The Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) On-board Blackbody Calibration System

Fred A. Best[a], Henry E. Revercomb[a], Robert O. Knuteson[a], David C. Tobin[a], Scott D. Ellington[a], Mark W. Werner[a], Douglas P. Adler[a], Raymond K. Garcia[a], Joseph K. Taylor[a], Nick N. Ciganovich[a], Willliam L. Smith[b], Gail E. Bingham[c], John D. Elwell[c], and Deron K. Scott[c]

[a]University of Wisconsin-Madison, Madison, WI
[b]Hampton University, Hampton, VA
[c]Utah State University, Logan, UT

ABSTRACT

The NASA New Millennium Program's Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) instrument provides enormous advances in water vapor, wind, temperature, and trace gas profiling from geostationary orbit. The top-level instrument calibration requirement is to measure brightness temperature to better than 1 K (3 sigma) over a broad range of atmospheric brightness temperatures, with a reproducibility of ±0.2 K. For in-flight radiometric calibration, GIFTS uses views of two on-board blackbody sources (290 K and 255 K) along with cold space, sequenced at regular programmable intervals. The blackbody references are cavities that follow the UW Atmospheric Emitted Radiance Interferometer (AERI) design, scaled to the GIFTS beam size. The cavity spectral emissivity is better than 0.998 with an absolute uncertainty of less than 0.001. Absolute blackbody temperature uncertainties are estimated at 0.07 K. This paper describes the detailed design of the GIFTS on-board calibration system that recently underwent its Critical Design Review. The blackbody cavities use ultra-stable thermistors to measure temperature, and are coated with high emissivity black paint. Monte Carlo modeling has been performed to calculate the cavity emissivity. Both absolute temperature and emissivity measurements are traceable to NIST, and detailed uncertainty budgets have been developed and used to show the overall system meets accuracy requirements. The blackbody controller is housed on a single electronics board and provides precise selectable set point temperature control, thermistor resistance measurement, and the digital interface to the GIFTS instrument. Plans for the NIST traceable ground calibration of the on-board blackbody system have also been developed and are presented in this paper.

Keywords: Imaging, FTS (Fourier Transform Spectrometer), Radiometric, Calibration, Blackbody, Remote Sensing

1. INTRODUCTION

The Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) instrument requires highly accurate radiometric calibration in order to provide its enormous advances in water vapor, wind, temperature, and trace gas profiling from geostationary orbit.[1,2,3] The unique GIFTS radiometric calibration scheme[4-7] uses two internal blackbody sources located behind the instrument telescope, combined with a space view, to provide end-to-end instrument calibration accuracy better than 1 K (3-sigma). The reproducibility is better than ±0.2 K. The calibration scheme builds on well-established general techniques for calibrating interferometer instruments.[8-10] There is a significant advantage to the internal blackbody approach used by GIFTS[4], in large part because it is practical to achieve a high emissivity with a small size blackbody. Because the blackbodies are small and internally located, they also provide significant immunity from solar forcing. The blackbodies are periodically viewed via a flip-in mirror that is located near the field stop behind the instrument telescope. The blackbodies, which are independently controlled to different temperatures, are located on a translating table that positions either the ambient (255 K) or hot (290 K) blackbody into the view of the flip-in mirror. An instrument-level GIFTS calibration model involving blackbody temperature and temperature uncertainty, blackbody emissivity and emissivity uncertainty, telescope and flat mirror element temperatures, and structural temperatures has been developed and used to assess and budget various blackbody parameter uncertainties. The budget allocation for the blackbody subsystem is ≤ 0.5 K. Figure 1 illustrates how this top-level blackbody requirement is flowed down to the key parameters of the blackbody subsystem. This paper deals with the first four boxes involving blackbody temperature and emissivity. The structural temperature box deals with the blackbody radiance reflected from the surroundings. This paper describes the design

and calibration of the GIFTS blackbody subsystem that consists of two nearly identical blackbodies and the associated controller that provides temperature readout and control. Table 1 presents the top-level requirements for the blackbody subsystem along with the current best estimate for each parameter. In all cases the design meets the requirements. An engineering model of all the hardware has been fabricated and is currently undergoing testing and calibration.
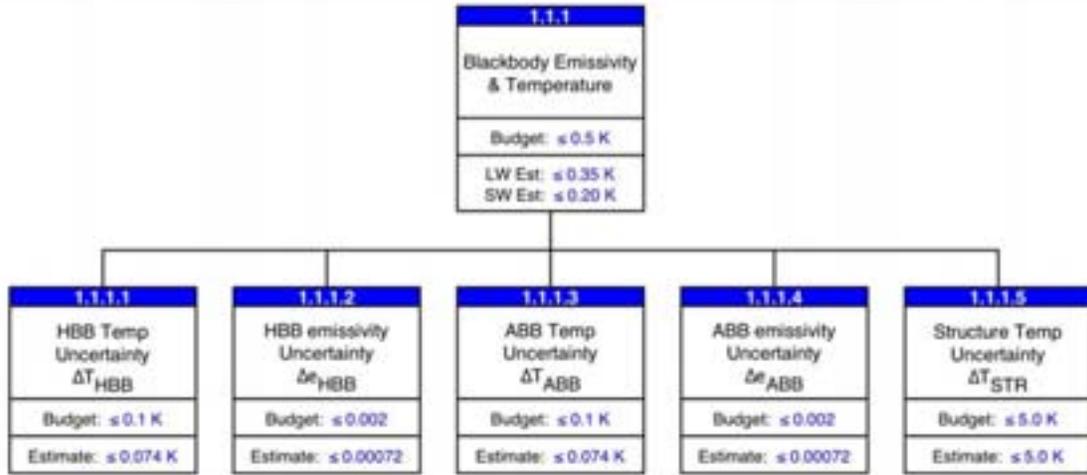

Figure 1. Top-level blackbody calibration error tree showing uncertainties associated with important subsystem parameters.

Table 1. Top-level blackbody subsystem specifications with current best estimates.

Parameter	Specification	Current Best Estimate
Ambient Blackbody Nominal Set Point	255 K	255 K
Hot Blackbody Nominal Set Point	290 K	290 K
Temperature Measurement Uncertainty	< 0.1 K (3 sigma)	< 0.074 K (3 sigma)
Ambient Blackbody Emissivity	> 0.996	> 0.998
Hot Blackbody Emissivity	> 0.996	> 0.998
Emissivity Uncertainty	< 0.002	< 0.00072 (3 sigma)
Wavelength	680 - 2,300 cm-1	680 - 2,300 cm-1
Source Aperture	2.54 cm	2.54 cm
Source FOV (full angle)	> 10°	> 10°
Mass (two blackbodies plus controller)	< 2.4 kg	< 2.1 kg
Power: average/max	< 2.2/5.2 W	< 2.2/5.2 W
Envelope	< 8 x 8 x 15.5 cm	< 8 x 8 x 15.4 cm

2. BLACKBODY MECHANICAL AND THERMAL DESIGN

The key objective of the blackbody design is to provide an isothermal emissivity-enhancing cavity, that uses minimal power to maintain stable temperatures above the surrounding environment. In addition, the design must be structurally sound in order for the blackbody to survive the launch environment. The mechanical design of the blackbody is illustrated in Figure 2. The two blackbodies (hot and ambient) are nearly identical – the main difference being the thermistor nominal resistance that was selected to optimize temperature measurement resolution.

2.1 Mechanical Design
The cavity is machined from aluminum and has an entrance aperture of 1.0 inch. The cavity shape is a scaled down version of the design used in the University of Wisconsin (UW) developed Atmospheric Emitted Radiance Interferometer (AERI).[11,12,13] The inner wall of the cavity is painted with Aeroglaze Z306 – a popular diffuse, high

emissivity (0.94 to 0.97), and low outgassing black polyurethane. A Minco thermofoil heater, used for temperature control, is located on the outer cylindrical section of the cavity. The cavity is mounted to a thin wall support tube and mounting base constructed of Noryl GFN3, a glass reinforced plastic from GE. The material was chosen for its high strength, low thermal conductivity, and low thermal expansion mismatch compared to aluminum (the survival temperature of the blackbody is 180 K). Four holes in corners of the mounting base (not visible in Figure 2) are used for attachment of the blackbody to the translating table of the GIFTS instrument. The outer enclosure is constructed of aluminum, which minimizes temperature gradients in the cavity. The enclosure has a load path to the mounting base through a flange located mid-way up the support tube. This configuration uses the Noryl support tube to provide thermal isolation from both the cavity and the mounting base.

The structural design of the blackbody provides the needed strength and stiffness to survive the launch environment. The quasi-static design limit load is 50 G, and the random vibration environment is 8 Grms. To minimize vibration coupling with GIFTS instrument the minimum natural frequency requirement for the blackbody is specified at 150 Hz. The lowest natural frequency measured after random vibration and thermal cycling tests is 180 Hz.
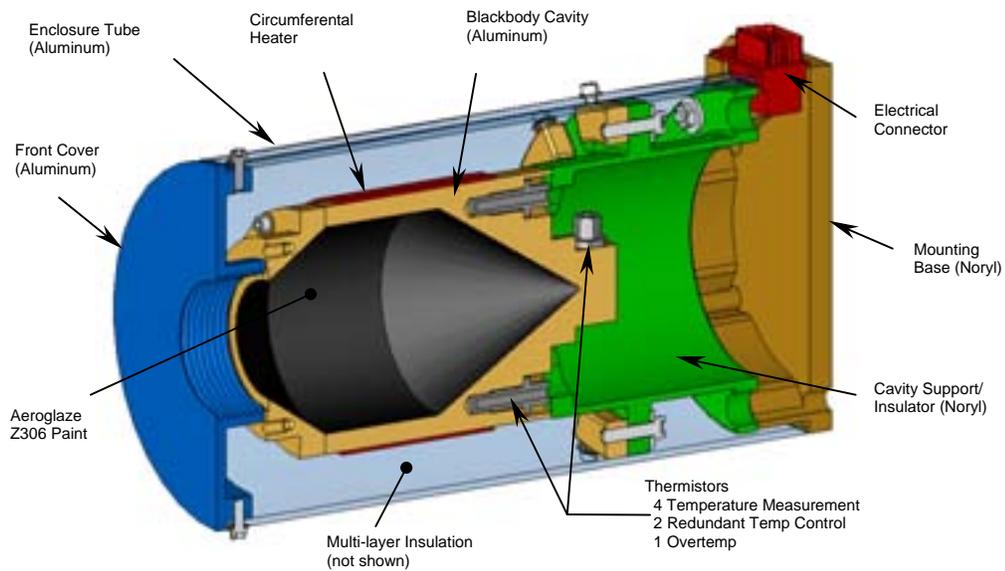

Figure 2. Blackbody section view illustrating key elements of the mechanical and thermal design. The heated isothermal cavity is supported structurally and isolated thermally via the Cavity Support Tube. Multi-layer insulation minimizes radiation heat transfer. The cavity entrance aperture (left side of figure) is 1.0 inch in diameter.

2.2 Thermal Design
In addition to withstanding payload launch loads, the blackbody structure provides robust thermal performance in a demanding environment. The blackbodies are mounted to a platform 60-110 K colder than the 255-290 K cavity operating temperatures, while the surroundings fluctuate from 140 to 300 K. The cavity temperatures must be extremely uniform (goal for maximum gradient is less than 0.2 K) and stable (goal for stability is within 10 mK over 10 minutes under maximum expected instrument thermal perturbation), therefore the cavity must be well insulated from the surrounding environment. To minimize radiant heat transfer Multi-Layer Insulation (MLI) is installed on the outside of the enclosure and between the enclosure and cavity. Due to the high temperature surroundings radiating heat into the black cavity, there is a risk of the ABB cavity temperature being driven above its set point. As a result the amount of insulation between the base and the cavity must be limited, requiring a tradeoff with heater power. In spite of this compromise the blackbodies are able to provide the set point temperatures with less than 0.5 W total heater power. The current estimate of the maximum temperature gradient within the cavity for the worst-case on-orbit condition is less than 0.09 K.

2.3 Thermistor Implementation
There are seven Thermometrics Ultra-stable SP-60 thermistors mounted into the cavity as detailed in Figure 3. Four of these sensors are used for reporting cavity temperature, two redundant sensors are used for temperature control, and one is dedicated to over-temperature protection. The thermistors were potted at Thermometrics into UW provided threaded aluminum housings, using methods similar to those used in their off-the-shelf probe assemblies.

The housing approach allows acceptance testing (including thermal cycling) and selection to be conducted on a thermistor assembly that is unlikely to change after being bonded with conductive epoxy into the cavity. The same thermistor type and similar mounting scheme were used successfully in the SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) instrument, developed by the Utah State University Space Dynamics Laboratory. The SP-60 thermistor is expected to provide long-term stability better than 50 mK over a period of 10 years. This includes effects of atomic diffusion of the metal oxide matrix material, and any thermally or mechanically induced micro crack migration to grain boundaries.

An important aspect of the thermistor mounting configuration is that it provides a minimal temperature bias from heat leaking out the thermistor lead wires. Modeling and testing predict that this bias will be less than 8 mK in the worst case on-orbit thermal environment (blackbody at 313 K, radiative environment at 140 K, and mounting interface at 190 K). This conservatively assumes that the planned additional thermal heat-sinking of the leads to the flat portion at the cavity apex is totally ineffectual.
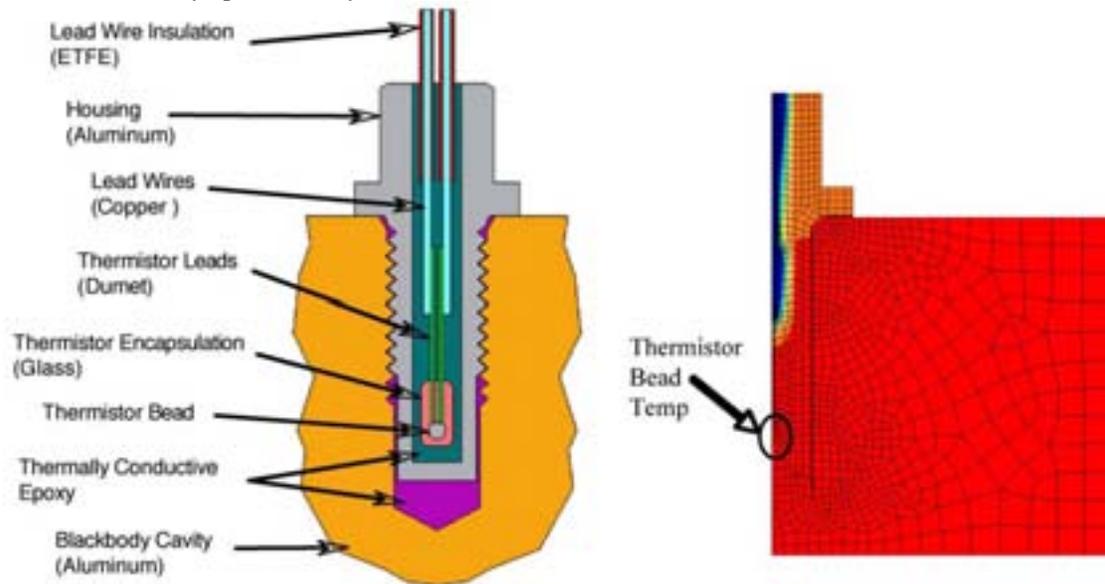

Figure 3. Section view of the thermistor mounting scheme, designed to provide a high degree of thermal coupling of the thermistor sensor to the aluminum cavity (left). Axisymmetric finite element thermal model (right) used to show a less than 8 mK gradient exists between the thermistor bead and surrounding cavity aluminum, due to the thermistor lead wire heat leak.

3. BLACKBODY EMISSIVITY MODELING AND UNCERTAINTY BUDGET

Monte Carlo ray tracing methods were used to calculate the cavity emissivity. The inputs to this modeling include, cavity geometry and paint reflection and diffusity as a function of wavelength. An emissivity error budget was developed that takes into account paint characteristics and modeling uncertainties.

3.1 Black Paint Properties
The blackbody cavity is painted with Aeroglaze Z306 diffuse black polyurethane. The left plot in Figure 4 presents the emissivity verses wavelength for up to three coats of this paint. The GIFTS blackbody will be painted with three coats providing a total thickness of 0.003 inches. The emissivity measurements shown were made by Labsphere on blackbody witness samples from a lot of AERI blackbodies. These measurements of Z306 emissivity agree, to within the stated uncertainty of < 0.004, with measurements by NIST of a sample they painted for a different application. The diffusity characteristics shown on the right plot in Figure 4 were estimated from data published by Persky[14], using a cosine angular dependence to fit measurements of Z306 made at 20° and 60°. No direct measurements of paint emissivity are made on the painted cavity because the testing apparatus is not physically compatible with this geometry. For this reason witness samples that are painted along with the cavities are used to characterize paint emissivity. During spray painting, a fixture is used to hold the witness samples in a configuration

that mimics the cavity cone section. This helps make the paint application on the witness samples better represent the actual cavity paint. NIST will measure the emissivity of the blackbody witness samples to within 0.4%.
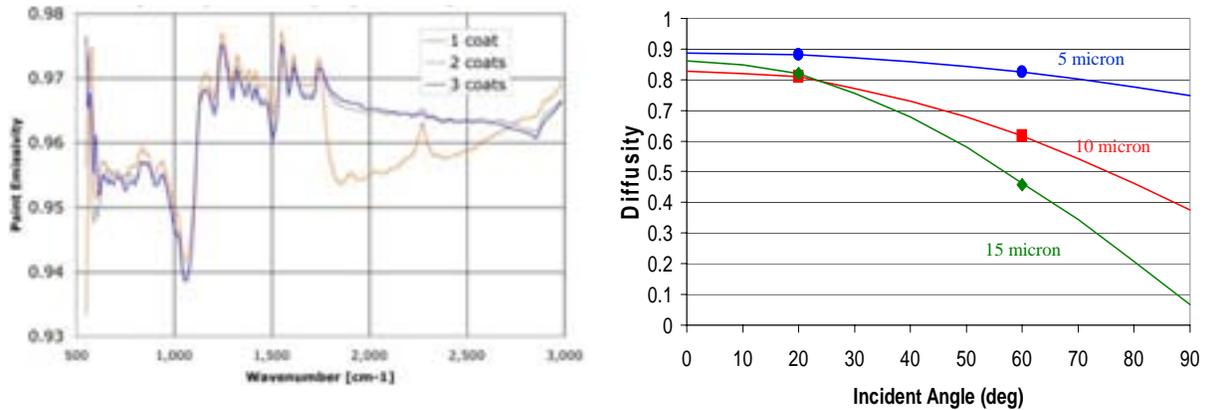

Figure 4. Aeroglaze Z306 emissivity (left) and diffusity (right) characteristics used in the Monte Carlo emissivity ray trace modeling. Three coats of paint are applied for a total thickness of 0.003 inches.

3.2 Monte Carlo Ray Tracing to Determine Cavity Emissivity

The GIFTS blackbody emissivity model uses a unique algorithm of the Monte Carlo method described in Prokhorov.[15] The algorithm is implemented for a wide class of axially symmetric cavities formed by rotation of polygonal line around the axis. The algorithm allows simulation of real radiometric systems containing radiating cavity with arbitrary axially symmetric temperature distribution, flat detector with circular sensitive element, and up to two apertures with arbitrary displacement of centers relative to the cavity axis. The cavity geometry used to simulate the GIFTS blackbodies is given in Figure 5.

GIFTS blackbody internal cavity cross-section (dimensions in inches)

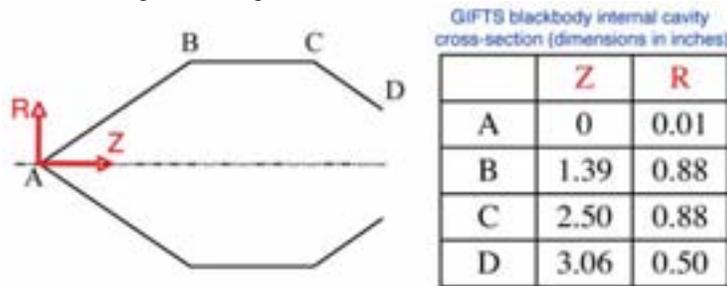|	Z	R
A	0	0.01
B	1.39	0.88
C	2.50	0.88
D	3.06	0.50

Figure 5. GIFTS blackbody cavity geometry used in Monte Carlo emissivity analysis.
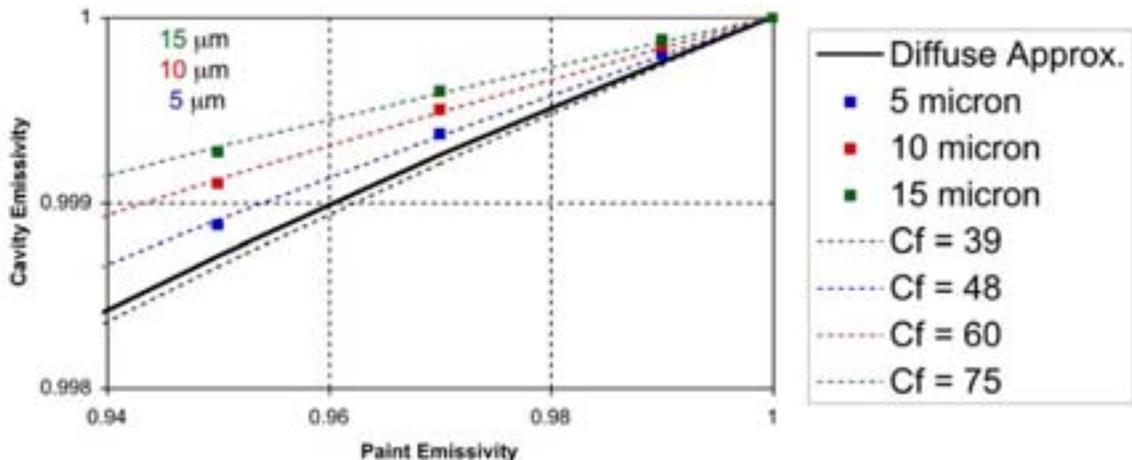
Figure 6. GIFTS blackbody isothermal cavity emissivity (average normal) computed using the STEEP3 model. The results for the diffusivity ratios shown in Fig. 4, for Aeroglaze Z306 are shown as symbols and a fit to the cavity factor approximation is shown as dashed lines. The solid line is the STEEP3 computation assuming the paint was entirely diffuse.

The GIFTS blackbody cavity is a relatively simple geometry with rotational symmetry about the central axis. The commercially available numerical model STEEP3 (Virial, Inc.) was used to compute the average normal emissivity using diffusity versus angle data from Persky (1999) at three wavelengths spanning the thermal infrared. The results are shown in Figure 6 compared with a fit to an approximate analytic equation that parameterizes the effective blackbody emissivity in terms a cavity factor. The analytic approximation to the GIFTS blackbody emissivity is given by: $C_f = (1-E^{-1}_{paint})/(1-E^{-1}_{cavity})$. This analytic formula is useful in the propagation of errors because it can be easily differentiated. The formula also is convenient to implement in data processing software. Figure 6 shows that the GIFTS cavity shape leads to an isothermal emissivity greater than 0.998 for all wavelengths.

3.3 Emissivity Uncertainty Budget

A budget has been developed for the uncertainty in the estimate of the GIFTS blackbody emissivity. This budget estimate takes into account four items; uncertainty in the paint witness sample measurement, uncertainty in the paint application variation, an estimate of the long-term paint stability, and an estimate of the error arising from using an approximate cavity factor to represent the Monte Carlo model calculations. The equation for cavity factor given in the previous subsection is used to propagate the sources of the errors into the final emissivity uncertainty. Three sigma errors are used throughout. The results of the budget analysis are given in Table 2.

Table 2. GIFTS blackbody emissivity error budget.

	Uncertainty (3 sigma)	Note	for Ep=0.94 f=39	²Ec	²Ec (3 sigma)
Paint Witness Sample Measurement	0.4% Ep	[1]	²Ep=0.0038	(1/f)*²Ep	0.00010
Paint Application Variation	1.0% Ep	[2]	²Ep=0.0094	(1/f)*²Ep	0.00024
Long-term Paint Stability	2.0% Ep	[3]	²Ep=0.0188	(1/f)*²Ep	0.00048
Cavity Factor	30% f	[4]	²f=11.7	(1-Ep)/f^2*²f	0.00046
				RSS	**0.00072**

Notes:
[1] Factor of 1.5 times NIST* Stated Accuracy for 2 sigma
[2] Worst case difference between 1 and 3 coats
[3] 2 x above
[4] Accounts of Cavity Model Uncertainty
* NIST Stated accuracy is 4% of Reflectivity (2 sigma)

4. BLACKBODY CONTROLLER

The blackbody controller measures and controls the temperature of both blackbodies. The controller has two modes: Constant Temperature and Constant Power. Mode may be selected independently for each blackbody. In the Constant Temperature mode, heater power is controlled to hold the blackbody temperature very close to the set point. In the Constant Power mode, the heater duty cycle is held constant at the commanded value. Heater power may be set to zero, in which case the blackbody temperature closely tracks the ambient temperature. A functional block diagram of the blackbody controller is shown in Figure 7. The controller communicates with the instrument Command and Data Handler through the SDL Bus interface. Commands may be sent to the controller to change operating modes and parameters.

Data is also sent to the C&DH through this interface. Thermistors are used to measure temperature of the blackbody cavity. Internal calibration resistors are measured during each sampling cycle to minimize measurement error. Dedicated redundant blackbody thermistors are used to control temperature. The temperature set point is set via the data interface.

4.1 Temperature Control

In the constant temperature mode, the blackbody temperature is maintained at a set point determined by the set point integer. One of the two dedicated redundant control thermistors on each blackbody is used to control its temperature. The difference between the thermistor resistance and the set point is processed by an analog Proportional-Integral-

Derivative (PID) circuit to determine the required heater power. A pulse width modulator (PWM) drives the blackbody heater. The heater switch operates at approximately 10 Hz, with low output slew rates to minimize EMI. PID parameters are determined by component values and are selected to match the characteristics of the blackbody. Figure 8 shows that blackbody temperature disturbances less than 2 mK result from the expected on-orbit changes in
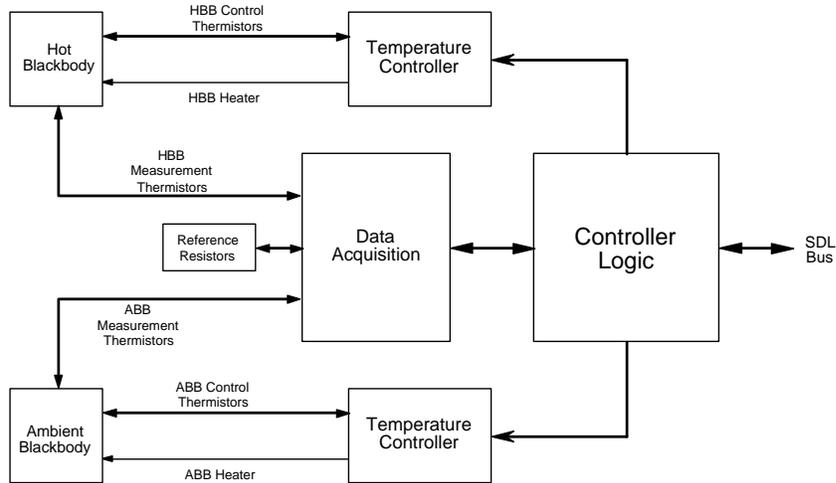
radiated power (140 mW) that arises from the re-positioning of the flip-in mirror for the GIFTS instrument calibration (presenting a view of the cold aft end of the instrument to the blackbody). In the Constant Power mode, the set point integer controls the heater duty cycle. In both modes, over-temperature protection is provided using a dedicated thermistor.

Figure 7. Functional block diagram of the blackbody controller. Each of the blackbodies is independently controlled. Communication to and from the instrument bus is through the controller logic block.
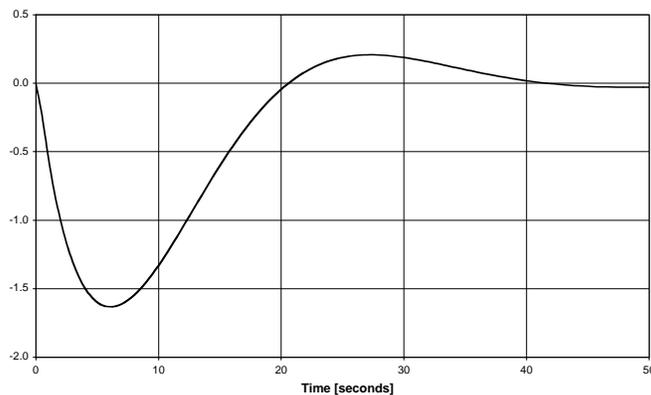

Figure 8. The blackbody response to a worse-case on-orbit perturbation leads to minimal temperature error. The plot shows the simulated response of the blackbody when the flip-in mirror is activated to present the view of the cold back of the instrument.

4.2 Temperature Measurement

The temperature measurement scheme is self-calibrating, based on continuous measurements of internal reference resistors. As a result, measurement accuracy is largely independent of offset and gain drift. Each thermistor and reference resistor is connected to a precision resistor and voltage source in a half-bridge configuration. The fixed excitation voltage setting is common to all 16 channels. The thermistor and reference resistors are measured sequentially. To improve resolution, 5 measurement ranges are used. Autoranging can be selected as a mode of operation.

The worst-case temperature measurement error due to reference resistor drift is less than 1 mK. Total measurement uncertainty due to the Blackbody Controller electronics at delivery is 14 mK. The additional uncertainty due to long-term electronics drift is less than 12 mK.

Table 3 lists the available blackbody controller control commands and data output information.

Table 3. Blackbody Controller Commands and Data Output

Control Commands	Data Output
Blackbody Modes (Constant Temp. or Constant Power)	Thermistor Data
Set Points	Calibration Resistor Data
Control Thermistor Select	Range Data
Temperature Measurement Range	Set Points
Autorange On/Off	Blackbody Modes
Reset Mode	Control Thermistor Selected
	Autorange On/Off
	Overtemperature Indicators
	Fail Indicators
	Frame Count

4.3 Blackbody Controller Implementation

Where possible, radiation hardened components were selected to tolerate the expected total incident dose (TID) of 61 kRad (Si) with at 2:1 safety factor. Where such components were not available, spot shielding was added to reduce the TID to an acceptable value. All parts were de-rated according to PPL-21.

The Blackbody Controller is constructed on a board approximately 10.2 by 6.3 inches (25.9 by 16.0 cm). The board plugs into a mother board (that is part of the GIFTS instrument electronics) and is secured by wedgelocks along the shorter sides, which provide a thermal path as well as structural support. The two blackbody connectors are located on the edge of the board opposite the motherboard connector. The left side of Figure 9 is a photograph of the board.

A thermal model of the board was developed (right side of Figure 9) and used to show that the warmest spot on the board is 54 C for the maximum dissipation case of 1.2 Watts, and assuming the worst case on-orbit warm environment and only conductive heat transfer (no radiative transfer). The board thermal design provides a worst case part junction temperature margin of better than 20 C.
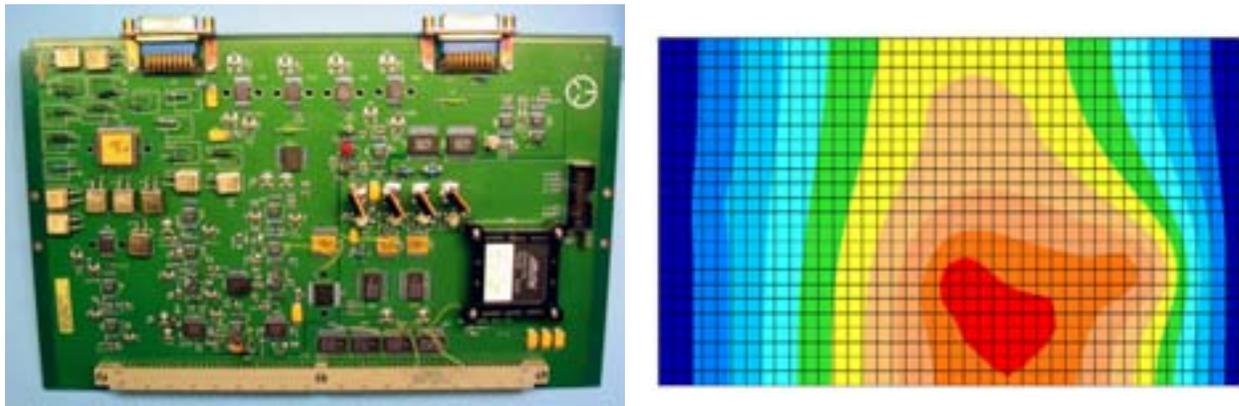

Figure 9. Engineering model blackbody controller board measuring 10.2 by 6.3 inches (left). Thermal model results of the board (right) indicate that the warmest part of the board will run at a 54 C, assuming warmest environment and no radiative transfer.

5. TEMPERATURE UNCERTAINTY BUDGET AND CALIBRATION

The temperature calibration of the blackbody is conducted end-to-end using a dedicated pair of blackbodies and a controller. A temperature uncertainty budget was developed that includes thermistor calibration errors, temperature gradients, electronics uncertainty, and long-term stability of both the thermistors and electronics.

5.1 Blackbody Temperature Calibration

This section describes the plans for the temperature calibration of the GIFTS blackbody subsystem and follows from previous work at UW on similar systems, including the Atmospheric Emitted Radiance Interferometer (AERI), Scanning High-resolution Interferometer (S-HIS), and NPOESS Atmospheric Sounder Testbed (NAST).[16-20] The functional block diagram of the calibration test configuration is shown in Figure 10. The calibration configuration consists of an ambient and hot blackbody connected to the blackbody controller that communicates with the calibration computer. Coupled to each blackbody cavity is a specially made Thermometrics SP-60 temperature calibration standard. These probes are connected to a Hart Scientific 2564 Thermistor Scanner Module and a Hart 3560 Extended Communications Module that communicates with the calibration computer. The Thermometrics temperature calibration standard with associated Hart electronics was calibrated as a combined system at Hart Scientific to an accuracy of better than 5 mK (3 sigma), over the temperature range from -40 to +40 C.

During calibration the blackbodies are located inside an insulated box that resides within a temperature chamber that can be controlled to the different calibration temperatures. Gradients between the blackbody thermistors and the temperature standard are expected to be less than 20 mK, based on previous experience with AERI and Scanning HIS blackbody calibrations. The controller can be independently brought to different operating temperatures as well, but for the engineering model testing it will be maintained at room temperature. At each calibration temperature the temperature reported from each of the calibration standards is combined with the resistance read from the blackbody controller electronics. For each excitation current range, there will be at least four calibration temperatures. For each thermistor at each current range, the temperature and resistance data will be regression fit to the standard 3-term Steinhart and Hart thermistor relationship. Previous experience with AERI and Scanning HIS blackbody systems and modeling of the potential GIFTS blackbody subsystem non-linearities has indicated that there will be less than 5 mK residual error in the calibration fitting equation.
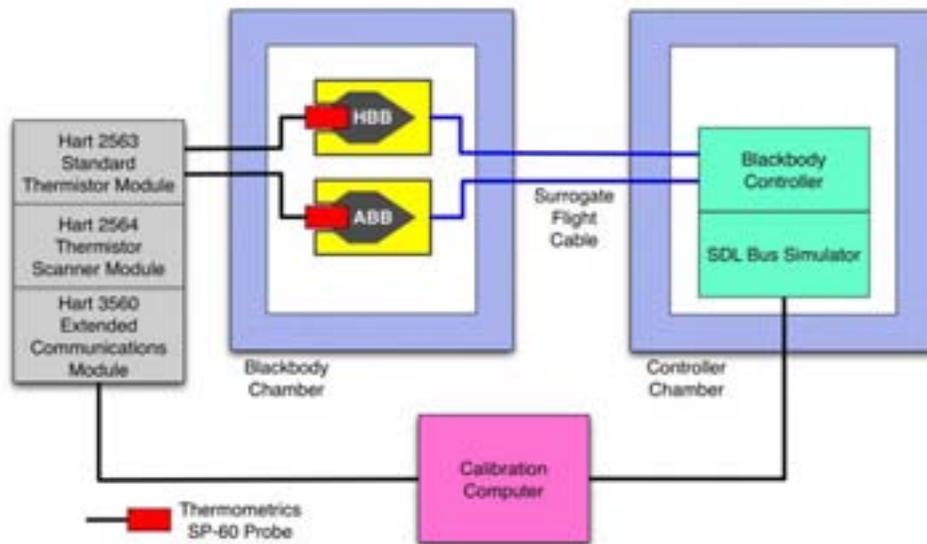

Figure 10. Blackbody thermistor calibration scheme functional block diagram.

5.2 Temperature Error Budget Summary

Table 3 summarizes the temperature uncertainty budget for the GIFTS blackbody subsystem. This budget shows the combined uncertainty due to all significant contributors is 0.074 K (3 sigma), compared to the allowable budget of 0.1 K. Most of the uncertainties have been described in earlier sections and will not be discussed further here. The cavity to thermistor gradient uncertainty is conservatively assumed to be 1/3 of the total predicted cavity gradient in the worst-case thermal environment. The temperature gradient uncertainty due to the thermistor wire heat leak is conservatively assumed to be the full value calculated for this effect in the worse case thermal environment and making conservative thermal coupling assumptions. The paint gradient arises from power lost by radiation out the blackbody aperture and is proportional to the ratio of paint thickness (76 µm) to paint conductivity (0.25 W m^{-1} K^{-1}). The value in the table for paint gradient uncertainty is the full predicted gradient assuming a 290 K blackbody

radiating to the cold aft end to the instrument (assumed be 60 K). The effective radiometric temperature weighting factor uncertainty is conservatively assumed to be 1/3 of the total predicted cavity gradient in the worst-case thermal environment. The weighting factors are applied to each measurement thermistor to best represent the radiometric temperature of the cavity. The weighting factors are computed from Monte Carlo ray trace modeling that uses the cavity geometry with the expected cavity temperature distribution.

Table 3. Temperature Uncertainty Budget Summary

Temperature Uncertainty	3 sigma error [K]	RSS [K]
Temperature Calibration Standard	0.005	
(Thermometrics SP60 Probe with Hart Scientific 2560 Thermistor Module)		
		0.005
Blackbody Readout Electronics Uncertainty		
Readout Electronics Uncertainty (at delivery)	0.014	
		0.014
Blackbody Thermistor Temperature Transfer Uncertainty		
Gradient Between Temperature Standard and Cavity Thermistors*	0.020	
Calibration Fitting Equation Residual Error*	0.005	
		0.021
Cavity Temperature Uniformity Uncertainty		
Cavity to Thermistor Gradient Uncertainty *(1/3 of total max expected gradient)*	0.030	
Thermistor Wire Heat Leak Temperature Bias Uncertainty	0.008	
Paint Gradient *(assumes nominal HBB Temp and conservative viewing geometry)*	0.018	
		0.036
Long-term Stability		
Blackbody Thermistor *(10 years of drift assuming 105 C)*	0.050	
Blackbody Controller Readout Electronics	0.012	
		0.051
Effective Radiometric Temperature Weighting Factor Uncertainty		
Monte Carlo Ray Trace Model Uncertainty in Determining Teff	0.030	
(1/3 of total max expected gradient)		
		0.030
*Based on experience with UW AERI Blackbodies		**0.074**

8. SUMMARY

A calibration blackbody subsystem suitable for space flight has been developed to meet the demanding requirements for the GIFTS instrument. This subsystem builds on the strong heritage of ground and aircraft based FTS instruments that have been developed at the University of Wisconsin. The engineering model of this subsystem has been fabricated and tested to show that requirements have been met. Further testing and temperature calibration are planned for the engineering model blackbody subsystem before it is delivered to the Utah State University Space Dynamics Laboratory for integration into GIFTS instrument Engineering Model cold test and calibration.

ACKNOWLEDGEMENTS

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