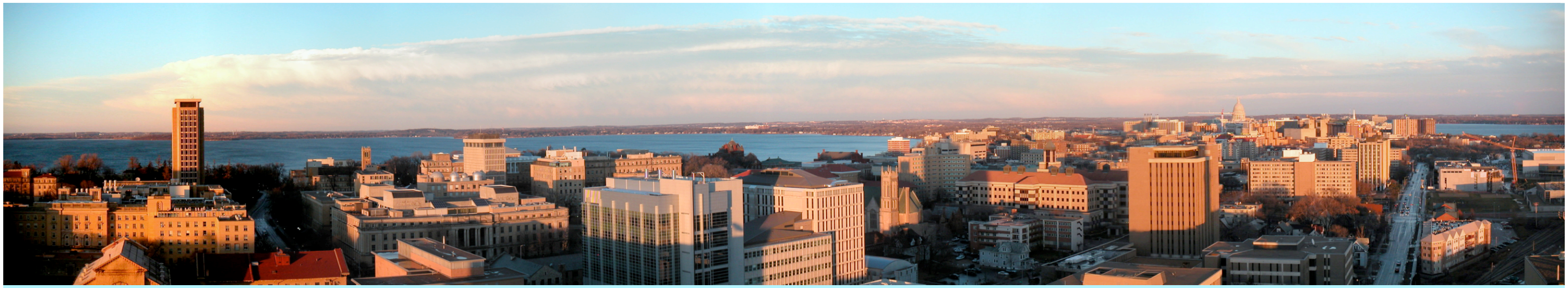

Calibration of the Geostationary Imaging Fourier Transform Spectrometer (GIFTS) On-board Blackbody Calibration System

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USU/SDL

CALCON 2005

Topics

- GIFTS Instrument Calibration Approach and Top-level Requirements
- Blackbody System Overview
- Blackbody temperature calibration
  - Resistance measurement calibration
  - Thermistor calibration
- Cavity painting and emissivity determination

GIFTS Instrument Calibration Approach and Top-level Requirements

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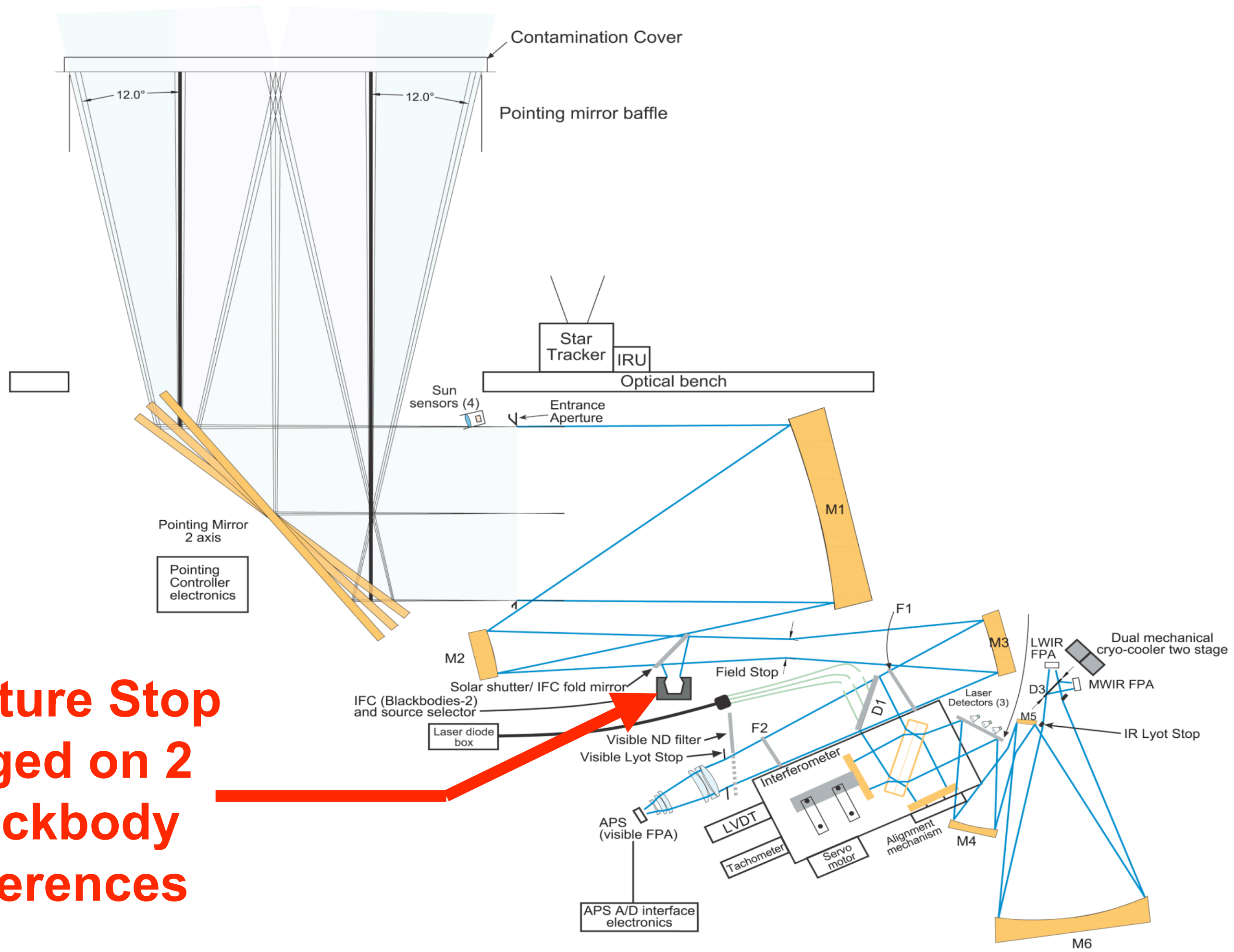
GIFTS Instrument
Radiometric Calibration Approach

- Two small reference Blackbodies located behind telescope, combined with Space View.
- Blackbody design is scaled from the UW ground-based design used on AERI and NAST / S-HIS aircraft instruments.
- Constraints on original S/C prevented traditional external large aperture blackbody configuration.
- Advantages compared to large external blackbody:
  (1) higher emissivity is practical with small size
  (2) effective T easier to characterize, and
  (3) protection from solar forcing gradients

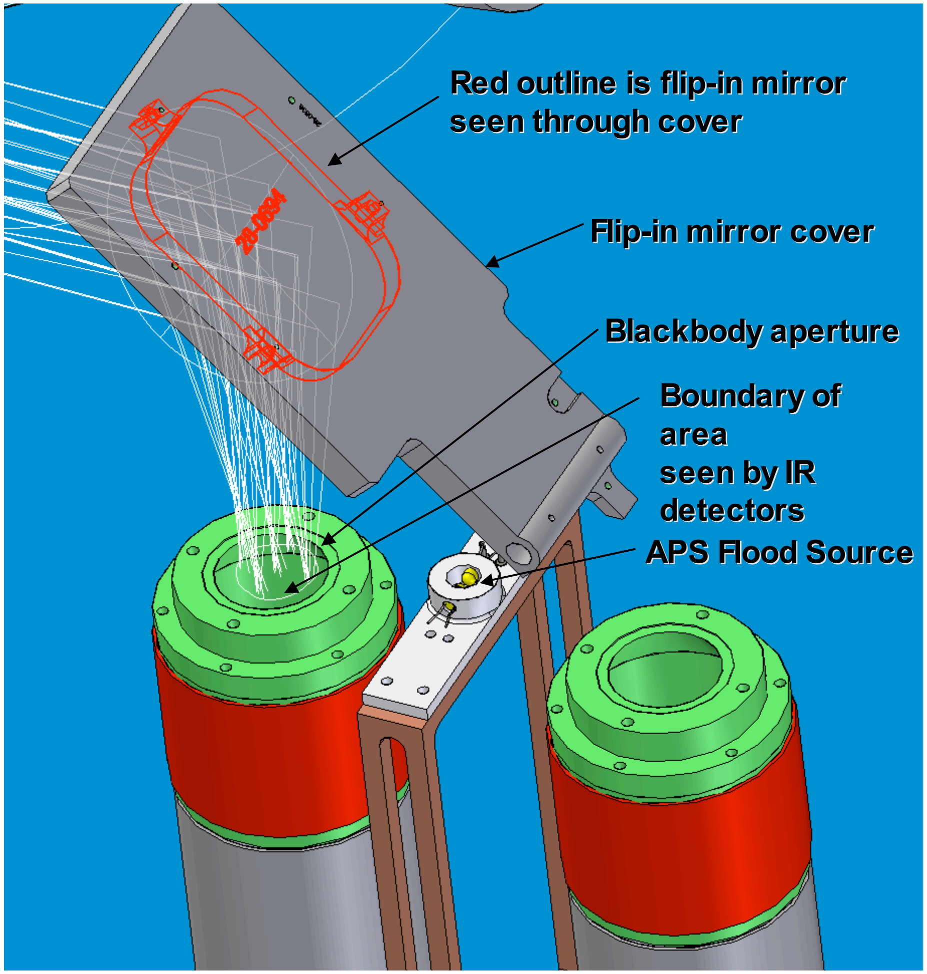
GIFTS Sensor Module Conceptual Layout



Aperture Stop Imaged on 2 Blackbody References

Internal Blackbody Configuration

- Two blackbodies and visible flood source are mounted on the same linear slide
- One source at a time is correctly positioned under flip-in mirror
- Blackbody aperture fills both IR Lyot stop and IR detector array
  - Blackbody aperture imaged at Lyot stop



GIFTS Top Level Calibration Error Budget

GIFTS Radiometric Calibration Error Requirement is ≤ 1K

GIRD
IR575

1.1 Radiometric Calibration Error

Required: ≤ 1 K

Budget: ≤ 0.8 K

LW Est: ≤ 0.60 K
SW Est: ≤ 0.55 K

1.1.1	1.1.2	1.1.3	1.1.4	1.1.5	1.1.6	1.1.7
Blackbody Emissivity & Temperature	Telescope & Mirror Transmittance	Instrument Temperature Stability	Residual Noise	Residual Non-linearity	Residual Pointing Mirror Polarization	Aliasing
Budget: ≤ 0.5 K	Budget: ≤ 0.3 K	Budget: ≤ 0.3 K	Budget: ≤ 0.2 K	Budget: ≤ 0.3 K	Budget: ≤ 0.2 K	Budget: ≤ 0.1 K
LW Est: ≤ 0.35 K	LW Est: ≤ 0.25 K	LW Est: ≤ 0.10 K	LW Est: ≤ 0.15 K	LW Est: ≤ TBD K	LW Est: ≤ TBD K	LW Est: ≤ TBD K
SW Est: ≤ 0.20 K	SW Est: ≤ 0.20 K	SW Est: ≤ 0.25 K*	SW Est: ≤ 0.10 K*	SW Est: ≤ TBD K	SW Est: ≤ TBD K	SW Est: ≤ TBD K

Notes:
* : @ 220 K Scene Temperature

GIFTS Blackbody Calibration Budget

Calibration budget for blackbody subsystem is 0.5 K (3-sigma) absolute & 0.1 K (3-sigma) reproducibility

1.1.1
Blackbody Emissivity & Temperature
Budget: ≤ 0.5 K
LW Est: ≤ 0.35 K
SW Est: ≤ 0.20 K

1.1.1.1	1.1.1.2	1.1.1.3	1.1.1.4	1.1.1.5
HBB Temp Uncertainty ΔT_{HBB}	HBB emissivity Uncertainty Δe_{HBB}	ABB Temp Uncertainty ΔT_{ABB}	ABB emissivity Uncertainty Δe_{ABB}	Structure Temp Uncertainty ΔT_{STR}
Budget: ≤ 0.1 K	Budget: ≤ 0.002	Budget: ≤ 0.1 K	Budget: ≤ 0.002 K	Budget: ≤ 5.0 K
Estimate: ≤ 0.074 K	Estimate: ≤ 0.00072	Estimate: ≤ 0.074 K	Estimate: ≤ 0.00072	Estimate: ≤ 5.0 K

Summary of Top Level Blackbody Requirements

	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)	< 0.056 K
Ambient Blackbody Emissivity	> 0.996	> 0.999
Hot Blackbody Emissivity	> 0.996	> 0.999
Emissivity Uncertainty	< 0.002 (3 sigma)	< 0.00072
Wavelength	680 - 2,300 cm^{-1}	680 - 2,300 cm^{-1}

***Derived From GIRD Using Radiometric Model**

Summary of Top Level Blackbody Requirements

	Specification*	Current Best Estimate
Source Aperture	2.54 cm	2.54 cm
Source FOV (full angle)	> 10°	> 10°
Mass (two blackbodies plus controller board)	< 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

***Imposed by GIFTS Sensor Module Design**

****Temperature of mounting base between 190 to 260 K**
Temperature of surrounding between 140 to 300 K

Blackbody System Overview

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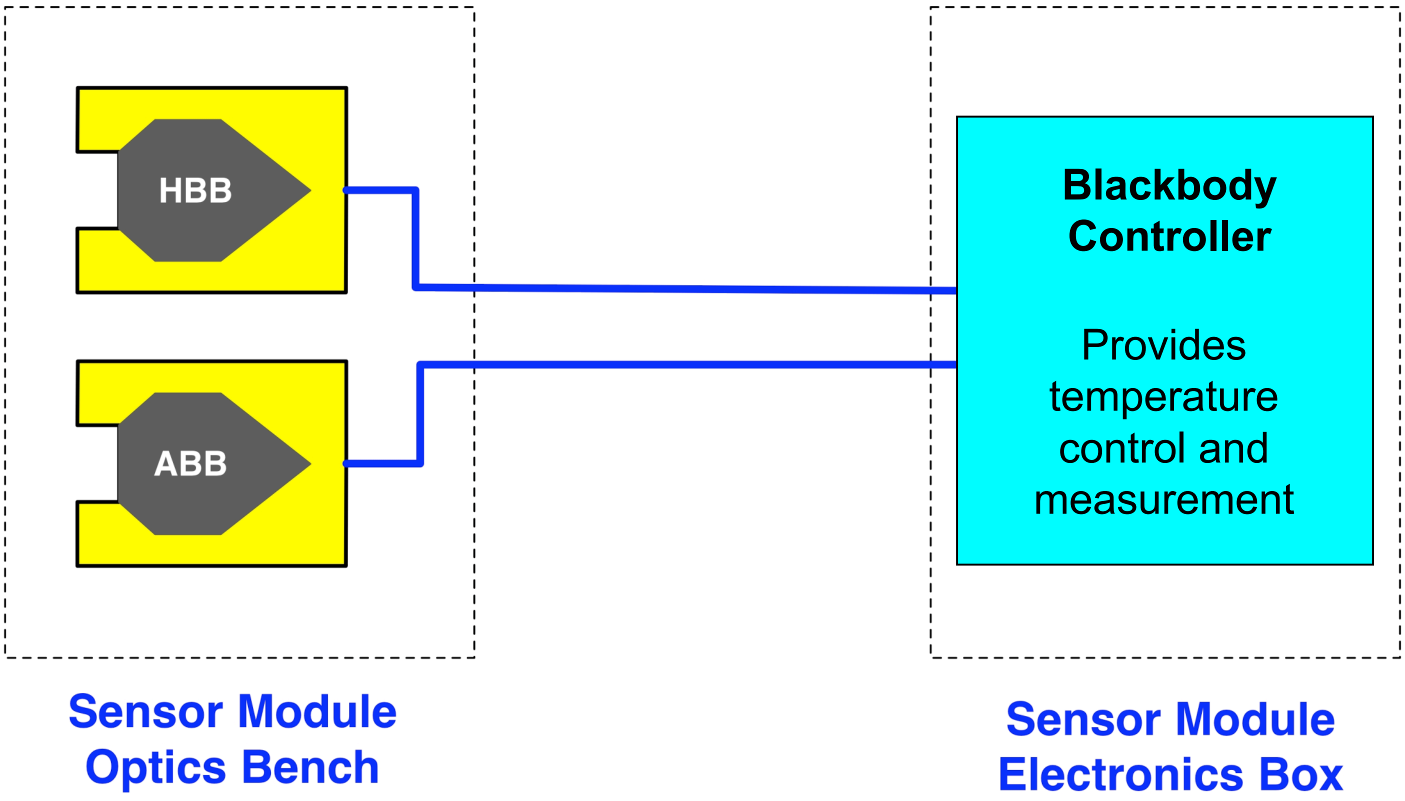
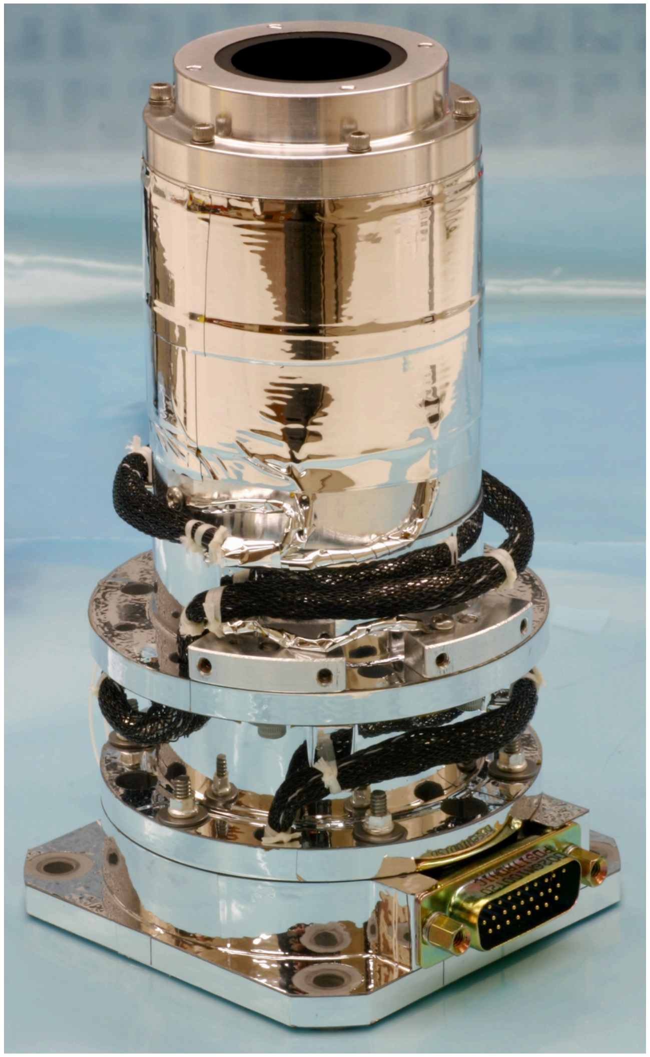
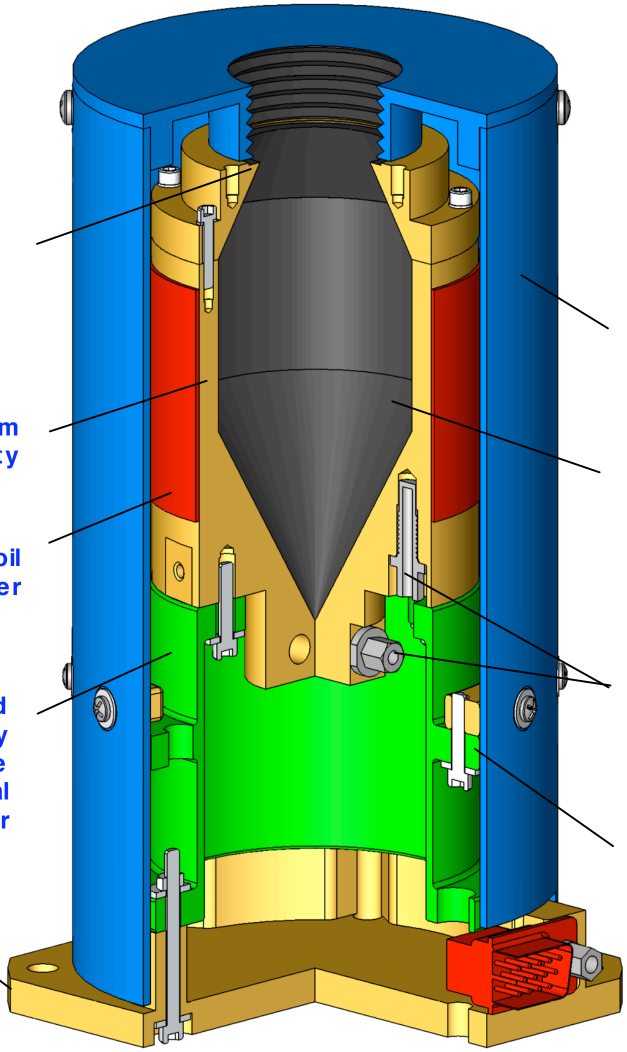
Top Level Block Diagram



Blackbody Design

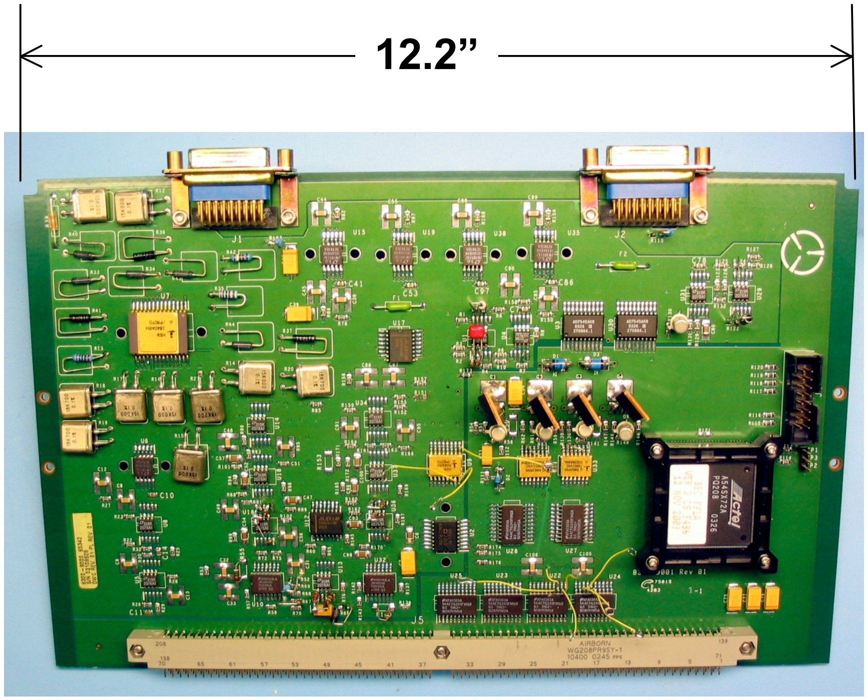
Engineering Model Blackbody

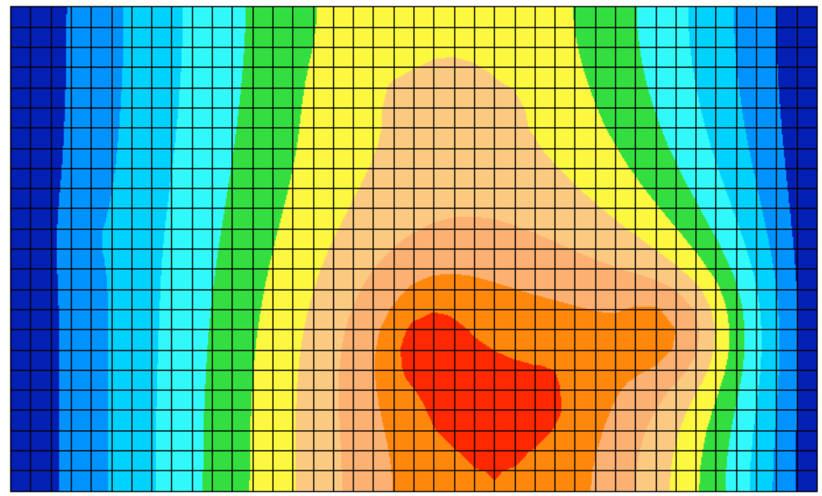




Blackbody builds on the strong heritage of ground and aircraft based FTS instruments developed at UW.

Engineering Model Blackbody Controller & Thermal model of board in on-orbit environment

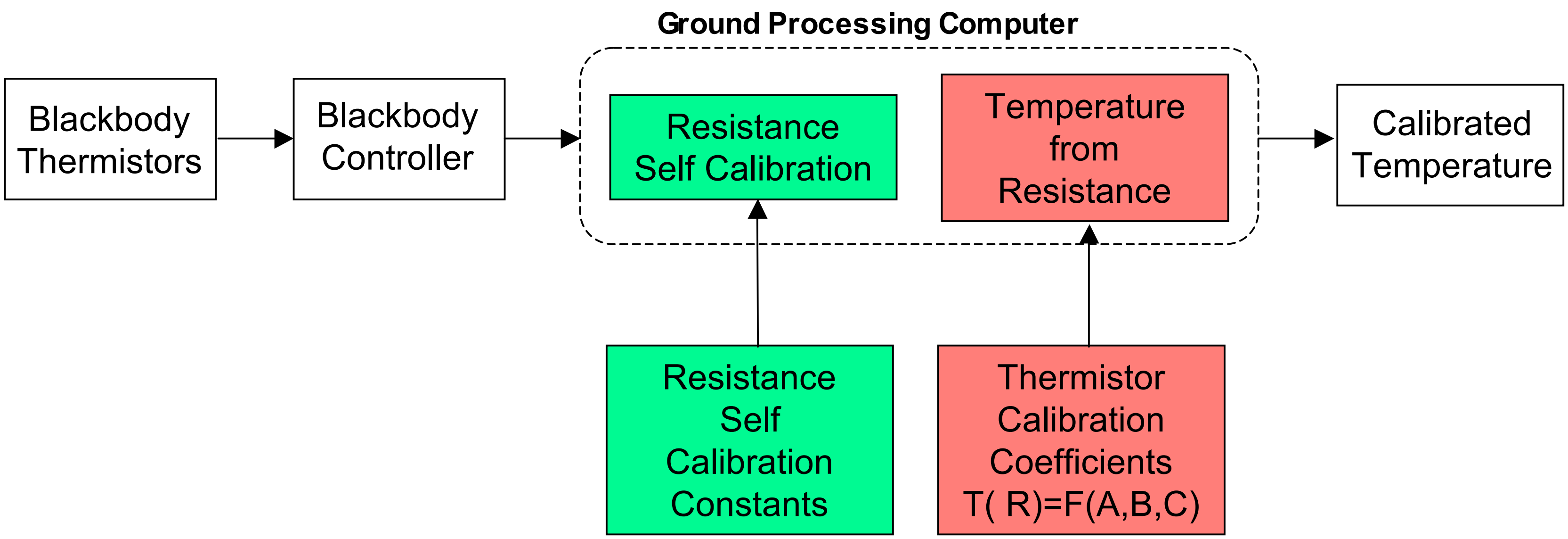




- Motherboard connector along bottom.
- Wedgelock clamps secure the full length of each of the short sides

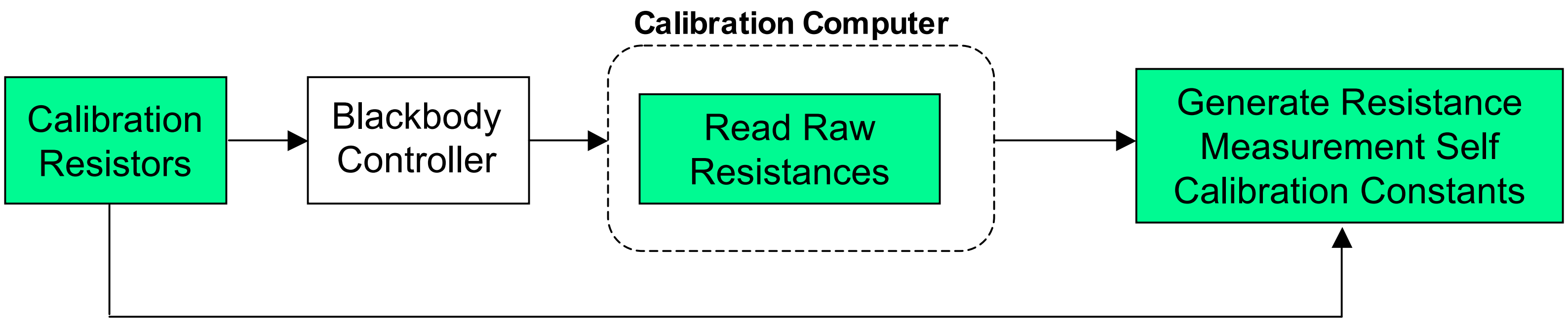
- Warmest spot on board runs at 54 C, assuming warmest on-orbit environment
- The board thermal design provides a worst case part junction temp. margin of better than 20 C.

Blackbody Thermistor Measurement
Use of Calibration Constants

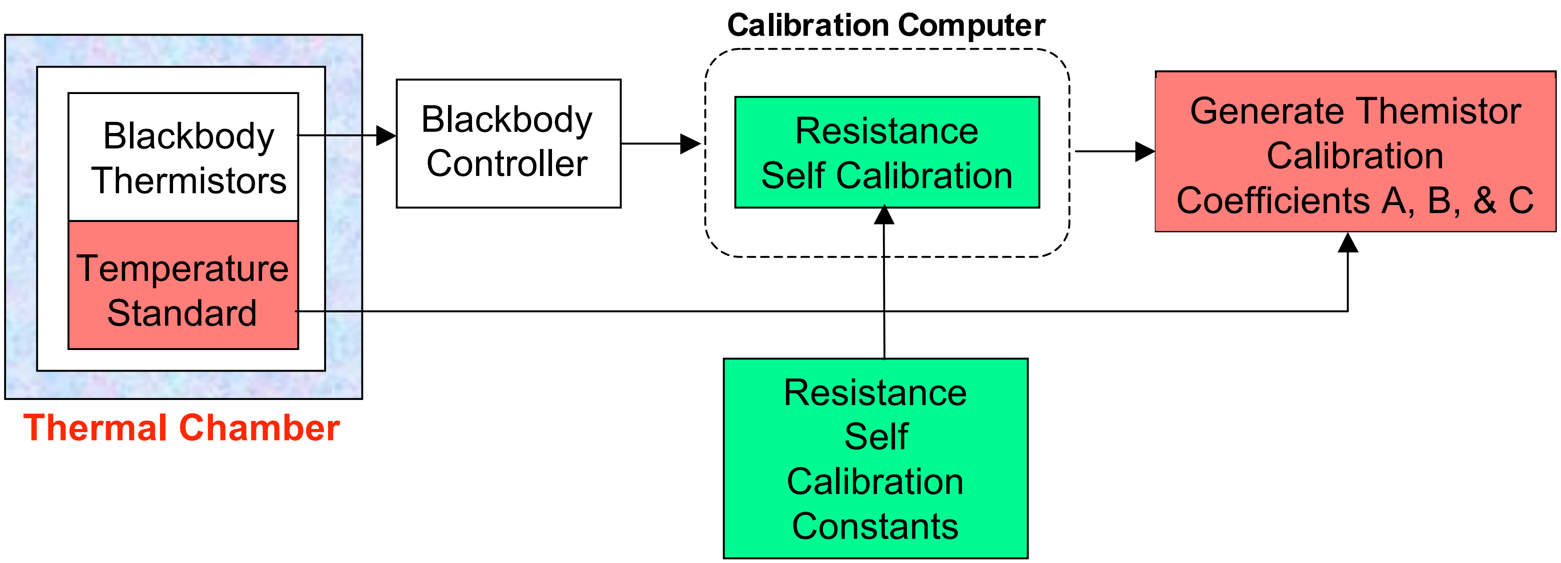


Resistance Calibration of the Blackbody Controller Electronics

Determining the Constants Needed for Self-calibration



Determining Thermistor Calibration Coefficients



Blackbody Controller Resistance Calibration

Determining the Resistance Measurement Self Calibration Constants

SSEC

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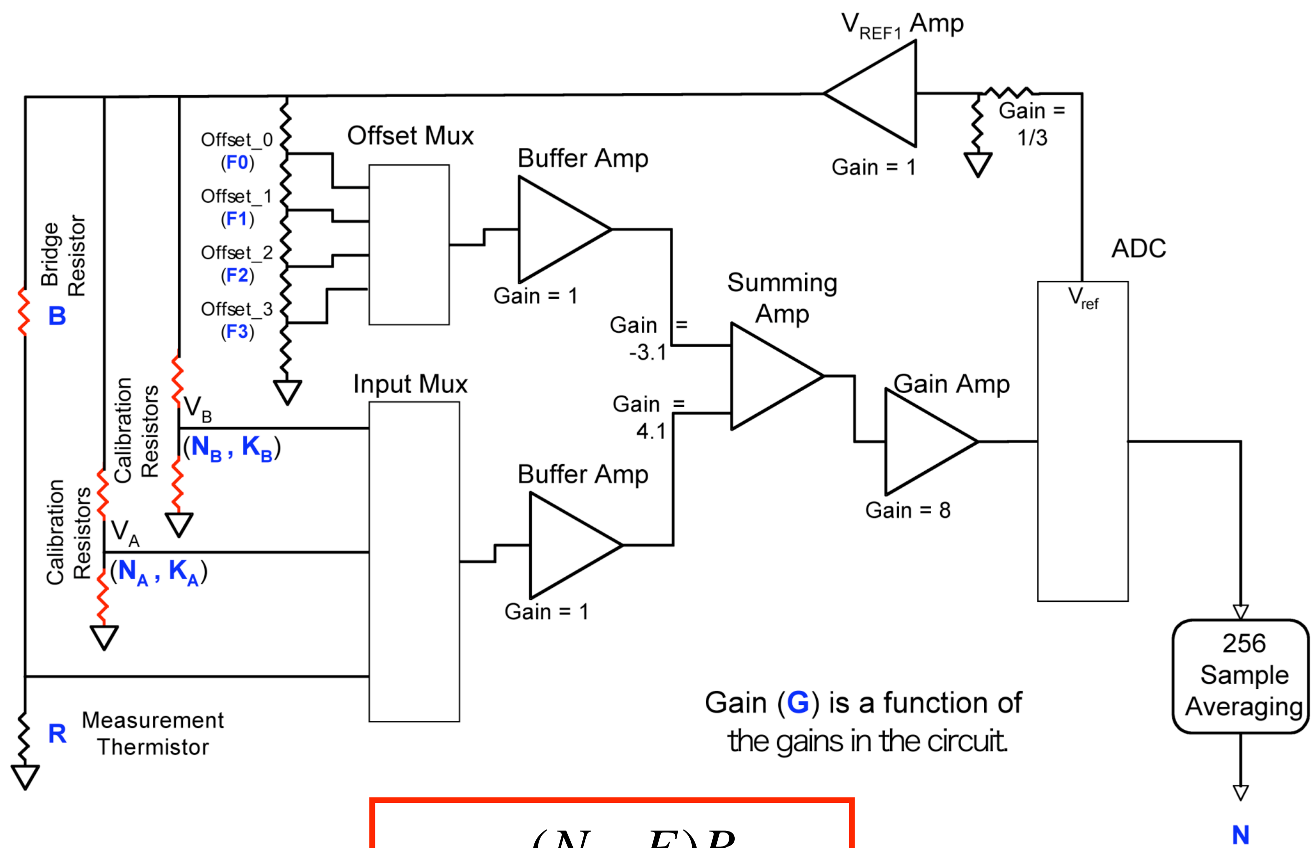
Self-calibrating Resistance Measurement Scheme



Gain (G) is a function of the gains in the circuit.

$$\boxed{R = \frac{(N - F)B}{G + F - N}}$$

External Calibration Resistor Values

Ambient Blackbody

Range	Nominal Resistance Range: Low	Nominal Resistance Range: High	Nominal Temperature Range: Associated with Low R	Nominal Temperature Range: Associated with High R
0	25,394.5	59,229.8	-28.4	-43.4
1	15,705.1	33,745.3	-19.2	-33.6
2	9,331.6	20,861.6	-8.6	-24.7
3	5,038.5	12,173.6	4.9	-14.1

	Resistor Label	Nominal Value	Measured Value (Kohms)	Nominal Equiv. T [C]
Range 0	1A00	27.4K	27.40349	-29.8
	3A00	29.4K	29.39068	-31.1
	5A00	38.3K	38.31340	-35.9
	7A00	49.9K	49.90540	-40.5
	9A00	54.9K	54.89922	-42.1
Range 1	1A01	16.5K	16.49754	-20.2
	3A01	17.8K	17.80062	-21.6
	5A01	22.6K	22.59973	-26.2
	7A01	29.4K	29.38854	-31.1
	9A01	30.9K	30.89072	-32.0
Range 2	1A02	10.0K	9.963586	-10.0
	3A02	10.7K	10.698577	-11.5
	5A02	13.7K	13.70086	-16.5
	7A02	17.8K	17.79990	-21.6
	9A02	19.06K	19.05953	-23.0
Range 3	1A03	5.36K	5.360126	3.5
	3A03	6.04K	6.098655	0.8
	5A03	8.25K	8.250112	-6.0
	7A03	10.7K	10.697523	-11.5
	9A03	11.5K	11.498589	-12.9

5/5/04

Hot Blackbody

Range	Nominal Resistance Range: Low	Nominal Resistance Range: High	Nominal Temperature Range: Associated with Low R	Nominal Temperature Range: Associated with High R
0	20,723.4	47,526.1	9.2	-7.1
1	12,613.4	26,361.8	19.8	4.3
2	7,522.5	16,027.9	31.6	14.6
3	4,017.4	9,782.4	47.1	25.5

	Resistor Label	Nominal Value	Measured Value (Ohms)	Nominal Equiv. T [C]
Range 0	1H00	21.5K	21.50040	8.4
	3H00	24.3K	24.29909	5.9
	5H00	30.1K	30.09966	1.7
	7H00	40.2K	40.20075	-3.9
	9H00	44.2K	44.20255	-5.7
Range 1	1H01	13.3K	13.30025	18.6
	3H01	14.3K	14.30104	17.1
	5H01	18.2K	18.19873	11.9
	7H01	24.3K	24.29286	5.9
	9H01	24.9K	24.89857	5.4
Range 2	1H02	7.87K	7.868968	30.5
	3H02	8.66K	8.653635	28.3
	5H02	11.0K	10.995917	22.8
	7H02	14.3K	14.301310	17.1
	9H02	15.4K	15.396980	15.5
Range 3	1H03	4.32K	4.319953	45.2
	3H03	4.87K	4.869875	42.2
	5H03	6.49K	6.490156	35.1
	7H03	8.66K	8.649098	28.3
	9H03	9.28K	9.277229	26.7

5/5/04

External Calibration Resistors were measured using an Agilent 7458A DVM, with calibration traceability to NIST

Worst case equivalent temperature uncertainty is 0.2mK

System Parameters Needed For Self-Calibration & Determination of Unknown Rt

Bridge Resistor (B)

	Range-0	Range-1	Range-2	Range-3
ABB-A	Babba			
ABB-B	Babbb			
ABB-C	Babbc			
ABB-D	Babbd			
HBB-A	Bhbba			
HBB-B	Bhbbb			
HBB-C	Bhbbc			
HBB-D	Bhbbd			

Gain (G)

	Range-0	Range-1	Range-2	Range-3
ABB-A	G			
ABB-B				
ABB-C				
ABB-D				
HBB-A				
HBB-B				
HBB-C				
HBB-D				

Offset (F)

	Range-0	Range-1	Range-2	Range-3
ABB-A	F0	F1	F2	F3
ABB-B				
ABB-C				
ABB-D				
HBB-A				
HBB-B				
HBB-C				
HBB-D				

13 Parameters Were Optimized to Fit Data From of all Ranges and Channels (both ABB & HBB) Using Data Collected From Reading External Calibration Resistors (160 files in all).

BBC Resistance Calibration Results

Solver Parameters

Babba	18,701.03
Babbb	18,701.12
Babbc	18,700.63
Babbd	18,701.93
Bhbba	15,001.36
Bhbbb	15,000.67
Bhbbc	15,001.08
Bhbbd	15,001.38
G	352,399.97
F0	-202,903.81
F1	-159,976.47
F2	-117,110.32
F3	-74,192.31
Target	18.39

Parameters Linked to Individual Channel Summaries

Target is sum of individual channel summary targets

	ABB-A	ABB-B	ABB-C	ABB-D	HBB-A	HBB-B	HBB-C	HBB-D	Average
B	18,701.03	18,701.12	18,700.63	18,701.93	15,001.36	15,000.67	15,001.08	15,001.38	16,851.15
G	352,399.97	352,399.97	352,399.97	352,399.97	352,399.97	352,399.97	352,399.97	352,399.97	352,399.97
F0	-202,903.81	-202,903.81	-202,903.81	-202,903.81	-202,903.81	-202,903.81	-202,903.81	-202,903.81	-202,903.81
F1	-159,976.47	-159,976.47	-159,976.47	-159,976.47	-159,976.47	-159,976.47	-159,976.47	-159,976.47	-159,976.47
F2	-117,110.32	-117,110.32	-117,110.32	-117,110.32	-117,110.32	-117,110.32	-117,110.32	-117,110.32	-117,110.32
F3	-74,192.31	-74,192.31	-74,192.31	-74,192.31	-74,192.31	-74,192.31	-74,192.31	-74,192.31	-74,192.31
Target	2.1390	2.4796	2.6196	2.8116	2.3243	2.1683	1.8965	1.9507	

	ABB-A	ABB-B	ABB-C	ABB-D	HBB-A	HBB-B	HBB-C	HBB-D
Cal4 Range-0	0.6116013	0.6116019	0.6116027	0.6116021	0.6116013	0.6116019	0.6116027	0.6116021
Cal4 Range-1	0.6116037	0.6116043	0.6116035	0.6116027	0.6116037	0.6116043	0.6116035	0.6116027
Cal3 Range-1	0.4884563	0.4884571	0.4884571	0.4884570	0.4884563	0.4884571	0.4884571	0.4884570
Cal3 Range-2	0.4884589	0.4884591	0.4884593	0.4884587	0.4884589	0.4884591	0.4884593	0.4884587
Cal2 Range-2	0.3650575	0.3650583	0.3650587	0.3650581	0.3650575	0.3650583	0.3650587	0.3650581
Cal2 Range-3	0.3650635	0.3650631	0.3650617	0.3650607	0.3650635	0.3650631	0.3650617	0.3650607

Agreement consistent with <1 mK temperature measurement error

Absolute Vaue of the Difference From Average of the 16 Readings

	ABB-A	ABB-B	ABB-C	ABB-D	HBB-A	HBB-B	HBB-C	HBB-D
Cal4 Range-0	1.46E-06	8.79E-07	4.21E-08	7.09E-07	1.46E-06	8.79E-07	4.21E-08	7.09E-07
Cal4 Range-1	9.11E-07	1.54E-06	6.84E-07	3.95E-08	9.11E-07	1.54E-06	6.84E-07	3.95E-08
Cal3 Range-1	1.67E-06	7.87E-07	8.29E-07	8.86E-07	1.67E-06	7.87E-07	8.29E-07	8.86E-07
Cal3 Range-2	9.18E-07	1.13E-06	1.37E-06	7.48E-07	9.18E-07	1.13E-06	1.37E-06	7.48E-07
Cal2 Range-2	2.65E-06	1.94E-06	1.50E-06	2.12E-06	2.65E-06	1.94E-06	1.50E-06	2.12E-06
Cal2 Range-3	3.32E-06	2.91E-06	1.47E-06	5.07E-07	3.32E-06	2.91E-06	1.47E-06	5.07E-07

Max Difference
Cal4
1.54E-06
Cal3
1.67E-06
Cal2
3.32E-06

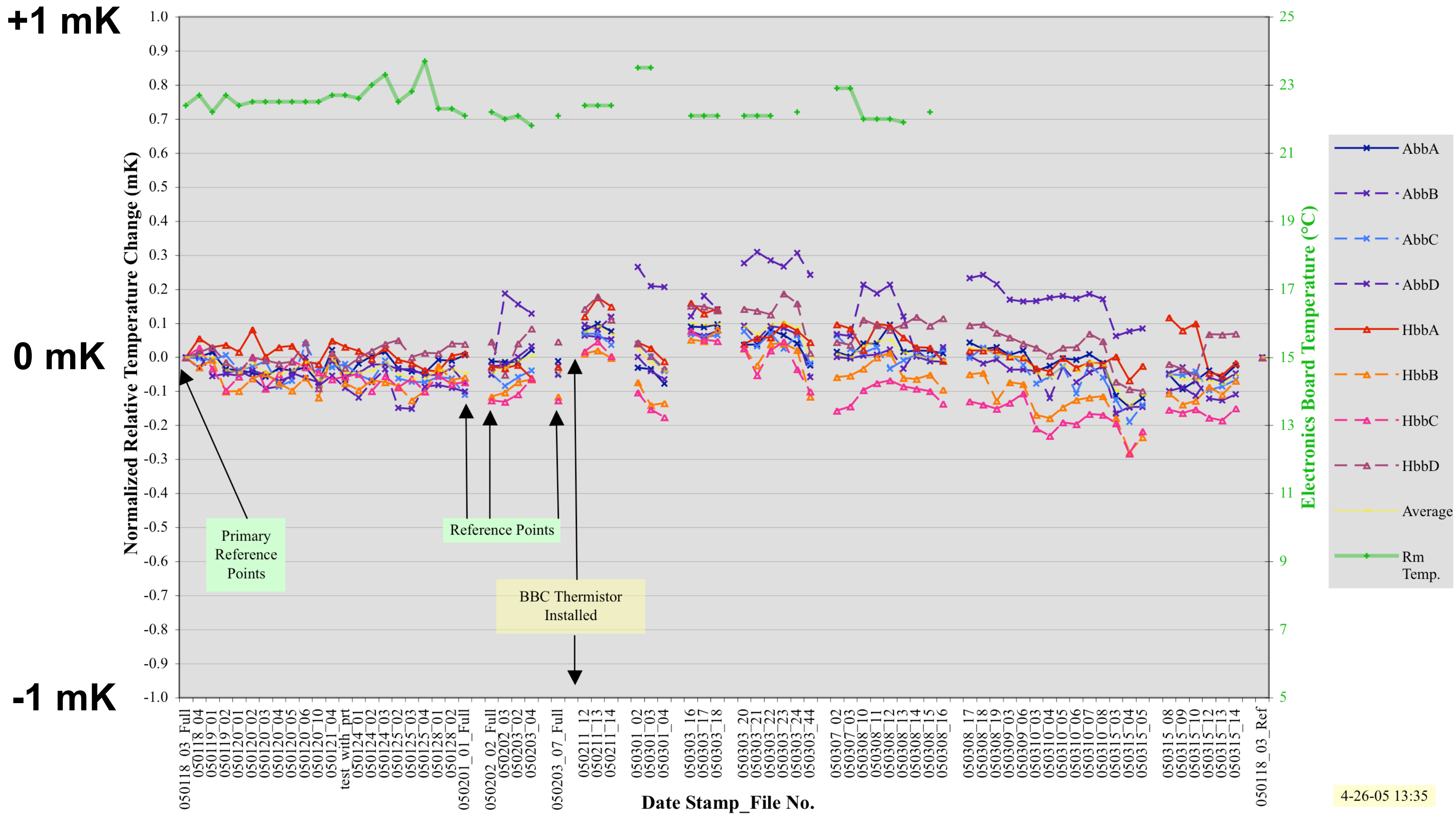
	Average Across All Channels		K=(N*-F*)/(G*+F*-N*)		Using Averages of Values at Left	
Range-0	Cal4low	12625	Ka	1.574679	Ka	1.574684
	Cal5	53381	Kb	2.666439	Kb	2.666439
Range-1	Cal3low	12156	Ka	0.954869	Ka	0.954873
	Cal4high	55553	Kb	1.574689	Kb	1.574684
Range-2	Cal2low	11536	Ka	0.574947	Ka	0.574952
	Cal3high	55023	Kb	0.954877	Kb	0.954873
Range-3	Cal1	12135	Ka	0.324449	Ka	0.324449
	Cal2high	54456	Kb	0.574958	Kb	0.574952

Equivalent Temperature Error Associated With Reading Same Resistance on Different Ranges is Very Small

		Temperature Error [C]			
Range Comparison	**Temperature [C]**	**AbbA**	**AbbB**	**AbbC**	**AbbD**
Range 0/1	-30.2	-0.0006	-0.0006	-0.0004	-0.0004
Range 1/2	-21.0	-0.0002	-0.0002	-0.0002	-0.0001
Range 2/3	-14.0	0.0000	0.0003	0.0000	0.0000

- Temperatures were computed using nominal Stienhart and Hart Coefficients
- The data helps validate the electronics resistance measurement self calibration scheme, set up for each range.

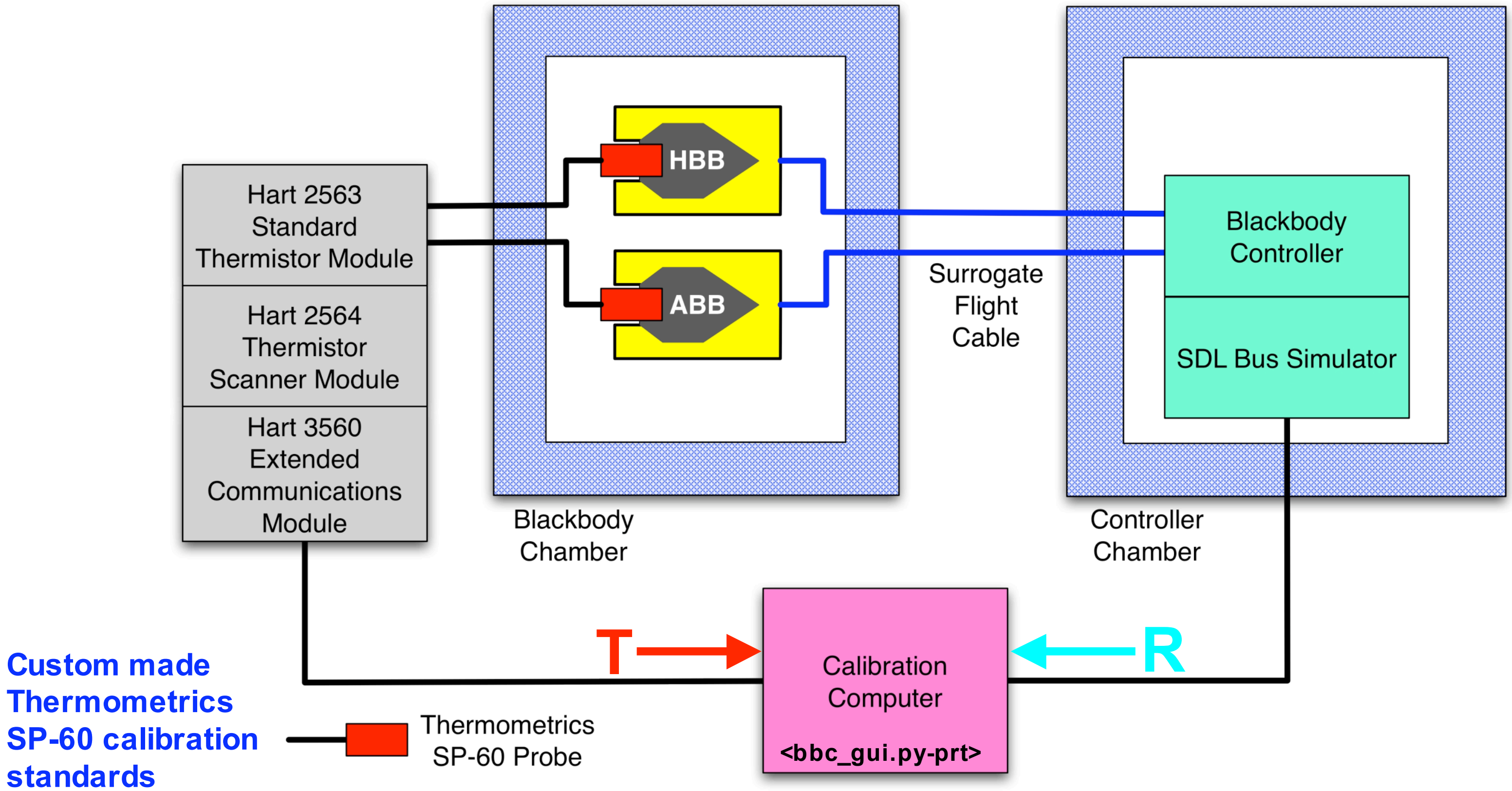
Electronics Stability Over 60 Day Test Period
(Equivalent to drift of < 0.6 mK/year.)



Other tests indicate that the error due to expected power supply voltage variations is less than 0.2 mK, and the error due to expected electronics temperature variation is less than 0.5 mK.

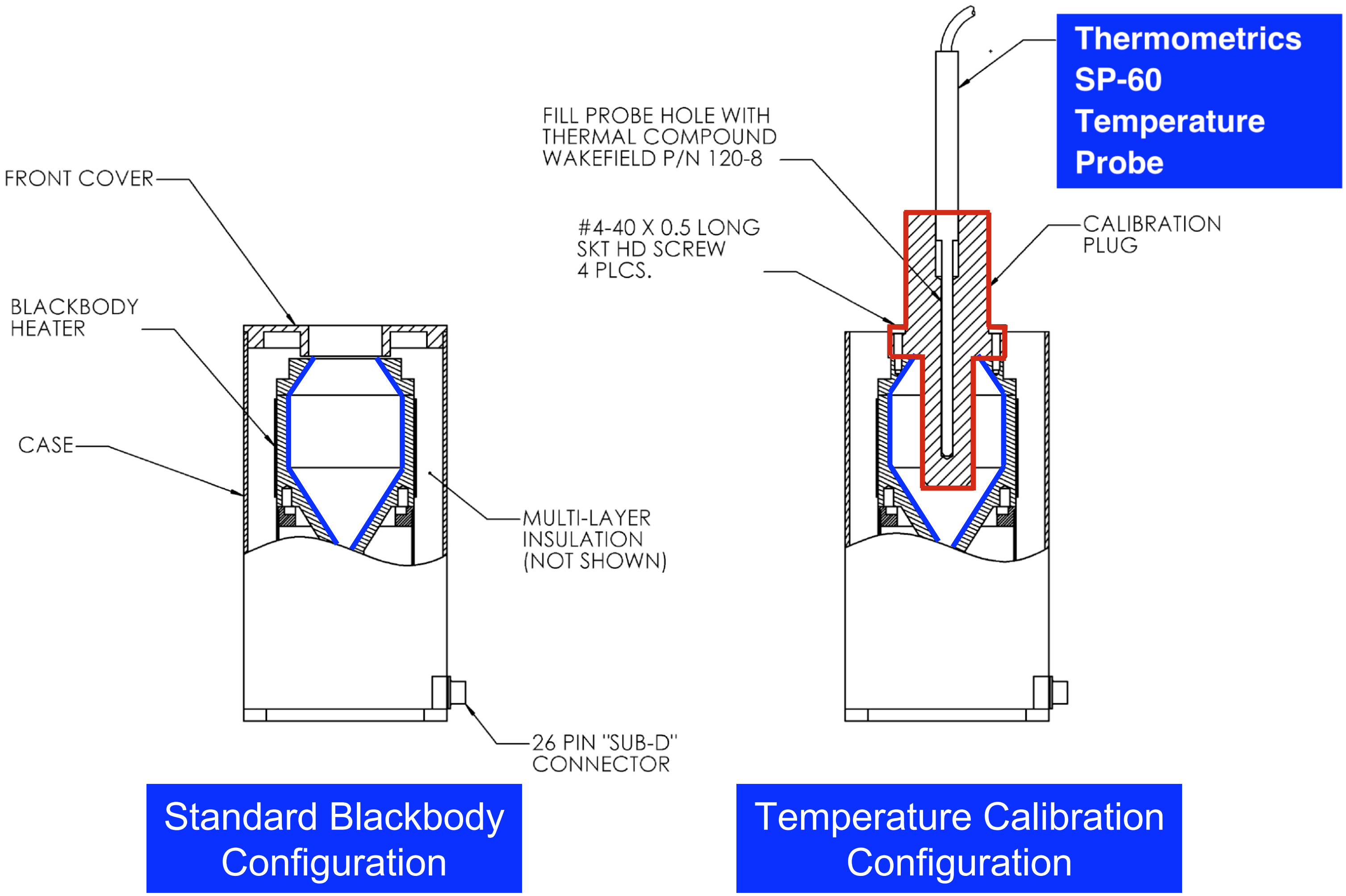
End-to-end System Temperature Calibration

Temperature Calibration Functional Block Diagram



System used to collect thermistor resistances (R) at various very well known temperatures (T)

Blackbody Temperature Calibration - Calibration Probe Closely Coupled to Cavity



Custom Absolute Temperature Calibration Standard +/- 0.005 K (3 sigma)

- **Hart 2563 Standard Thermistor Module**
- **Hart 2564 Thermistor Scanner Module**
- **Hart 3560 Extended Communications Module**
- **Calibration Computer**

Thermometrics SP-60 Probes (2)

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Accounted for in the uncertainty evaluation are all known influence quantities affecting the reference thermometer system at the time of calibration including long-term behavior of the calibration system, measurement noise, bath uniformity and bath stability. The observed errors and estimated uncertainties are shown in the table below.

AS LEFT

Probe Model No: ABB		Probe Serial No: 0201-220		Channel: 1		Current: 0.01 mA	
A0=	1.1534085 E-03	A1=	2.8959232 E-04	A2=	-2.7828555 E-06	A3=	2.5689558 E-07
B0=	-4.8421000 E00	B1=	3.9686737 E03	B2=	-2.4451777 E04	B3=	-1.1427676 E07

NOMINAL (t_{90} (°C))	ACTUAL t_{90} (°C)	INDICATED VALUE t_{90} (°C)	AS LEFT ERROR t_{90} (°C)	TOLERANCE t_{90} (°C)	PASS/FAIL	Uncertainty (k=2) t_{90} (°C)
-50.000	-50.0165	-50.0191	-0.0026	0.003	P	0.003
-40.000	-40.0019	-40.0014	0.0005	0.003	P	0.003
-30.000	-30.0097	-30.0094	0.0003	0.002	P	0.003
-20.000	-20.0185	-20.0180	0.0005	0.002	P	0.003
-10.000	-9.9993	-9.9995	-0.0002	0.002	P	0.003
0.000	-0.0090	-0.0091	-0.0001	0.002	P	0.003
10.000	9.9800	9.9798	-0.0002	0.002	P	0.003

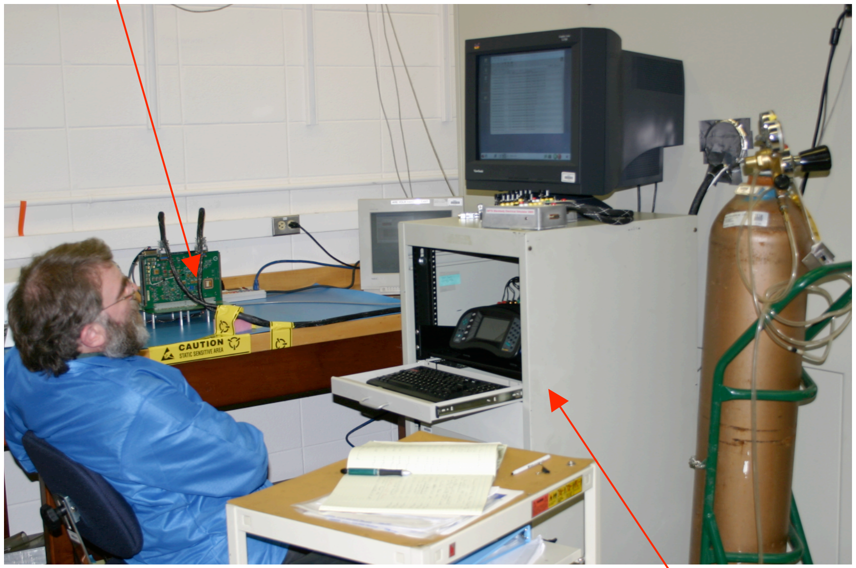
Special Notes: This system was done new. No as found is available. Calibration was performed and as left data taken.

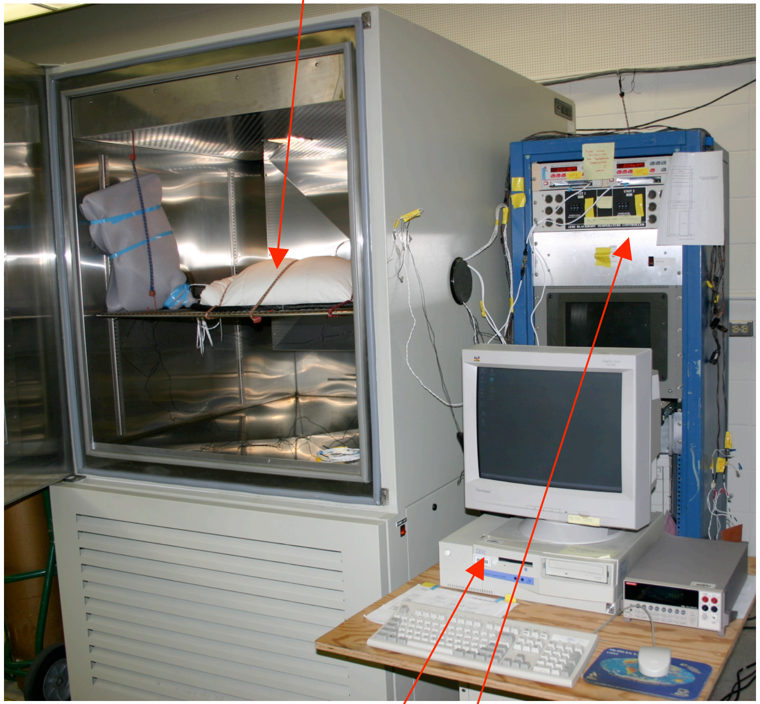
Absolute Temperature Calibration of end-to-end System at Hart has Uncertainty Of +/- 0.003 K (k=2)

Thermistor Calibration Test Set-up

UW Blackbody Controller and
SDL C&DH Simulator Board

Blackbody Wrapped in
Insulation Inside Chamber





Calibration Computer and
Hart Thermistor Read-out

Engineering Temperature
Data Collection

Thermistor Fitting Equation (Steinhart & Hart)

$$T = \frac{1}{A + B \bullet \ln(R) + C \bullet (\ln(R))^3}$$

- At each calibration temperature:
  - The T_i come from the Calibration Probe
  - The R_i come from the Blackbody Controller, using the Self Calibration.
- Regression fit to N points (R_i,T_i),:

$$\begin{vmatrix} N & \sum \ln(R_i) & \sum (\ln(R_i))^3 \\ \sum \ln(R_i) & \sum (\ln(R_i))^2 & \sum (\ln(R_i))^4 \\ \sum (\ln(R_i))^3 & \sum (\ln(R_i))^4 & \sum (\ln(R_i))^6 \end{vmatrix} \bullet \begin{vmatrix} A \\ B \\ C \end{vmatrix} = \begin{vmatrix} \sum (1/T_i) \\ \sum (1/T_i) \cdot (\ln(R_i)) \\ \sum (1/T_i) \cdot (\ln(R_i))^3 \end{vmatrix}$$

$$[R] \bullet \begin{vmatrix} A \\ B \\ C \end{vmatrix} = [Z] \qquad \begin{vmatrix} A \\ B \\ C \end{vmatrix} = [R]^{-1} \bullet [Z]$$

Example of Generation of ABB Range-2 Calibration Coefficients - 5 Points

N	$\Sigma(\ln(R_i))$	$\Sigma(\ln(R_i))^3$	*	A	=	$\Sigma(1/T_i)$
$\Sigma(\ln(R_i))$	$\Sigma(\ln(R_i))^2$	$\Sigma(\ln(R_i))^4$		B		$\Sigma(1/T_i)*(\ln(R_i))$
$\Sigma(\ln(R_i))^3$	$\Sigma(\ln(R_i))^4$	$\Sigma(\ln(R_i))^6$		C		$\Sigma(1/T_i)*(\ln(R_i))^3$

AbbA

	5.00000000E+00	4.77753662E+01	4.37007992E+03				1.95506919E-02
[R] =	4.77753662E+01	4.56784233E+02	4.18347107E+04				1.86896534E-01
	4.37007992E+03	4.18347107E+04	3.84086966E+06				1.71116765E+01
	3.47787057E+05	-5.47587596E+04	2.00725279E+02				
$[R]^{-1}$ =	-5.47587596E+04	8.62260955E+03	-3.16137310E+01				
	2.00725279E+02	-3.16137310E+01	1.15954672E-01				
	1.00000000E+00	-5.58793545E-09	-2.38418579E-07		A		**1.2512661028E-03**
$[R]^{-1}*[R]$ =	2.91038305E-11	1.00000000E+00	7.45058060E-08		B	=	**2.6358804359E-04**
	1.13686838E-13	-9.09494702E-13	1.00000000E+00		C		**1.6048815965E-07**

S&H Coefficients

AbbA

Tprobe	Resistance	Tcalc	Tcal-Tprobe
-10.0415	9,879.895	-10.0417	-0.00019
-13.9719	11,933.404	-13.9714	0.00047
-18.0117	14,562.231	-18.0120	-0.00030
-20.9813	16,911.993	-20.9814	-0.00012
-23.5610	19,303.610	-23.5608	0.00014

Fit Residuals

Thermistors B, C, and D calculations not shown

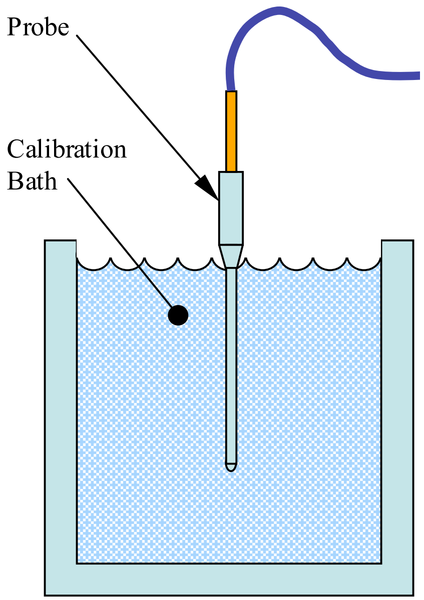
Calibration Configuration Characterizations

Minimizing Unwanted Sources of Temperature Error

- Temperature Calibration Probe Immersion Error Characterized to be on the order of 6 mK (worst case).
- Temperature error due to Blackbody Controller cable heat leak measured to be insignificant.
- Temperature error due to the gradient between the probe and themistors arising from a rate of change in blackbody temperature during calibration was measured to be insignificant at the stability criteria (dT/dt) adopted for calibration.
- Temperature error arising from the inability of the Stienhart Hart equation to capture a 1 Ohm fixed cable resistance in series with the thermistors was shown by modeling to be insignificant.
- Next slides present more detail on our approach to quantify each of these potential error sources.

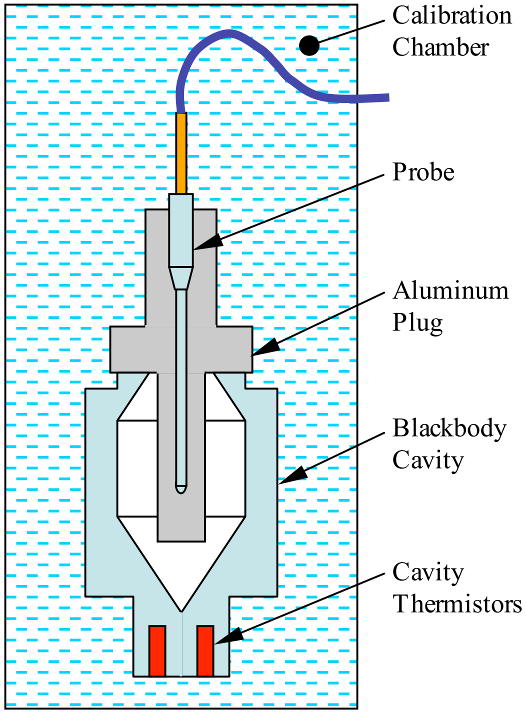
Temperature Calibration Probe Immersion Error

is on the order of 6 mK (worst case)

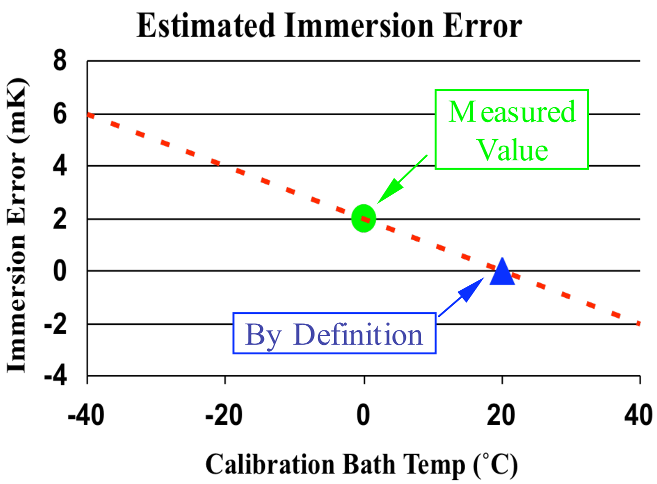


During Probe Calibration at Hart Scientific, probes were immersed as shown in the calibration bath, with top of probe exposed to room temp air

During GIFTS Blackbody Calibration, entire probe (including cable) and cavity were isothermal at calibration temp



This difference in configuration gives rise to a temperature dependent probe immersion error that is carried through to the GIFTS Blackbody calibration



- By measuring the immersion error in a 0°C bath in 20°C air, we can estimate the immersion error over the calibration ranges
- To obtain sufficient precision the test was done in a Triple Point of Water (TPW) cell

Temperature Uncertainty Budget

Temperature Uncertainty	3 sigma error [K]	RSS [K]
Temperature Calibration Standard (Thermometrics SP60 Probe with Hart Scientific 2560 Thermistor Module)	0.005	
		0.005
Blackbody Readout Electronics Uncertainty		
Readout Electronics Uncertainty (at delivery)	0.005	
		0.005
Blackbody Thermistor Temperature Transfer Uncertainty		
Gradient Between Temperature Standard and Cavity Thermistors	0.010	
Calibration Fitting Equation Residual Error	0.001	
		0.010
Cavity Temperature Uniformity Uncertainty		
Cavity to Thermistor Gradient Uncertainty *(1/3 of total max expected gradient)*	0.025	
Thermistor Wire Heat Leak Temperature Bias Uncertainty*	0.008	
Paint Gradient *(assumes fulll alue at nominal HBB Temp and conservative viewing geometry)*	0.018	
		0.032
Long-term Stability		
Blackbody Thermistor *(8 years of drift assuming 100 C)*	0.030	
Blackbody Controller Readout Electronics	0.012	
		0.032
Effective Radiometric Temperature Weighting Factor Uncertainty		
Monte Carlo Ray Trace Model Uncertainty in Determining Teff *(1/3 of total max expected gradient)*	0.030	
		0.030
		0.056

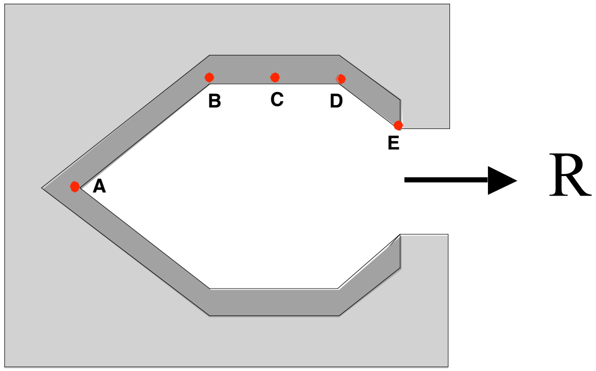
*(conservatively assumed to be the full value calculated for the effect in the worse case thermal environment and making conservative thermal coupling assumptions)

Budget ≤ 0.1K

Blackbody Painting and Emissivity Determination

GIFTS BB Radiance Model

$$R(\lambda) = \varepsilon(\lambda) * B(T_{EFF}, \lambda) + (1 - \varepsilon(\lambda)) * B(T_{ENV}, \lambda)$$



where,

$B(T, \lambda)$ = Planck radiance at T and wavelength λ,

$\varepsilon(\lambda)$ = cavity isothermal emissivity,

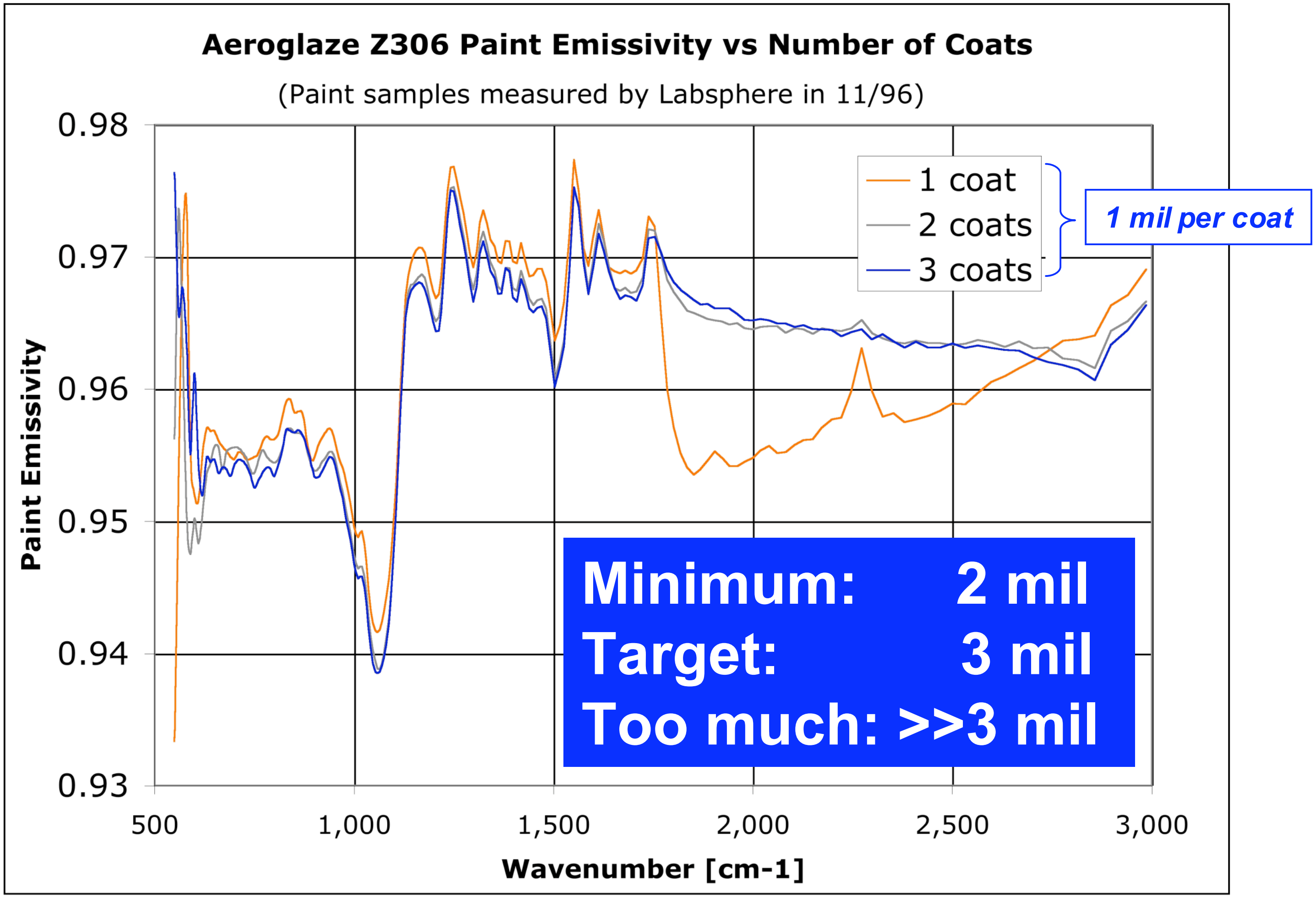
$T_{EFF} = w_A * T_A + w_B * T_B$

is the effective emitting temperature, and

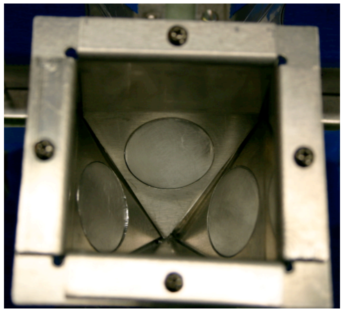
T_{ENV} = environmental temperature.

ε, w_A, and w_B are pre-computed using a numerical model while T_A, T_B, and T_{ENV} are measured in flight.

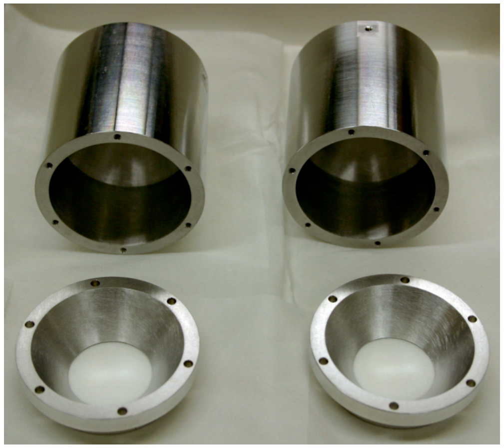
Paint Thickness is Important

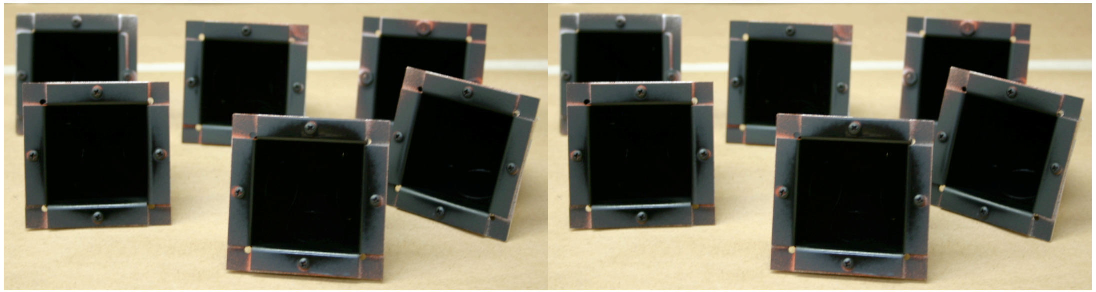


Paint Witness Samples Mimic Cavity Cones

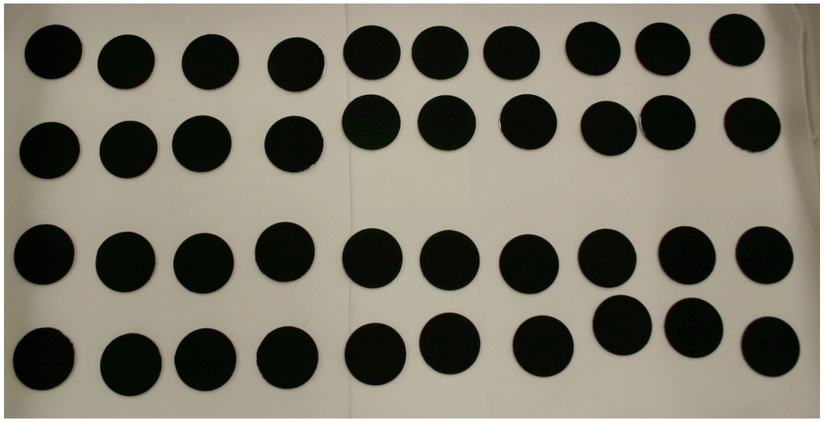


Fixture Mimics
Cavity Cone Geometry
(4 Samples / Fixture)



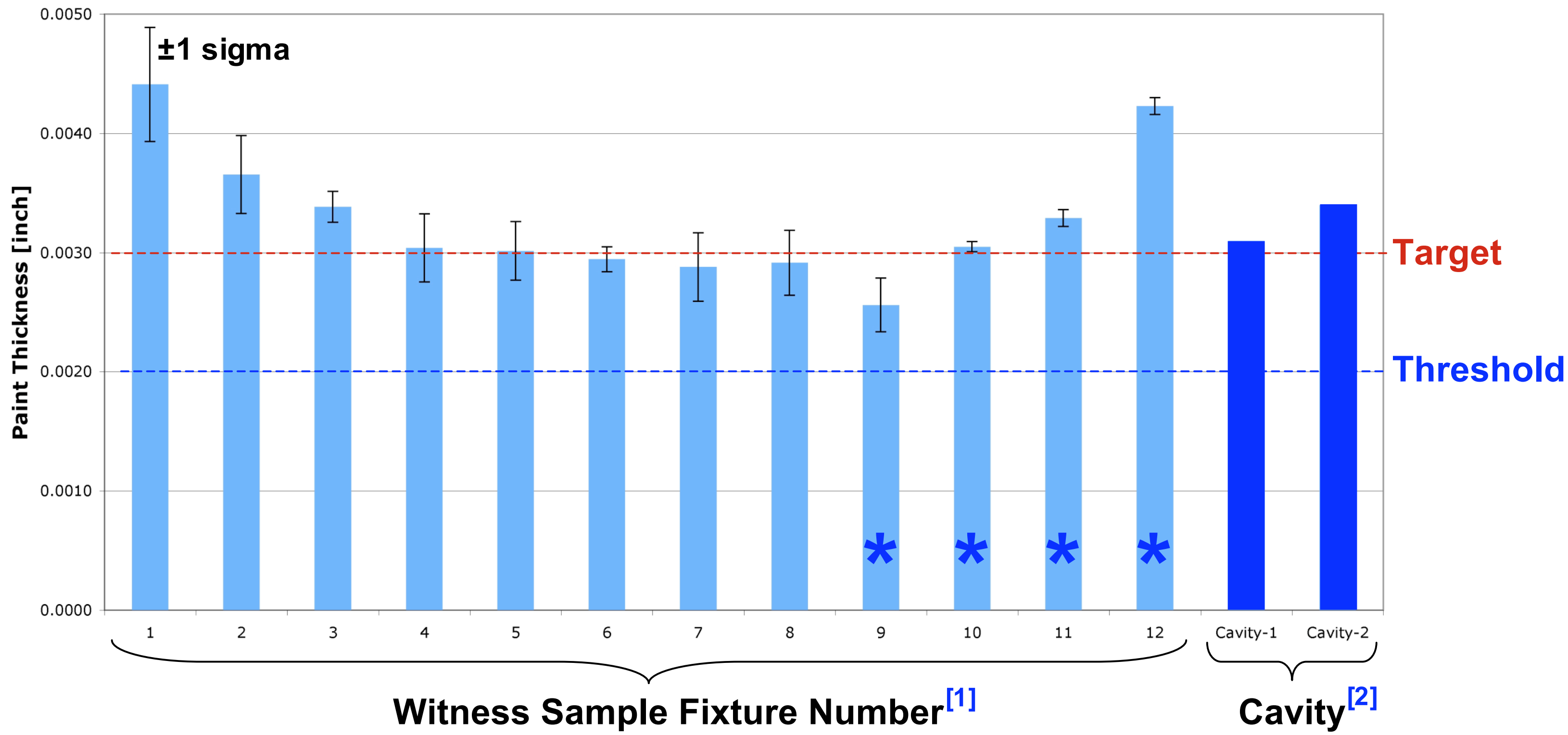


12 Fixtures (four 1” dia samples each)



48 total samples

Desired Paint Thickness Achieved



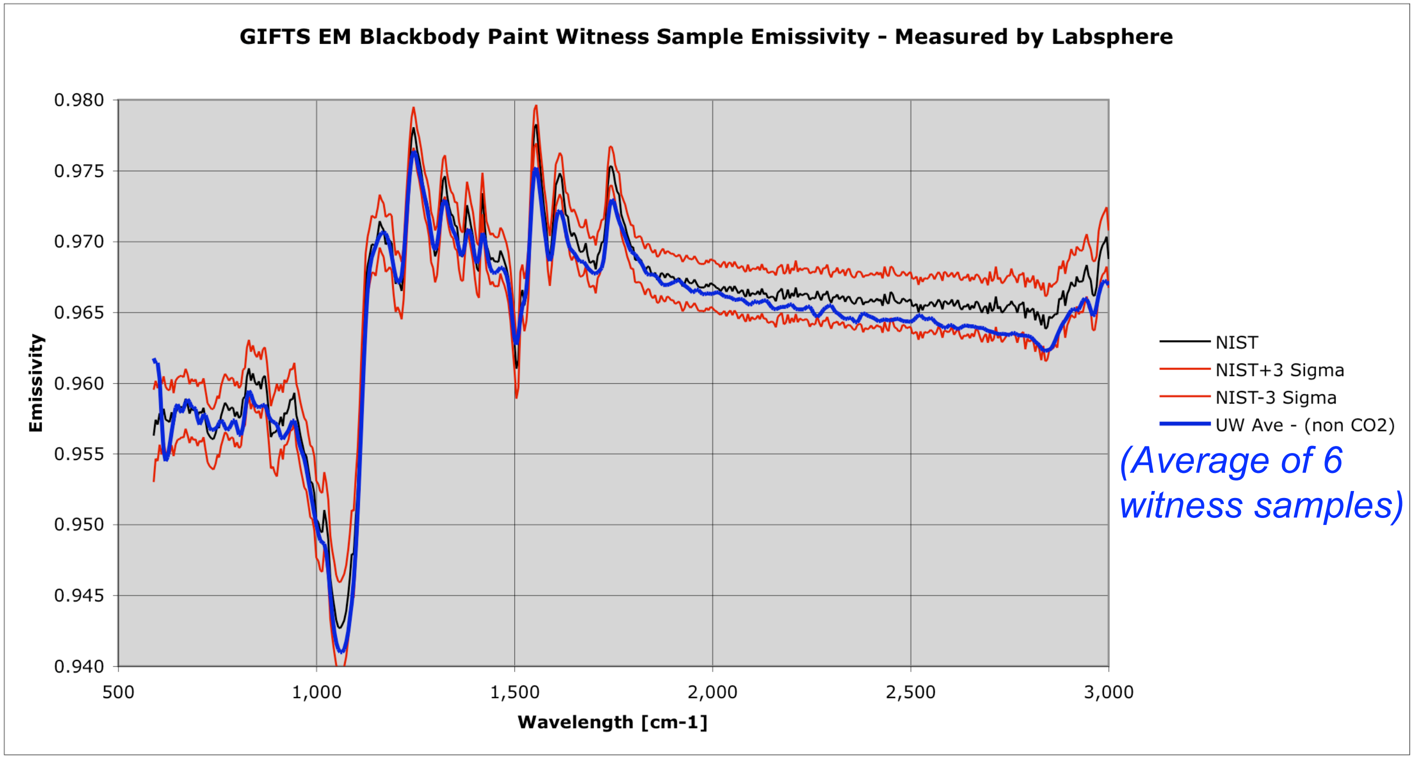
*Used for Cavity emissivity characterization

[1] Four samples per fixture, five measurements per sample

[2] Cavity paint thickness computed from weight measurements

GIFTS Blackbody Witness Sample Emissivity

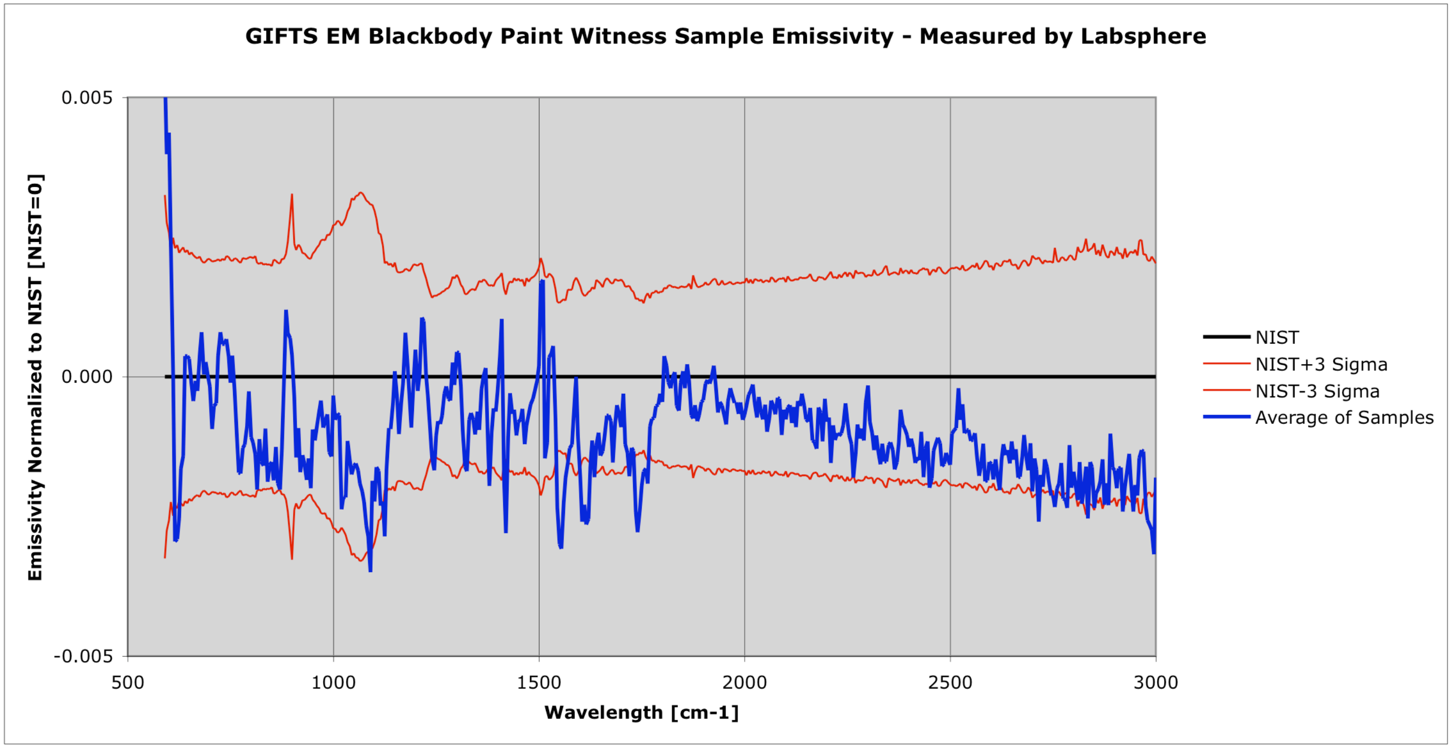
✓Emissivity measurements of 6 GIFTS BB witness samples are in excellent agreement with previously obtained NIST test data from a NIST painted sample.



(Average of 6 witness samples)

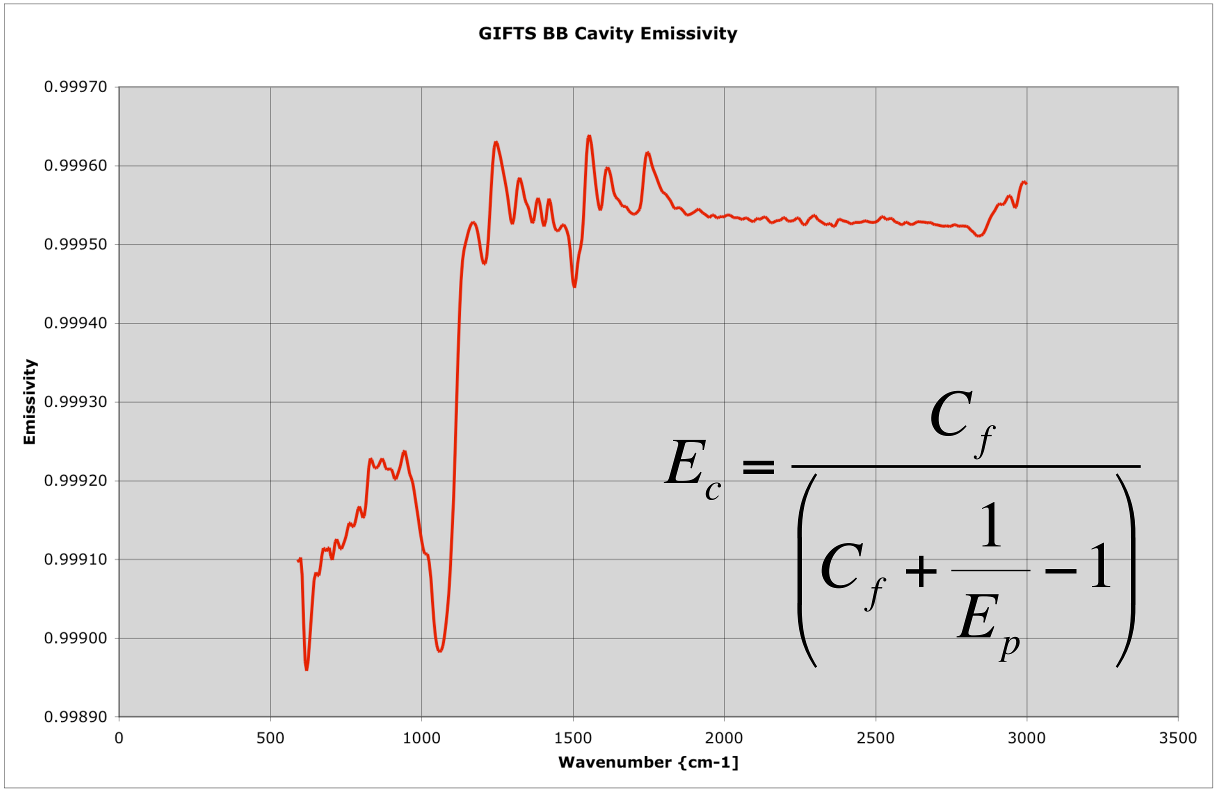
NIST Data is from “Joe Rice” Sample sent to UW in July of 2003 by Leonard Hannsen of NIST

GIFTS Blackbody Witness Sample Emissivity (normalized to NIST Sample)



NIST Data is from "Joe Rice" Sample sent to UW in July of 2003 by Leonard Hannsen of NIST

GIFTS Blackbody Cavity Isothermal Emissivity



$$E_c = \frac{C_f}{\left(C_f + \frac{1}{E_p} - 1\right)}$$

Paint emissivity (Ep) is the measured GIFTS Blackbody Witness Sample data, and cavity factor (Cf) is the quadratic fit of the Monte Carlo Cf vs Wavelength model results.

Emissivity Uncertainty Budget

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

Budget ≤ 0.002

f=(1-Ep)/(1-Ec)

f=Cavity Factor
Ep=Emissivity of Paint
Ec=Emissivity of Cavity

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)

Summary and Conclusions

- A blackbody calibration system suitable for spaceflight has been developed to meet the demanding requirements of the GIFTS instrument.
- The system builds on the strong heritage of the ground and aircraft based FTS instruments developed at UW.
- The engineering model version of this system was fully calibrated and and shown to exceed required temperature and emissivity accuracies.
- The engineering model system has been delivered to SDL for integration into the GIFTS EDU, which is currently undergoing thermal vacuum testing.