some equivalent temperature would emit.

$$(1-\epsilon_{mirror})\, e_{\lambda b}(\lambda, T_{scene}) + \epsilon_{mirror}\, e_{\lambda b}(\lambda, T_{mirror}) = e_{\lambda b}(\lambda, T_e) \qquad (3)$$

The equivalent temperature (T_e) can be obtained from equations (2) and (3) for a given scene temperature, wavelength band, scan mirror emittance and scan mirror temperature. The error is the difference between the equivalent temperature and the scene temperature . This can be repeated for several scan mirror temperatures to produce a curve of calibration error versus scan mirror temperature (see figure 3).

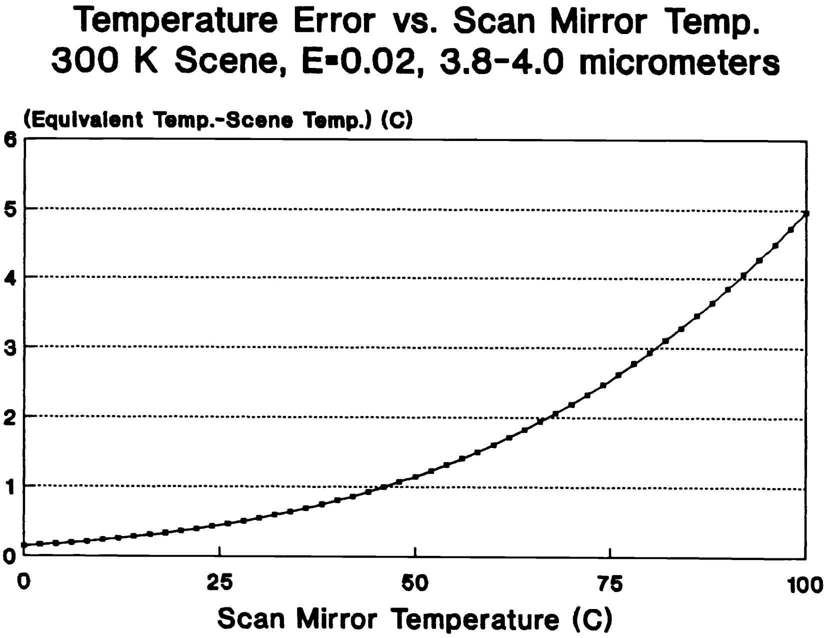

Figure 3

Each time that a space look is performed this error is calibrated out of the system so only the change in error ($\Delta E/\Delta T$) contributes to calibration error. The engineer can use equation 3, predictions of scan mirror temperatures and knowledge to the time between space looks to evaluate the calibration error caused by the scan mirror. With the change in error represented as ΔE, the change in scan mirror temperature represented as ΔT and time between space looks represented as Δt this can be written as:

$$\frac{\Delta E}{\Delta T} \times \frac{\Delta T}{\Delta t} \times \Delta t = \Delta E \qquad (4)$$

It can be seen from figure 3 that the rate of change of error ΔE/ΔT increases with the temperature of the scan mirror. Equation 4 shows that calibration error increases with the rate of scan mirror temperature change. An evaluation of an open back and closed back scan mirror (see figure 4) would show that an open back mirror would contribute less to calibration error than a closed back mirror because the closed back mirror has both higher rates of temperature change and higher temperatures. The importance of the difference between these calibration errors will depend on the total calibration error allowed and the contributions of other error sources to the total error.

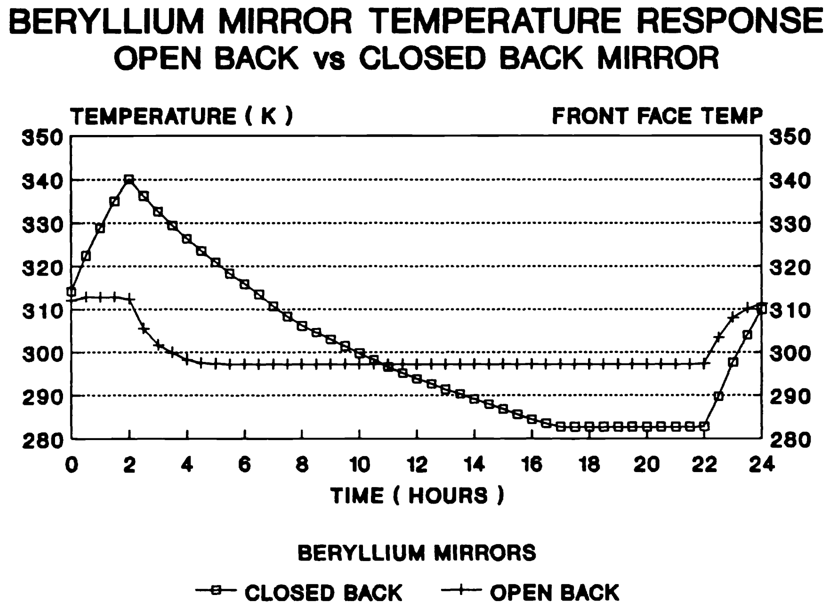

Figure 4

Thermal Control Systems

A thermal control system is used to control the flow of heat to, from and inside the radiometer. The system must control both constant electronics dissipations and the variable solar heat loads entering the aperture. This system can be simple and passive (paint on surfaces and multiple layer insulation blankets) or it can be complex (heat pipes, louver systems and active heater controls). The level of complexity needed will depend on radiometric and location accuracy requirements as well as the structural design of the instrument.

The goals of a thermal control system design are to minimize temperature variations of the instrument structure and to minimize radiometric (and calibration) errors, with as little impact to the total instrument weight and power requirements as possible. Ideally the thermal control system would maintain the instrument at the assembly temperature (typically 21°C). This would eliminate all temperature induced distortions and radiometric errors. Unfortunately the variation in heat load, due to solar energy entering the aperture, makes constant temperature control practically impossible.

The most effective way of controlling the temperature of an instrument structure is to shield the structure from exposure to solar energy with lightweight shields and to connect these shields to a radiator for heat rejection. This approach will result in rapidly changing shield temperatures which will lead to calibration error problems. To maintain adequate calibration a design of this type would require a very "black" calibration target and more frequent space looks during periods of time that solar energy is entering the aperture.

Another thermal control approach is to allow the (relatively massive) instrument structure to absorb all incident solar energy and connect this structure to a radiator for heat rejection. This maintains low calibration errors but results in location accuracy problems due to temperature changes of the instrument structure. A design of this type would require a structure made of a light weight material that has a high thermal conductivity, high thermal capacitance, and a low CTE.

Both of the thermal control approaches mentioned above have strengths and weaknesses. The best thermal control system for a radiometer in a GEO environment will depend on the location accuracy, registration accuracy and calibration accuracy requirements specified for the instrument. Choice of the "best" thermal control system can only be made after first order tradeoffs between instrument temperatures and pointing, registration, and calibration errors have been made. The methods mentioned above can be used by engineers to evaluate the impacts of instrument temperatures on calibration errors. Predictions of instrument temperatures can also be combined with structural models to predict thermally induced distortions of optical elements and of the instrument structure.

The most common element of any thermal control system for a GEO instrument is the aperture sunshade. This device limits the amount of time that the solar energy can enter the instrument aperture, which limits the total heat load. The aperture sunshade (see figure 5) must remain outside of the field of view of the instrument.

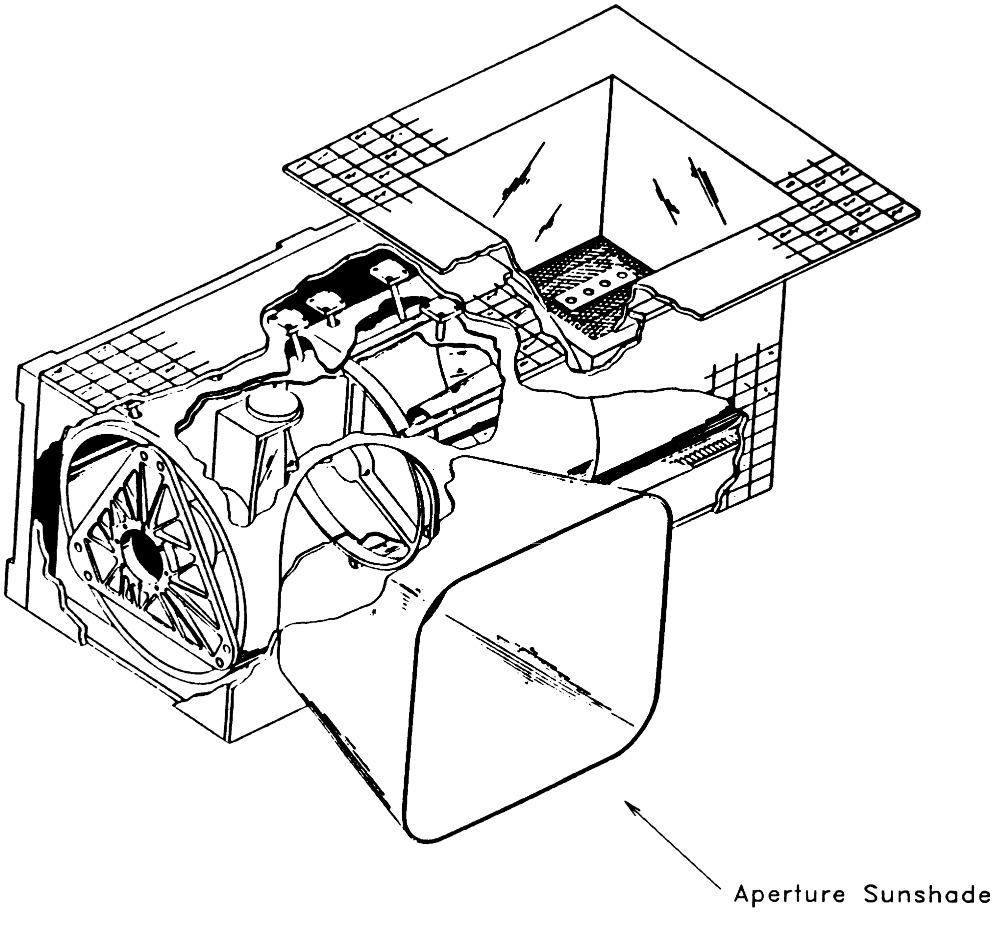

Figure 5

The sunshade cannot eliminate all solar energy entering the aperture but it can greatly reduce the total amount of energy that enters the aperture. By approximating the sunshade as a cone (see figure 6) the total energy entering the sunshade can be calculated as a function of cone height to diameter ratio.

Solar Illumination through
an Aperture Sunshade

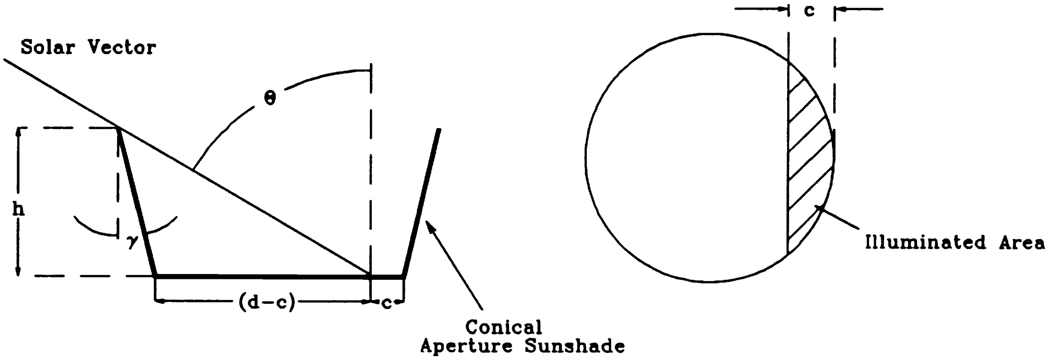

Figure 6

Figure 7 shows the results of this calculation. This figure shows that the total energy gain decreases asymptotically with increasing h/d ratio. Most of the benefit from a sunshade is obtained with an h/d ratio between 2 and 3, exceeding this ratio adds structural complexity and weight but not much reduction in total energy gain. In most applications an h/d of 1 or above will have to be a deployable sunshade because of space constraints and to limit launch loads on the sunshade.

Total Solar Energy Entering a Sunshade
(Conical Sunshade, S=0.90 W/sq.in)

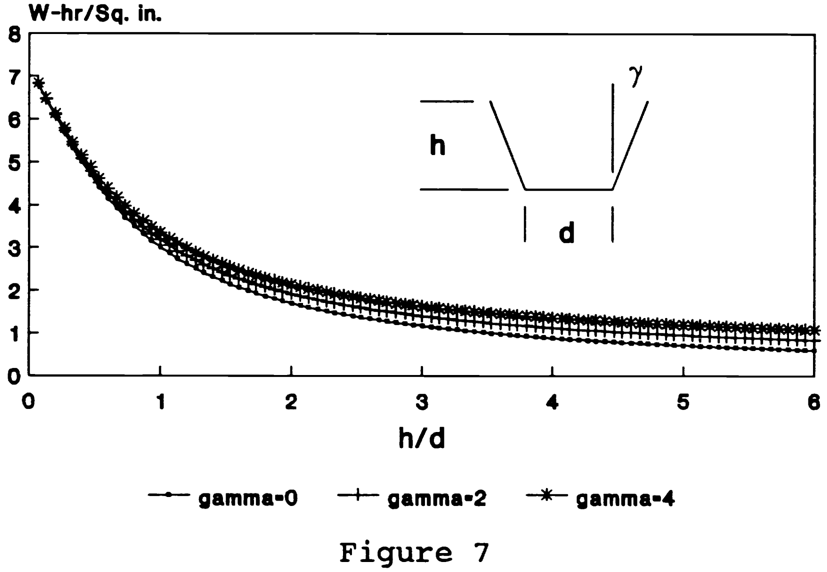

Figure 7

For the GEO environment the thermal and structural designs are very tightly coupled. The thermal control system relies on the structure for support with the structural design dictating conduction path lengths, maximum radiator areas and available radiator locations. On the other hand the effectiveness of the thermal control system will strongly influence the selection of materials used for the structure and the optical elements.

Structural Design

The radiometer is held together by a structure whose primary purpose is to maintain the optical components in proper alignment. The requirements which drive the design of this structure are survival of the launch environment, and optical component alignment requirements.

Survival of the launch environment means that the structure and all components it supports must not break (fall apart) during launch. It also means that after the launch is completed all optical alignments will remain within specified tolerances, and that moving assemblies (scan systems, filter wheels, deployment mechanisms, etc.) will still function properly.

The requirement to maintain alignments during operation in a GEO orbit is driven by the pointing accuracy, channel to channel co-registration and image quality requirements placed on the radiometer. These requirements must be translated into maximum allowable structural distortions. With temperature predictions, material properties, and structural models the thermally induced distortions of the structure and optical elements can be predicted. The engineer can reduce distortions by using kinematic mounts, strain relief devices (flexures) and by using materials with similar CTE's. The most promising method of maintaining small distortions and surviving the launch environment is to combine the use of very low CTE materials (Silicon Carbide, Graphite Epoxy, etc) with strain relief devices to create a stable structure. In fact when very low CTE materials are used, strain relief is required at transitions to common, high CTE materials such as aluminum.

By combining a low CTE, stable structure with a thermal control system that decreases daily temperature changes, pointing and alignment errors will be minimized.

Assembly and Test Concerns

Radiometers built to operate in space are generally "one of a kind". Several instruments of each design may be built but each one will be slightly different. The design is always updated to include improvements desired by the customer or to correct for design flaws discovered during the previous build and test cycle. An instrument design should provide easy access to adjustment points for optical alignments and should allow as much flexibility in the assembly and test cycle as possible. A good design will result in a final assembly process that is simply a matter of integrating several subassemblies together and making some fine adjustments on optical alignments and electrical parameters.

The radiometer is assembled and tested on earth in a 1 g gravity field. All of the assembly and most of the testing is carried out in air at 21° C. The instrument design as well as the assembly and test procedures must account for this. Distortion of the optical system due to gravity sag can be minimized by the structural design and by controlling the orientation of the instrument during assembly and testing. Generally the thermal control system will not be affected by testing in a gravity field but if heat pipes are used the orientation of the heat pipes must be considered in addition to the orientation of the optical components. The thermal control system will strongly influence thermal vacuum testing of the instrument. In orbit the instrument temperature distribution is always transient and is determined by the amount of solar energy entering the aperture, the end of life solar absorptances and the thermal capacities of components inside the instrument.

Thermal vacuum testing is performed without solar energy and generally at a steady state temperature condition. This limits the magnitude of temperatures and temperature gradients that can be maintained during thermal vacuum testing. Special heaters may need to be added to the instrument design for the sole purpose of achieving the desired test conditions.

During testing some temperature information will be available from the telemetry points that will provide temperature information while the radiometer is in space. Additional temperature information will be required during thermal vacuum testing and acceleration information will be required during vibration testing. Generally temperature sensors and accelerometers are added for testing purposes and removed when testing is completed. Some of the locations of these additional temperature sensors and accelerometers are inaccessible when the instrument is completely assembled and ready for testing making their removal difficult if not impossible. All sensors (and heaters) required for thermal vacuum and vibration testing should be included in the instrument design with a separate wiring harness and/or test connectors. This eliminates the danger of hardware damage due to removal of the sensors, simplifies preparation for environmental testing and provides easy access to additional test points during spacecraft level testing.

To simplify the final assembly task, interfaces between major components should be designed so that subassemblies can be pre-aligned and pre-tested before integration to the instrument. This minimizes the time and effort required to achieve proper alignments and reduces the cost of removing damaged or faulty sub-assemblies discovered during the test cycle.

Conclusions

When determining the type of structure and thermal control system for a radiometer that will operate in a GEO environment the engineer must consider the impact of instrument temperature on calibration error. Equations (1) and (2) can be used to estimate the impact of instrument interior temperature and ICT "non-blackness" on calibration error. The engineer can use this information to set limits on interior temperatures for the thermal control system design or to decide if a "blacker" ICT design is more cost effective. Equations (2),(3) and (4) along with scan mirror temperature predictions can be used in the evaluation of scan mirror designs or to estimate the minimum acceptable time between space look calibrations.

For a radiometer in a GEO orbit the total energy entering the aperture sunshade strongly influences the instrument temperature distribution. The total energy entering an instrument can be reduced by lengthening the aperture sunshade. Figure 7 shows the total heat (per unit aperture area) entering a conical sunshade as a function of h/d ratio. The use of ratios between 2 and 3 is suggested.

Due to the (GEO) environment and the need to find a lightweight design, the thermal control system and the structural design must be compatible. They must both strive to reduce distortion due to thermal expansion and contraction. The design of the thermal control system must minimize both maximum temperatures and temperature variations. The structural design must minimize the response of the structure to temperature changes.