A Thermal Study of the Early NGST Instrument Module

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ABSTRACT

*A study was performed on the GSFC-led design of the NGST Integrated Science Instrument Module (ISIM) to gauge the sensitivities of the optical bench temperatures to various parameters, and to generally assess the likelihood of passively cooling the Near IR (NIR) InSb detectors to the 30-35˚K range. Radiator efficiencies were varied, along with ISIM-Sunshade distances, detector heat loads, and emissivities of various surfaces. The very best cases produced temperatures of around 32.8˚K at the optical bench for 160 mW dissipated power by the detectors. A 40% increase in radiator area was shown to drop this temperature to 30.2˚K. It was concluded that managing and rejecting heat from the detectors inside the ISIM was critical, and that given the radiator area limited by the planned launch vehicle, it would be possible to passively cool the NIR Science Instruments to the 30-35˚K range, but with little margin. **Note:** Since the time of this study, further investigations by the GSFC engineering team determined that the baseline design should be altered to assume a larger launcher and a subsequently larger ISIM. Warmer OTA designs and active cooling are being rigorously addressed.*

1. Introduction

The NGST designs are dynamic as optimum price-packaging-performance solutions are sought. The general GSFC-led "yardstick" design remains an f/1.2 8-meter 8-petal segmented open Optical Telescope Assembly (OTA), with 0.6-5.0 µm baseline NIR science capability and 5.0 - 30 µm thermal IR (TIR) extended mission (Fig. 1) . At the time of this study (late 1997) the spacecraft was planned to be packaged into an Atlas IIARS/ EPF launch vehicle (Fig. 2), which would deliver it to a halo orbit around the L2 Sun-Earth Lagrangian point, where a deployable spacecraft sunshade and other design features would passively cool the NIR detectors to the 30-35˚K range. This temperature was considered the goal for the baseline NIR capability and was driven mainly by the InSb

detector's dark current (Fig. 3). The extended TIR capability requires temperatures $< 8°$K and clearly requires active cooling.

Working with: a simplified overall structure for the ISIM and its contents; certain dimensions constrained ultimately by the launch vehicle shroud; and heat loading from sources at temperatures calculated elsewhere (Parrish & Stanley, 1997), we investigated the temperatures achievable at the detectors and their dependencies, as a preliminary and flexible study to check against more detailed analyses.
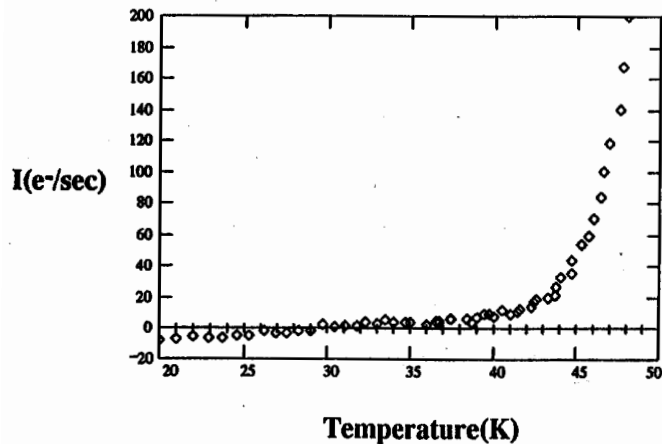
Figure 1: The General GSFC NGST Yardstick Concept
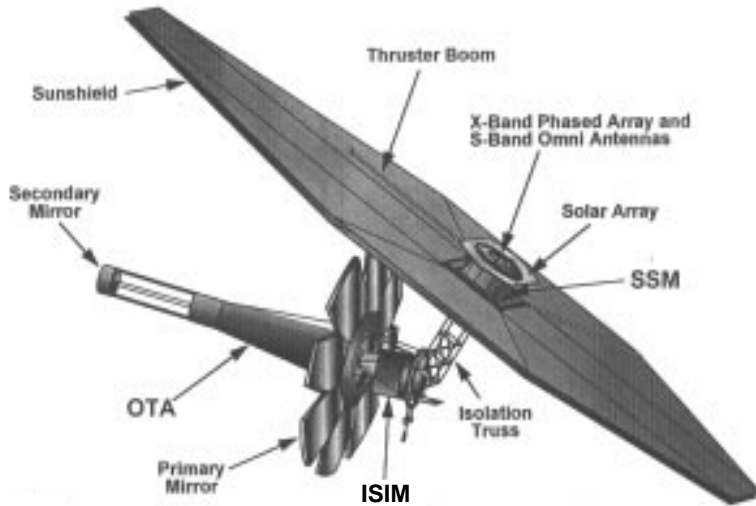
Figure 2: Packaging Constraints (Atlas IIARS-Extended Payload Faring)

Faring Station numbers represent reference positions in inches.
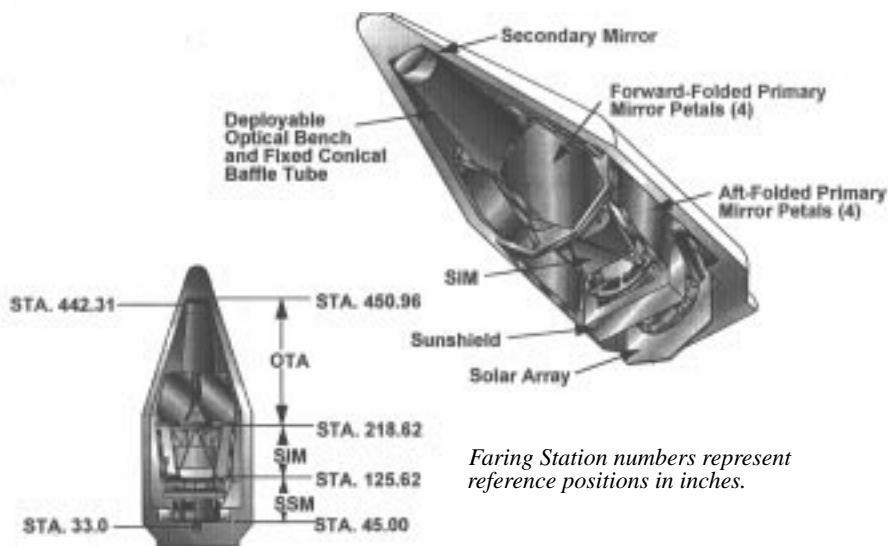
Figure 3: InSb Detector Dark Current

2. The Model

The software used in this analysis was *TAK3* by K&K Assoc., Westminster, CO. TAK3 is a 'finite differencing' analyzer. The user defines a thermal network composed of isothermal nodes which are connected by conductors. For this software, a conductor simply represents a thermal connection between nodes, whether radiative, conductive, or mass flows. In our study radiation was the only mechanism considered, since the design of NGST renders heat flow via conduction very small compared to the radiation transfers. Small amounts of parasitic loading via wiring and cables, and fed through the ISIM-OTA bipod flexure attachments are estimated but are not part of the model. For our purposes, a steady state solution was appropriate, with TAK3 computing final temperatures for all the nodes, and heat flow through all the conductors.

The conductor values connecting nodes must be manually computed for each transfer and supplied to the TAK3 input file. This value describing the radiative transfer between two nodes involves a relation between the nodes' areas, separations, emissivities, and orientations with respect to one another. To express the total interchange, the emissivities and areas are combined with a calculated *view factor* (Fig. 4). To verify our calculations, we compared results for a series of standard configuration with those described in Hamilton, 1952.

Essentially, the model can be simplified as follows; there is a large (33 X 14 meter) diamond shaped multilayered sunshade, whose OTA-facing side has a certain temperature distribution. These values are very nearly constant over the +/- 23° range of tilt around the perpendicular sun line. The sunshade lies at the end of a thermally isolating truss at a given distance from the ISIM and OTA. Though the sunshade design has iterated many times, results of a GSFC study (Parrish & Stanley, 1997) provided us with temperatures for the OTA-facing side, which were based on a low *e* (reflective) sunshade. The sunshade

heat sources were assumed to have infinite capacitance (T constant). The temperature distribution over the shade back was handled by dividing the shade into 19 isothermal nodes (Fig. 5). Engineering judgement must be used throughout the model to insure a number of nodes adequate for fidelity. The other major contributor of heat to the ISIM was the ISIM-facing reflective back side of the primary mirror. Temperatures for these 8 nodes (8 mirror petals) were also assumed infinite capacitance and taken from the Parrish results. Note that all input temperatures to the model were for end of life (EOL). This assumes degradation of the sunshade materials expected at the end of mission and represent warmest cases.

In order to find the final temperature of interest at the detectors, details of the ISIM structure itself become important. Baseline ISIM characteristics were provided by Bely (1997). A description of our ISIM model and assumptions are given in outline form below.
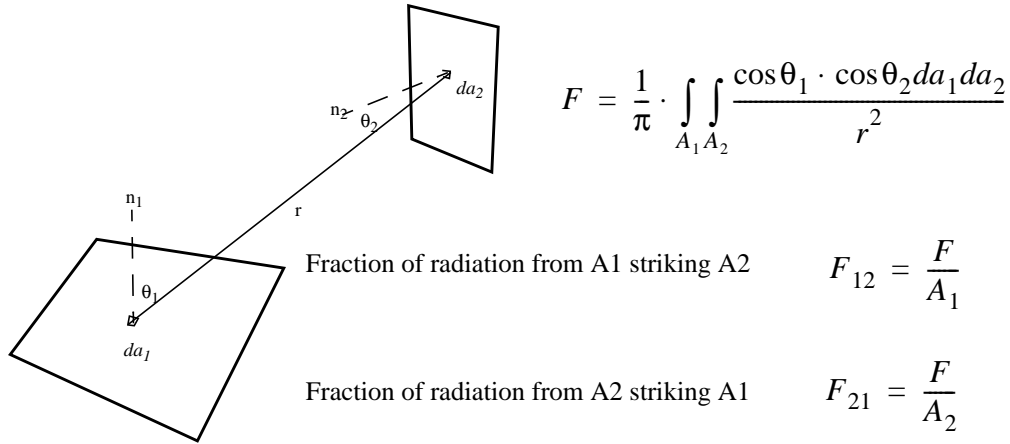
Instrument Module, ISIM (Fig. 6)
- ISIM model assumed 2X2 meter cube:
    - ISIM axes canted 20° w.r.t sunshade plane
    - 4 sides facing sunshade wrapped in MLI
    - side facing space is a radiator
    - top side facing OTA unmodeled (no connectors: negligible contributor)
    - ISIM view to some sunshade nodes obstructed by primary mirror
- Internal structure:
    - outer MLI blanket (4 nodes; 1 per side)
    - radiatively cooled shield connected to parasitic radiators (1 node)
    - inner MLI blanket (1 node)
    - enclosure (box containing optical bench and detectors. 1 node)
    - test cube (volume filling enclosure, simulating detectors, to which the heat source is applied)
    - radiator (1 node) Main radiator, perfectly conductively coupled to enclosure, and radiatively coupled to test cube
- Best case by far has all surfaces in ISIM reflective except the test cube itself and the inner surface of the enclosure.

An important part of the model is the test cube and the heat load applied to it. The test cube represents the detectors, and is the final node of interest. The variable heat load represents the detectors and related electronics' power dissipation. All other forms of ISIM heating (sunshade, primary, small amounts of conduction) are referred to as 'parasitic' heat loads. Higher fidelity models must accurately model the distribution of electronics within the ISIM interior and examine in detail the conduction coupling between the electronics and the optical bench. However, since the heat in the interior of the ISIM must be dumped via conduction or radiation to the main 2 X 2 meter radiator, which is found to be already working at nearly its theoretical limit of ~184 mW at 30˚K, such details within the ISIM would not alter the overall result significantly.

Since the time of this ISIM concept, further investigations by the GSFC engineering team led by Code 740 determined in March '98 that for thermal and other SI packaging considerations, the baseline NGST design should be altered to assume a larger launch vehicle (EELV 5m faring) and a subsequently larger ISIM. This would result in an increase in radiator area by approximately 60% over the 2 X 2 meter design. In addition to the larger size, active cooling is being rigorously studied, as well as warmer OTA designs.

Figure 4: Radiative Transfer Integral

$$F = \frac{1}{\pi} \cdot \int\limits_{A_1} \int\limits_{A_2} \frac{\cos\theta_1 \cdot \cos\theta_2 \, da_1 \, da_2}{r^2}$$

Fraction of radiation from A1 striking A2
$$F_{12} = \frac{F}{A_1}$$

Fraction of radiation from A2 striking A1
$$F_{21} = \frac{F}{A_2}$$
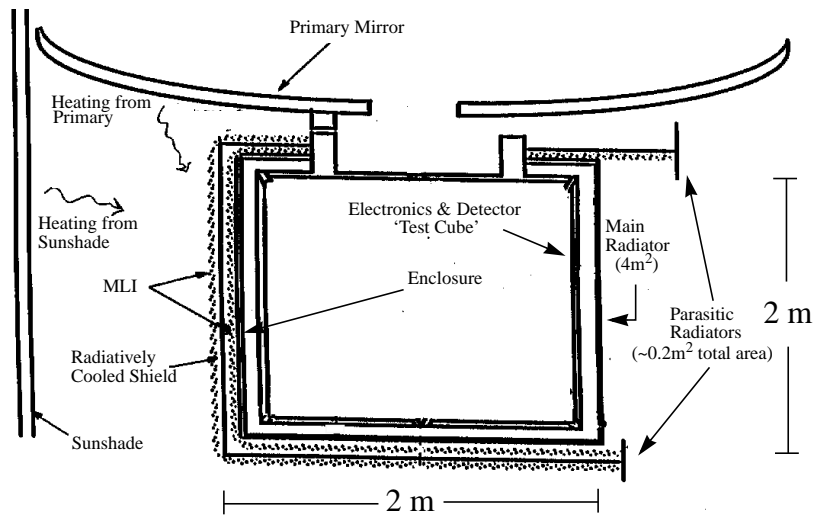
With emissivities e_1 and e_2, total transfer function is, allowing for multiple reflections

$$G = \frac{e_1 \cdot e_2 \cdot F}{1 - F_{12} \cdot F_{21} \cdot (1 - e_1) \cdot (1 - e_2)}$$

Figure 5: Input Sunshade Temperatures & Geometry

Figure 6: The ISIM Model

Primary Mirror

Heating from Primary

Heating from Sunshade

MLI

Radiatively Cooled Shield

Sunshade

Electronics & Detector 'Test Cube'

Enclosure

Main Radiator (4m^2)

Parasitic Radiators (~0.2m^2 total area)

2 m

2 m
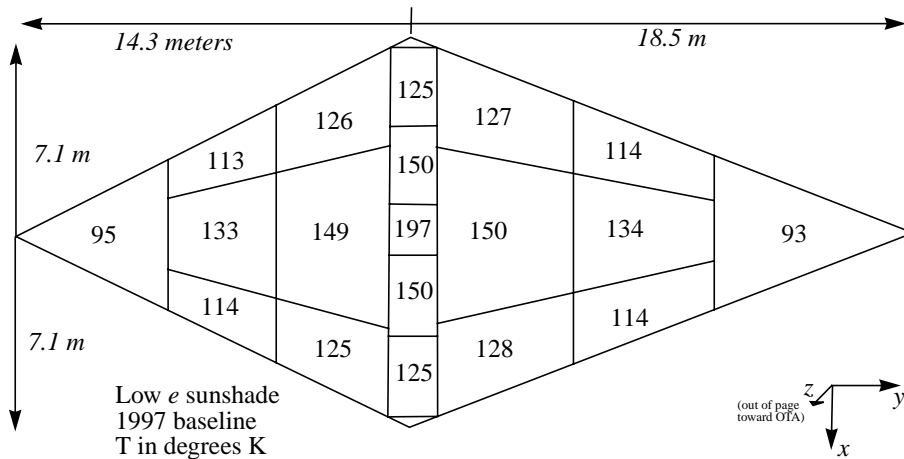
3. Findings & Conclusions

The resulting heat load balances indicated that a multilayered, insulating ISIM (Fig. 6) with low e (reflective) layers and panels, and small parasitic radiators effectively rejects the input heating from the sunshade and the mirror back. Low e reflective surfaces for the outer faces of the ISIM reject most of the heat loading from the shade and OTA while most of what remains is dumped to space via the radiatively cooled shield's parasitic radiators. Only about 20 mW of power reach the ISIM interior from outside sources. The issue becomes rejecting the nominal 150 to 200 mW of dissipated power from the detectors themselves. The NGST design features SI-related electronics such as power supplies being located across the isolating truss on the warm spacecraft bus at the center of the sunshade. This keeps the heat dissipated inside the ISIM to a minimum. The best scenario to reject the detector heat resulted from a high e (absorptive) ISIM interior and a high e test cube. This intuitive layout maximizes heat flow from the interior to the main radiator which forms the deep-space facing side of the ISIM. Ideal conductive coupling between the ISIM enclosure and main radiator was assumed. Various efficiencies of radiative coupling between the test cube (representing the detectors) and the main radiator were examined. Figure 7 shows equilibrium temperatures at the test cube and radiator as a function of power dissipated by the detectors. Two cases are plotted; the 4 m^2 radiator, and one with 40% more area. The 'nominal' 160 mW power figure is far from a fixed value, and much effort is ongoing to reduce this value by creative detector readout schemes and management of the duty cycle of the instruments. (Stockman, 1998). Figure 8 shows, for the 160 mW case, the variation of test cube temperature with radiator emissivity. Over the range of $e = 0.7$ (flat black paint) to $e = 0.95$ (very efficient radiator) the temperature varies

by 2.3°K. Figure 9 illustrates the test cube's relative insensitivity to practical isolation truss length changes, or distance from the sunshade.

Main conclusions are that passively cooling the 2 X 2 meter ISIM for the baseline NIR mission is possible, but that the margin is small. Active cooling is a must for the TIR mission (ISIM < 6-8°K). For the passively cooled case, near-ideal conductive coupling between the detectors and the radiator/enclosure is needed. The limited radiator areas and the power dissipated inside the ISIM by the detectors are the key factors. Detector operating schemes must be chosen with reducing dissipated heat a prime concern. Parasitics via conduction into the ISIM through the OTA attachments, electrical wires and any other sources must be very carefully managed. The recent switch to the larger baseline will lighten these concerns, and dramatically so if active cooling is baselined.
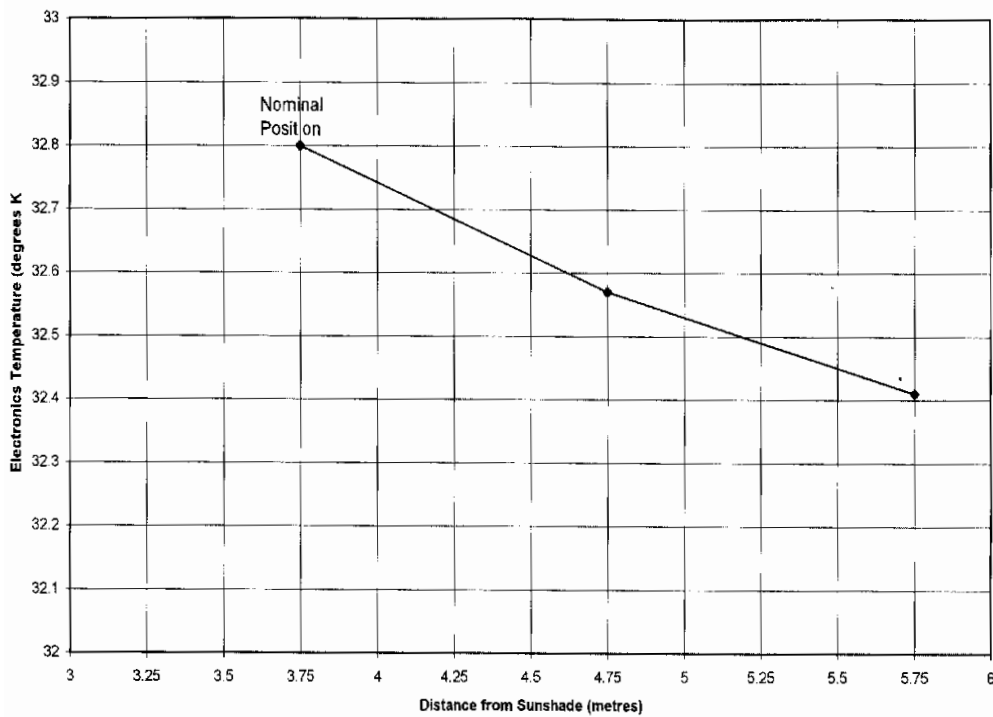
Figure 7: Detector & Radiator Temperature vs. Dissipated Power

7
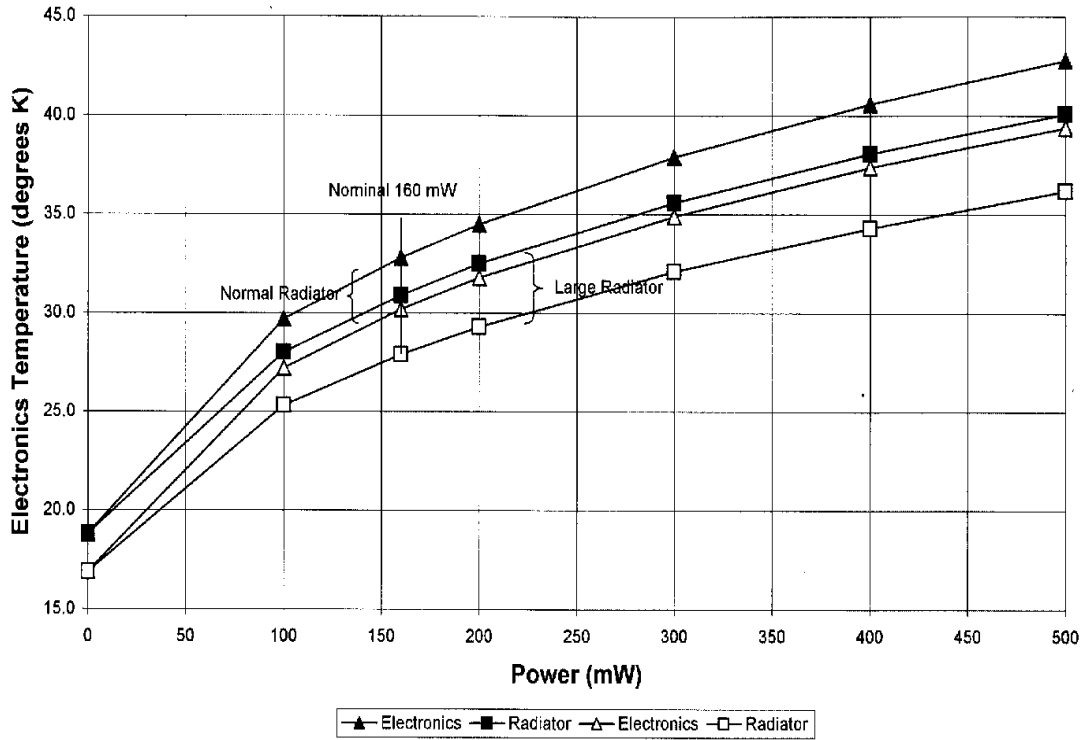
Figure 8: Temperature vs. Radiator Emissivity
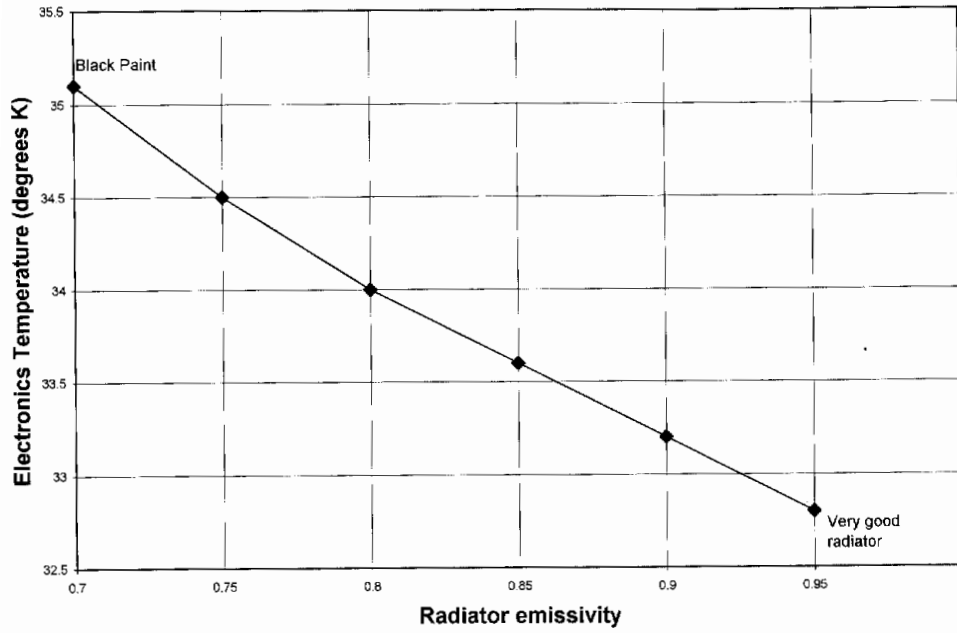
Figure 9: Temperature vs. Distance from Sunshade

4. References

Bely, P., 1997, SIM Presentation to the NGST Study Office.

Hamilton, D.C., Morgan, W.R., 1952, *Radiant Interchange Configuration Factors,* NACA Report TN-2836

Parrish, K., 1997, private communication.

Stockman, H. P., 1998, private communication.

5. Appendix

The Thermal Model (TAK3 input)

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HEADER OPTIONS DATA

c      NGST ISIM Thermal Model (rev Feb 98 Lallo/Cox)
c      Contribution from primary and sunshade
       SOLRTN = ssiter
       UID = SI

HEADER CONTROL DATA

       SSCRIT  = .001,  ABSZRO = 0.,  SIGMA = 5.67E-08
       Area1      = 2.*2.    $ Area of ISIM enclosure sides & radiator (meters)
       Area2      = .20      $ Area of parasitic radiator attached to shield
       Area3      = 0.       $ Area for detectors to view space
       e_shade    = 0.03     $ sunshade back facing ISIM
       e_mli      = 0.03     $ 3 to 5 layer MLI
       e_coat     = 0.03     $ reflective coatings
       e_petal    = 0.03     $ primary mirror petal back emittance
       e_radiator = 0.95     $ radiator value (Ball)
       e_paint    = 0.7      $ black paint value (MSFC)
       power      = 0.160    $ power dissipated in ISIM by electronics

HEADER NODE DATA

c ISIM NODES
       101, 55., 1.0         $ MLI outer, toward sunshade
       102, 55., 1.0         $ MLI outer, lower surface
       103, 55., 1.0         $ MLI outer, side
       104, 55., 1.0         $ MLI outer, side
       200, 50., 1.0         $ Radiatively cooled shield
       250, 45., 1.0         $ inner MLI
       275, 42., 1.0         $ enclosure
       300, 20., 1.0         $ SI test cube

c PRIMARY MIRROR PETAL NODES
c reflective case; no strapping; temps from Parrish
c mirror petals assumed infinite capacitance

      -800, 30., 1.0         $ cold petal, facing radiator
      -810, 35., 1.0         $ petal facing radiator & node 104
      -820, 42., 1.0         $ petal facing ISIM node 104
      -830, 50., 1.0         $ petal facing nodes 104 & 101
      -840, 55., 1.0         $ petal facing node 101
      -850, 50., 1.0         $ petal facing nodes 101 & 103
      -860, 42., 1.0         $ petal facing node 103
      -870, 35., 1.0         $ petal facing node 103 & radiator

c SUNSHADE NODES
c temps and distributions from Parrish

      -980, 93., 1.0         $ shadenode980
      -981, 114., 1.0        $ shadenode981
      -982, 134., 1.0        $ shadenode982
      -983, 114., 1.0        $ shadenode983
      -984, 127., 1.0        $ shadenode984
      -985, 150., 1.0        $ shadenode985
      -986, 128., 1.0        $ shadenode986
      -987, 125., 1.0        $ shadenode987
      -988, 150., 1.0        $ shadenode988
      -989, 197., 1.0        $ shadenode989
      -990, 150., 1.0        $ shadenode990
      -991, 125., 1.0        $ shadenode991
      -992, 126., 1.0        $ shadenode992
      -993, 149., 1.0        $ shadenode993
      -994, 125., 1.0        $ shadenode994
      -995, 113., 1.0        $ shadenode995
      -996, 133., 1.0        $ shadenode996
      -997, 114., 1.0        $ shadenode997
      -998, 95., 1.0         $ shadenode998

c SPACE
      -999,  6., 1.0         $ Space @ L2
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HEADER CONDUCTOR DATA
c ***********************SUNSHADE TO ISIM EXCHANGE**********************

c   Radiation from shadenode 980 to ISIM outer MLI
c    ISIM view blocked by primary mirror

c   Radiation from shadenode 981 to ISIM outer MLI
c    ISIM view blocked by primary mirror

c   Radiation from shadenode 982 to ISIM outer MLI
c    ISIM view blocked by primary mirror

c   Radiation from shadenode 983 to ISIM outer MLI
c    ISIM view blocked by primary mirror

c   Radiation from shadenode 984 to ISIM outer MLI
    -1017, 984, 101, 1.40e-4
    -1018, 984, 102, 1.86e-6
    -1019, 984, 103, 2.33e-4
    -1020, 984, 104, 0.

c   Radiation from shadenode 985 to ISIM outer MLI
    -1021, 985, 101, 1.74e-3
    -1022, 985, 102, 2.02e-5
    -1023, 985, 103, 1.29e-4
    -1024, 985, 104, 1.29e-4

c   Radiation from shadenode 986 to ISIM outer MLI
    -1025, 986, 101, 1.40e-4
    -1026, 986, 102, 1.86e-6
    -1027, 986, 103, 0.
    -1028, 986, 104, 2.33e-4

c   Radiation from shadenode 987 to ISIM outer MLI
    -1029, 987, 101, 1.71e-5
    -1030, 987, 102, 7.07e-6
    -1031, 987, 103, 6.82e-5
    -1032, 987, 104, 0.

c   Radiation from shadenode 988 to ISIM outer MLI
    -1033, 988, 101, 1.08e-4
    -1034, 988, 102, 3.85e-5
    -1035, 988, 103, 7.72e-5
    -1036, 988, 104, 0.

c   Radiation from shadenode 989 to ISIM outer MLI
    -1037, 989, 101, 1.58e-4
    -1038, 989, 102, 3.55e-5
    -1039, 989, 103, 0.
    -1040, 989, 104, 0.

c   Radiation from shadenode 990 to ISIM outer MLI
    -1041, 990, 101, 1.08e-4
    -1042, 990, 102, 3.85e-5
    -1043, 990, 103, 0.
    -1044, 990, 104, 7.72e-5

c   Radiation from shadenode 991 to ISIM outer MLI
    -1045, 991, 101,  1.71e-5
    -1046, 991, 102,  7.07e-6
    -1047, 991, 103,  0.
    -1048, 991, 104,  6.82e-5

c   Radiation from shadenode 992 to ISIM outer MLI
    -1049, 992, 101, 1.85e-5
    -1050, 992, 102, 3.80e-5
    -1051, 992, 103, 9.17e-5
    -1052, 992, 104, 0.

c   Radiation from shadenode 993 to ISIM outer MLI
    -1053, 993, 101, 9.09e-5
    -1054, 993, 102, 2.09e-4
    -1055, 993, 103, 3.77e-5
    -1056, 993, 104, 3.77e-5

c   Radiation from shadenode 994 to ISIM outer MLI
    -1057, 994, 101,  1.85e-5
    -1058, 994, 102,  3.80e-5
    -1059, 994, 103,  0.
    -1060, 994, 104,  9.17e-5

c   Radiation from shadenode 995 to ISIM outer MLI
    -1061, 995, 101,  1.49e-6
    -1062, 995, 102,  1.67e-5
    -1063, 995, 103,  1.00e-5
    -1064, 995, 104,  0.

c   Radiation from shadenode 996 to ISIM outer MLI
    -1065, 996, 101, 3.49e-6
    -1066, 996, 102, 4.21e-5
    -1067, 996, 103, 1.39e-6
    -1068, 996, 104, 1.39e-6

c   Radiation from shadenode 997 to ISIM outer MLI
    -1069, 997, 101, 1.49e-6
    -1070, 997, 102, 1.67e-5
    -1071, 997, 103, 0.
    -1072, 997, 104, 1.00e-5

c   Radiation from shadenode 998 to ISIM outer MLI
    -1073, 998, 101, 4.60e-8
    -1074, 998, 102, 8.43e-6
    -1075, 998, 103, 1.47e-7
    -1076, 998, 104, 1.47e-7
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c ****************PRIMARY MIRROR BACK TO ISIM EXCHANGE*****************
     -1800, 800, 275, .0057
     -1801, 800, 103, 1.55e-8
     -1802, 800, 104, 1.55e-8

     -1810, 810, 275, .0020
     -1811, 810, 104, 6.27e-5

     -1820, 820, 104, 1.79e-4
     -1821, 820, 275, 4.89e-7
     -1822, 820, 101, 1.55e-8

     -1830, 830, 104, 6.27e-5
     -1831, 830, 101, 6.27e-5

     -1840, 840, 101, 1.79e-4
     -1841, 840, 103, 1.55e-8
     -1842, 840, 104, 1.55e-8

     -1850, 850, 103, 6.27e-5
     -1851, 850, 101, 6.27e-5

     -1860, 860, 103, 1.79e-4
     -1861, 860, 275, 4.89e-7
     -1862, 860, 101, 1.55e-8

     -1870, 870, 275, .0020
     -1871, 870, 103, 6.27e-5


c *******************FLOW WITHIN ISIM AND ENVIRONMENT*******************
c Best case is low e ISIM (high e facing interior)

c    Radiation from outer MLI to space
c    (based on fraction of panels' radiation not seeing shade or mirror)
     -1101, 101, 999, Area1 * e_mli * (.15-.085)
     -1102, 102, 999, Area1 * e_mli * (.85-.085)
     -1103, 103, 999, Area1 * e_mli * (.82-.085)
     -1104, 104, 999, Area1 * e_mli * (.82-.085)

c    Radiation from outer MLI to radiatively cooled shield (low e shield)
     -1201, 101, 200, Area1 * 1./(1./e_mli+1./e_coat-1.)
     -1202, 102, 200, Area1 * 1./(1./e_mli+1./e_coat-1.)
     -1203, 103, 200, Area1 * 1./(1./e_mli+1./e_coat-1.)
     -1204, 104, 200, Area1 * 1./(1./e_mli+1./e_coat-1.)

c    Radiation from radiatively cooled shield's parasitic radiator
c    (based on fraction of radiation not seeing primary)
     -1301, 200, 999, Area2 * e_radiator * (1.-.085)

c    Radiation from radiatively cooled shield to inner MLI
c    (assuming isothermal r.c.shield)
     -1401, 200, 250, 4. * Area1 * 1./(1./e_mli+1./e_coat-1.)

c    Radiation from inner MLI to enclosure (low e enclosure)
     -1501, 250, 275, 4. * Area1 * 1./(1./e_mli+1./e_coat-1.)

c    Radiation from enclosure's large radiator
c    (based on fraction of radiation not seeing primary)
     -1601, 275, 999, Area1 * e_radiator * (1.-.085)

c    Radiation from enclosure interior to SI test cube
      -1701, 275, 300, 4. * Area1 * 1./(1./e_paint+1./e_paint-1.)

c    Radiation of test cube out top of enclosure to space (refine)
      -1710, 300, 999, Area3 * e_paint

c    Radiation from test cube to main radiator
      -1720, 300, 275, Area1 * 1./(1./e_paint+1./e_radiator-1.)


HEADER SOURCE DATA
      300, power    $ heat dissipated in SI test cube


END OF DATA
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