A parametric design tool for Large Space Telescope Sunshields

Christopher G. Paine\textsuperscript{a}, Charles M. Bradford\textsuperscript{a}, Mark C. Dragovan\textsuperscript{a}, Harold W. Yorke\textsuperscript{a}

\textsuperscript{a} Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA USA

ABSTRACT

We have developed a thermal-optical-mechanical model of a representative sunshield and telescope assembly, appropriate to 10-m class far-infrared large space telescopes such as SAFIR, SPECs, SPIRIT, and CMBPol. The model provides a tool for sensitivity analysis for design parameters, including material properties and structural configuration, provides performance predictions, and has been used to direct technology development for large space telescope structures and materials.

The sunshield model incorporates a flight-like design support structure for the five-layer combined sunshield and V-groove radiator, including temperature-dependent thermal, mechanical, and optical properties for the structure and deployed sunshield layers. Heat lift from mechanical cryocoolers is included, in fixed-temperature or power-balance conditions, at arbitrary points on the sunshields and support structure.

The model properly accounts the wavelength dependence of radiative transfer between surfaces of widely different temperature, which capacity has not been available from commercial codes for the infrared thermal band (source temperatures 300 K—15 K) until very recently. A simplified model of the zodiacal background to be experienced at the Sun-Earth L2 point is used which, with the wavelength-dependent thermal transfer, improves the fidelity of temperature and heat lift requirements predictions for the coldest sunshield layer and telescope assembly.

Keywords: SAFIR, large space telescope, sunshield, V-groove radiator

1. INTRODUCTION

Future far-infrared observatories such as SAFIR will require operational conditions which make ground testing at the required performance levels impractical. The ability to design such structures, with confidence that the performance will be as predicted, will require advances in thermal modeling capabilities, understanding of thermophysical and optical properties of materials, and the interaction of mechanical design and thermal radiation interchange. To address these issues, we have developed a thermal-mechanical model of a representative architecture, focusing primarily on the thermal performance of the sunshield—V-groove radiator portion of the assembly. In what follows, we describe the thermal-mechanical model, the thermo-optical properties assumed for the components, and the environment which influences the thermal performance. Following this, we present predictions of performance sensitivity to variation in some of the optical characteristics. Studies of the performance sensitivity are continuing, to inform the direction of technology investment for further development of capabilities for large space telescopes.

2. THE SUNSHIELD THERMAL-MECHANICAL MODEL

2.1 Mechanical structure

Figure 1 shows the thermal model representation of a SAFIR-type spacecraft. Figure 1a shows a view of the SAFIR structure sun-facing side. The solar array is sized for 4000 watts. Mechanical cryocoolers radiate waste heat from the sides of the spacecraft bus; this is considered in the radiant load on the warmest, sun-facing, layer of the sunshield. The sunshield area is chosen as 20 m x 40 m; the size is probably larger than would be required for a 10 m diameter primary mirror, but is selected to provide a reasonable worst-case analysis for passive radiative heat rejection.

In 1b, the five layers of the sunshield assembly are visible. The “bookfold” geometry, in which the shields are angled along only one axis, was used for this study, for reasons of simplicity in parametrizing the model, and because folding on a second axis does not appreciably change the sensitivity of the thermal performance to variation in surface or bulk properties or configuration variation; this conclusion is based upon simple trades done with a similar geometry. Since the model is intended as a trade study tool, not as a physical design representation, the simplicity of the geometry is an advantage.
Shield 1, the sun-facing layer, is planar. Each subsequent shield is angled 5 degrees from the adjacent shield, with vertex separation of 20 cm, in the nominal configuration; both of these values are adjustable for each shield independently.

The individual shields are comprised of a rigid, honeycomb section, 2 m x 2 m, to which are attached membranes of aluminized Kapton which form the remainder of the shield. The rigid sections are assumed to have an aluminum facing on each side, resulting in a relatively high thermal conductance. Thermal conductance of the VDA Kapton membrane material is an adjustable parameter, but in practice is quite small. Physical and thermo-optical properties of the sunshield components are discussed in greater detail in the section on thermal performance.

For this study we have assumed a deployed structure (i.e. we have not modeled the deployment system, just the deployed configuration), while including thermal characteristics of the mechanisms which perform the deployment. Extensible booms attached in the planes of the middle shield extend outward from the central structure, carrying the membranes into deployed position; these are visible as four lines under the third shield, which while not physically representative, incorporate assumed thermal and optical characteristics of such booms. A spreader bar on the end of each boom separates and tensions each of the five shield membranes. We have assumed that the spreader bar penetrates the three inner shields but not the two outer, and therefore is not a radiative or scattering source within more than one shield bay. Thermal conductance along the spreader bars is included in the model. The membrane material is Kapton, 0.025 mm thick, with 100 nm vapor-deposited aluminum (VDA) on both sides; this is a standard product of Sheldahl.

In 1c is shown the central carry-through structure for the sunshield assembly. The ring-and-hexapod structure is fabricated of low-thermal-conductance materials, with mechanical properties sized for launch loads of the sunshield assembly plus the telescope and instrument package. A telescope plus instrument mass of 3400 Kg, and sunshield mass of 550 Kg, were assumed, following the JPL Team X study of SAFIR architecture. The telescope primary support structure is not physically representative.

2.2 Thermophysical and optical properties of the sunshield assembly

Thermophysical properties, primarily thermal conductance as a function of temperature, for the structural elements of the model were taken from White. Thermal conductance appropriate to the mechanical structure is included in the thermal model. The hexapod structure can be thermalized at individual shield sections, or isolated; and each hexapod—shield interface has provision for defining external heat lift, as would be available with a mechanical cryocooler, as either a fixed temperature or fixed heat lift. Parametrization of a heat lift—temperature relationship is possible within this model, but is not currently implemented. For a baseline design, the hexapod struts were assumed to be G-10 FRP. The thermal conductance of the structure was multiplied by a factor of 1.5 to account for wiring parasitic loads.

Heat transfer between adjacent stages of the sunshield assembly is dominated by thermal radiation between the deployed shields. Low emissivity surfaces minimize the probability of photon emission and absorption, so low emissivity at all energy-exchanging shield surfaces minimizes the transfer of energy to, and thus the temperature of, the coldest shield. High emissivity on the space-facing side of the coldest shield minimizes temperature there, but other considerations apply, as will be discussed in the trade study results.

Apart from the sunfacing side of shield 1, all components of the sunshield assembly are assumed to be highly reflective, or to be covered with a highly reflective material such as multi-layer insulation (MLI) made of VDA on Kapton. Emissivity as a function of wavelength, for this range of temperature, wavelength, and operating conditions, is well-approximated by the Hagen-Rubens relation:

\[
\alpha(\lambda, T) = \varepsilon(\lambda, T) = \frac{4y/c\mu/R_s}{(2 + y/c\mu/R_s)^2}
\]

where:
- \(\alpha(\lambda, T)\), \(\varepsilon(\lambda, T)\) = absorbivity, emissivity at wavelength \(\lambda\) for a surface at temperature \(T\)
- \(y = c\mu/R_s\)
- \(c\) = velocity of light
- \(\mu\) = magnetic permeability of the metal film
- \(R_s\) = surface resistivity of the metal film (which is a function of temperature)
- \(\theta\) = angle of incidence (emission) of radiation.
Electrical resistivity of the VDA layer is a function of temperature, but varies considerably less than is the case for bulk aluminum; RRR values for bulk aluminum exceed 1000, while typical RRR values for VDA are about 4. From measurement of the DC surface resistivity performed on 100 nm and 500 nm Sheldahl VDA on Kapton, we have modeled the emissivity as a function of temperature and wavelength. These values are used in the SAFIR model, for wavelengths longer than a few microns, which is the case for most of the thermal radiative transfer. The exceptions are 1) a small component of the zodiacal background centered at 0.5 um, for which we have fixed the emissivity at 0.13; the source and effect of this component is described in the section on zodiacal background environment; and 2), the sun-facing side of shield 1, which is assigned typical values for silverized teflon.

Fig. 1. Views of thermal model of SAFIR spacecraft. 1a: top view with representative 10 m diameter primary mirror, 5 V-groove radiator shields at 5 degree angles and 20 cm vertex separation, 20 m x 40 m area. 1b: bottom view with spacecraft bus and solar arrays. 1c: hexapod carrythrough structure with core sections of shields 1, 3, 5.

2.3 Wavelength dependence of the thermal radiative transfer in SAFIR

Until recently, all commercial radiative transfer codes (so far as we are aware) made the approximation that the probability of emission and of absorption of thermal radiation are equal, for a given surface element (the “grey radiative exchange” approximation). While this is an excellent approximation for radiative exchange between surfaces close in temperature, the approximation fails when the temperatures of the surfaces exchanging radiation differ significantly, with the result that the thermal transfer from warmer to colder surfaces is underestimated. For the conditions expected in the SAFIR sunshield, this underestimate can be a factor of 1.5—2.0 for each pair of shields. The problem arises from failure to consider the wavelength-dependence of the absorbtivity.

For any surface, the emissivity and absorbtivity for radiation at any wavelength are equal (Kirchoff’s Law). For a conductive surface at fixed temperature, the emissivity is proportional to $\lambda^{-1/2}$, as given by the Hagen-Rubens formula, above. The surface radiates over a broad range of wavelength, but the value usually selected as the “effective emissivity” is the value for the wavelength band over which emission occurs preferentially, according to the Planck
blackbody curve. Figure 2 shows the normalized blackbody radiation curves for 15 K and 45 K, and the emissivity relationship given by the Hagen-Rubens function. Formally,

$$\varepsilon_{\text{eff}}(T) = \frac{\int d\lambda \varepsilon(\lambda, T) P(\lambda, T)}{\int d\lambda P(\lambda, T)}$$

is the effective emissivity of a surface at temperature T, given by the convolution of the wavelength- and temperature-dependent emissivity $\varepsilon(\lambda)$ and blackbody power emittance density $P(\lambda, T)$, normalized to the blackbody radiance.

This value of “effective emissivity of the surface at temperature T” is a reasonable approximation for the emissivity of the surface at any particular temperature. However, when a surface at one temperature (surface 1) has incident upon it thermal radiation from a surface at a significantly different temperature (surface 2), the incident radiation has spectral content different from that emitted by surface 1; thus the “effective emissivity” of surface 1 is a poor approximation for the absorptivity at surface 1, for radiation received from surface 2. For the temperatures shown in Figure 2, the absorptivity of the 15 K surface is larger than its emissivity by approximately $(45 \text{ K}/15 \text{ K})^{0.5} = 1.73$. In other words, assuming equal emissivity and absorptivity underestimates the thermal transfer, from the warmer to colder surface, by a factor 1.7. The inverse transfer is overestimated by the same factor, but is much smaller in absolute terms.

Accurate modeling of the SAFIR sunshield performance will require the correct physical processes for radiative transfer throughout the entire temperature range be implemented in the models. As noted above, most or all software packages currently make the assumption of equal emissivity and absorptivity, which is valid for surfaces at similar temperature. It is perhaps worth noting that this is not fundamentally a cryogenic issue; the same inaccuracy occurs for radiative transfer calculations between 300 K—100 K, as for 45 K—15 K; the temperature ratio is in both cases a factor of 3, and the emissivity ratio may be larger in the warmer case since the electrical resistivity has not decreased to a near-constant value.

The recently-released version 4.8 of Thermal Desktop allows for multiple, user-defined wavelength bands to be assigned within a radiation-exchange model. Essentially, the problem is broken into contiguous wavelength bands, with transfer properties within each band treated as “grey”, i.e., not wavelength-dependent, although temperature-dependence is retained. For the SAFIR analysis, in which there are 7 mostly non-overlapping temperature distributions, the band boundaries were selected as the peak thermal wavelengths of the midpoints between distributions; this kept the radiative properties of each surface or source mostly within a single grey band. Again the solar component of the zodiacal background was the exception; a narrow band below 3 um was used.
2.4 Model of zodiacal background as it limits the SAFIR performance

To predict the temperatures attainable by a SAFIR-type sunshield at L2, it is necessary to account for all significant radiant inputs to the spacecraft. Radiant energy from the zodiacal background has seldom if ever been a significant contribution to thermal performance of a telescope (though of course it is a significant contributor to instrument performance). However, with shield 5 temperatures approaching 15 K, the zodiacal background is a significant contributor to SAFIR sunshield performance. Accordingly we have developed a simple model for the dominant, large-scale zodiacal background as it affects sunshield performance.

The model considers only the dominant power contribution from the zodiacal background, but not the details of the chemical or physical makeup of the interplanetary dust that is the source of emission and scattering. In general, the dominant components are backscattered solar radiation (of near solar spectrum, slightly reddened) and thermal emission due to local dust, which is densest in the ecliptic plane. The 2.7 K CMB is ignorable as a thermal power source.

Wright\(^7\) gives data for the zodi background in the Lockman hole, from 1.25 um (longer than solar maximum) to 240 um. Abraham\(^8\) et al show predictions from the DIRBE model, for 12 um and as a function of latitude, which suggest that the power varies by at least a factor of 10 depending upon whether one points in or out of the ecliptic plane. The temperature of the thermal component is selected to be 260 K, in accord with the results of Reach\(^9\) and Ootsubo\(^10\), who find fits to different sections of their data in the range 250—290 K; 260 K best fits the data of Wright.

If one wishes to observe with minimal photon noise, the Lockman hole is one location in which the local foregrounds are small, and the telescope beam transfers only a small angular segment of sky to the instruments. However, the SAFIR sunshield layer 5 will have a large viewing angle to space, close to 2\(\pi\) sr, and presumably the overall effect of zodiacal background on shield temperature will be due to all the source regions, high and low power alike. To account for this, we have fit the data of Wright to a 5785 K greybody plus a 260 K greybody, and increased the intensity in each band by a factor of 5 to account for the effect of the higher power areas, which appears to be reasonably consistent with the results of Abraham. This yields an effective solar greybody emittance of 3.46E-13 for a 5785 K uniform background due to solar backscatter, and an effective thermal greybody emittance of 3.34E-7 for a 260 K uniform background due to thermal radiation from the local dust. This value of solar greybody emittance is in reasonable accord with that found from the data of Levasseur-Regourd\(^11\), which range from 3.09—10.0 E-14 for 0.55 um.

The radiant power incident on shield 5 from these zodiacal sources is approximately that from a 6.6 K blackbody. However, as described above, the absorbance of shield 5 for radiation in the 260 K thermal (11 um peak) and 5785 K solar (0.5 um peak) bands will be significantly larger than would be the case for 6.6 K thermal (440 um peak) radiation. Using the solar absorbance of 0.13 selected earlier, and the Hagen-Rubens—derived values for longer wavelengths, one finds that the absorbed zodiacal power equates to that from a 9.9 K blackbody. While the solar component of the zodiacal background accounts for only 0.20 of the incident power, it provides 0.52 of the absorbed power, due to the much larger absorbance at short wavelengths. The absorbed power is approximately 0.24 of the power emitted by a low-emissivity 15 K shield 5, thus is significant in determining the shield 5 equilibrium temperature.

Figure 3 shows the incident and absorbed power spectral density of the model zodiacal background, and the PSD of blackbody sources for corresponding incident and absorbed powers.

3. MODEL PERFORMANCE RESULTS

We have exercised the thermal model to predict temperature distributions within the sunshield assembly, for various conditions and material characteristics, including

i. wavelength-dependent versus grey radiation exchange;

ii. specularity of the sunshield VDA layers;

iii. emissivity of the sunshield VDA layers, globally and for single energy-exchanging pairs.

Figure 4 shows the temperature distributions on the four colder shields, for the baseline condition of wavelength-dependent exchange and the material properties as described in the section on Thermophysical and Optical Properties. The warmest shield is essentially constant in temperature, with minor variation where it is shaded by the solar arrays and spacecraft bus.
For comparing the results of the varied conditions with the baseline, it is convenient to have a common basis for comparison. To find such a basis, we have considered the operating conditions expected to be required for a SAFIR-type mission. It seems commonly accepted that a telescope-facing shield temperature of 15 K with emissivity of 0.01 would provide a sufficiently low-background environment within which the telescope and instruments could operate to return the required science. Accordingly, we have defined an “equivalent-power temperature” for each shield, defined as the temperature of a surface of the same size as the shield, with emissivity 0.01, which would radiate the same total power as the physical shield. Formally,

\[0.01 \times T_{ept} = \sum_{i} \frac{A_i \varepsilon_i(T)}{\pi^2} T_i^4\]

where \(A_i\) is the area of each element, \(T_i\) is the temperature of that element, and \(\varepsilon_i(T)\) is the emissivity of the element that temperature. The results of the trade studies are reported in equivalent-power temperatures or variation in same. Tables 1—3 show the results of the trade studies.

Table 1. Grey versus wavelength-dependent radiative thermal transfer. Specularity on all surfaces = 1.0.

<table>
<thead>
<tr>
<th>shield 5 (T_{ept}) [K]</th>
<th>type</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.32</td>
<td>WL-dep</td>
</tr>
<tr>
<td>5.79</td>
<td>grey</td>
</tr>
</tbody>
</table>

Table 2. Specularity = 0.6 and 1.0 for all VDA surfaces

<table>
<thead>
<tr>
<th>shield 5 (T_{ept}) [K]</th>
<th>specularity</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.32</td>
<td>1.0</td>
</tr>
<tr>
<td>12.47</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 3. Emissivity for various VDA surfaces as function of temperature- and wavelength-dependent emissivity as derived above.

<table>
<thead>
<tr>
<th>shield 5 (T_{ept}) [K]</th>
<th>emissivity multiplicative factor</th>
<th>surface(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.32</td>
<td>1.0</td>
<td>all</td>
</tr>
<tr>
<td>7.97</td>
<td>1.2</td>
<td>all</td>
</tr>
<tr>
<td>8.92</td>
<td>1.4</td>
<td>all</td>
</tr>
<tr>
<td>7.75</td>
<td>1.6</td>
<td>S1 cold</td>
</tr>
<tr>
<td>8.03</td>
<td>2.0</td>
<td>S1 cold</td>
</tr>
<tr>
<td>8.63</td>
<td>3.0</td>
<td>S1 cold</td>
</tr>
<tr>
<td>7.63</td>
<td>1.6</td>
<td>S3 both</td>
</tr>
<tr>
<td>8.27</td>
<td>3.0</td>
<td>S3 both</td>
</tr>
<tr>
<td>8.64</td>
<td>4.0</td>
<td>S5 both</td>
</tr>
<tr>
<td>9.60</td>
<td>3.0</td>
<td>S5 both</td>
</tr>
<tr>
<td>10.29</td>
<td>4.0</td>
<td>S5 both</td>
</tr>
</tbody>
</table>

Minimum temperature on the coldest, telescope-facing side of the V-groove radiator can be obtained if that surface has high emissivity; however, this may be undesirable for the science instruments. High emissivity on only the outward-facing shield 5 surface increases the emissive efficiency, but the power transferred to shield 5 from shield 4 and from the zodiacal background both increase. The net effect is to more than double the power emitted by shield 5 toward the telescope, and to shift that power to longer wavelength. Whether this is beneficial or detrimental to the science mission will depend upon details of spectral sensitivity of the instruments; thus the environment supplied to the telescope should consider more than just the temperature of the surroundings, but also the radiative properties of those surroundings.
Incident and absorbed zodiacal background power spectral density and conditional-equivalent blackbody PSD

Fig. 3. Incident and absorbed zodiacal background power spectral density. Blue, upper solid: incident PSD from model zodi background. Red, solid: absorbed PSD assuming 0.13 absorbance for solar spectrum and Hagen-Rubens relationship for longer wavelength absorption of 15 K surface. Blue, dashed: PSD of 6.6 K blackbody, with incident power equal to incident PSD. Red, dashed: 9.9 K blackbody, which if absorbed by 15 K surface with model absorbivity would supply power equivalent to zodiacal absorption.

Fig. 4. Temperature distributions on shield 2,3,4,5 for SAFIR sunshield model. Shield 1 is essentially uniform 280 K.

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.
REFERENCES

1 Sheldahl, http://sheldahl.com
4 Bauer, S, “Optical Properties of a Metal Film and its Application as an Infrared Absorber and as a Beam Splitter”, *Amer. J. Physics* 60(3) 257-261 (1992)
5 M. DiPirro (private communication)