Traceability of Absolute Radiometric Calibration for the Atmospheric Emitted Radiance Interferometer (AERI)

Fred A. Best, Henry E. Revercomb, Robert O. Knuteson, Dave C. Tobin, Ralph G. Dedecker, Tim P. Dirkx, Mark P. Mulligan, Nick N. Ciganovich, Yao Te

University of Wisconsin
Space Science and Engineering Center

fred.best@ssec.wisc.edu

USU/SDL

CALCON 2003

Abstract

The Atmospheric Emitted Radiance Interferometer (AERI) is a ground-based spectroradiometer that was developed at the University of Wisconsin for the DOE Atmospheric Radiation Measurement (ARM) program to measure the downwelling infrared emission from CO_2, H_2O, and clouds. Twelve continuously operating AERIs are deployed throughout the world, including three marine-based instruments (MAERIs) that are configured to measure sea surface temperature. The AERI instruments are used to improve our understanding of atmospheric radiation transfer and cloud properties for climate studies, and for boundary level temperature and water vapor retrieval and water vapor transport for weather applications.

During operation, the AERI uses two high emissivity blackbody sources to provide instrument absolute calibration accuracies to better than 1% of the ambient radiance. A calibration methodology with traceability to NIST has been successfully implemented for the blackbodies. Absolute radiometric performance of the AERI was verified using the 3^{rd} generation water-bath based NIST blackbody source, with agreement better than 0.065 K over the temperature range from 293 K to 333 K. Instrument repeatability has been demonstrated during a 14 day cruise where two MAERI instruments operating side-by-side measuring sea surface temperature showed agreement to within 0.02 K.

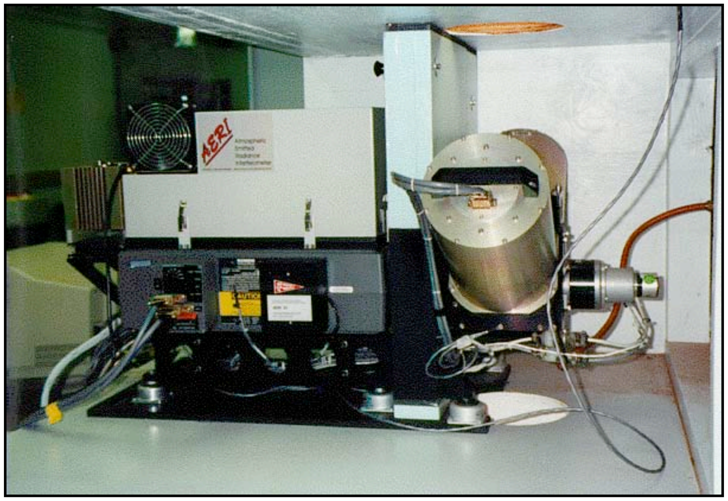
An uncertainty analysis based on the instrument calibration equation was used to allocate the allowable blackbody temperature and emisssivity uncertainties. A detailed budget was developed to account for all contributions to both temperature and emissivity uncertainty, including contributions from the instrument spectral calibration. Both temperature and emissivity measurements have traceability to NIST.

Topics

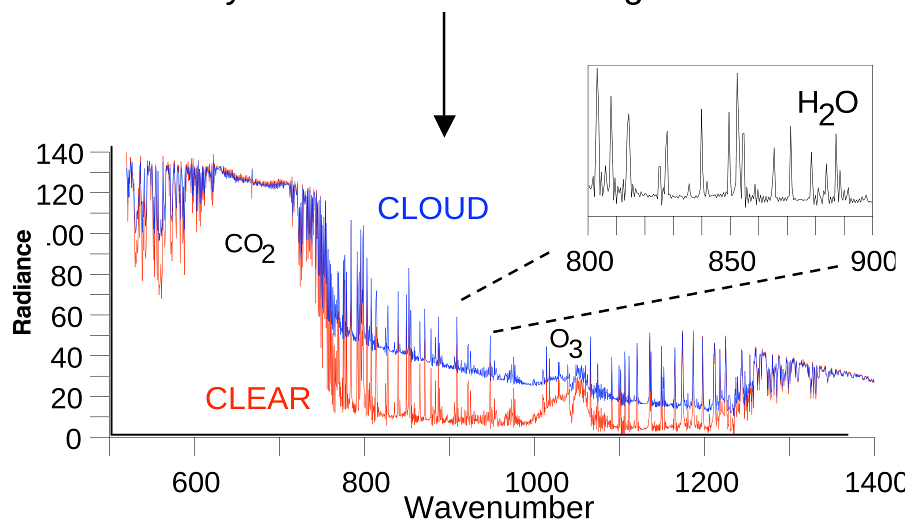
- Overview of AERI and Top Level Radiometric Performance Requirements
- Instrument Calibration Model and Predicted Radiometric Performance
- Blackbody Design and Calibration
- Instrument End-to-end Performance
- Summary

AERI Overview and Radiometric Performance Specification

Atmospheric Emitted Radiance Interferometer (AERI)



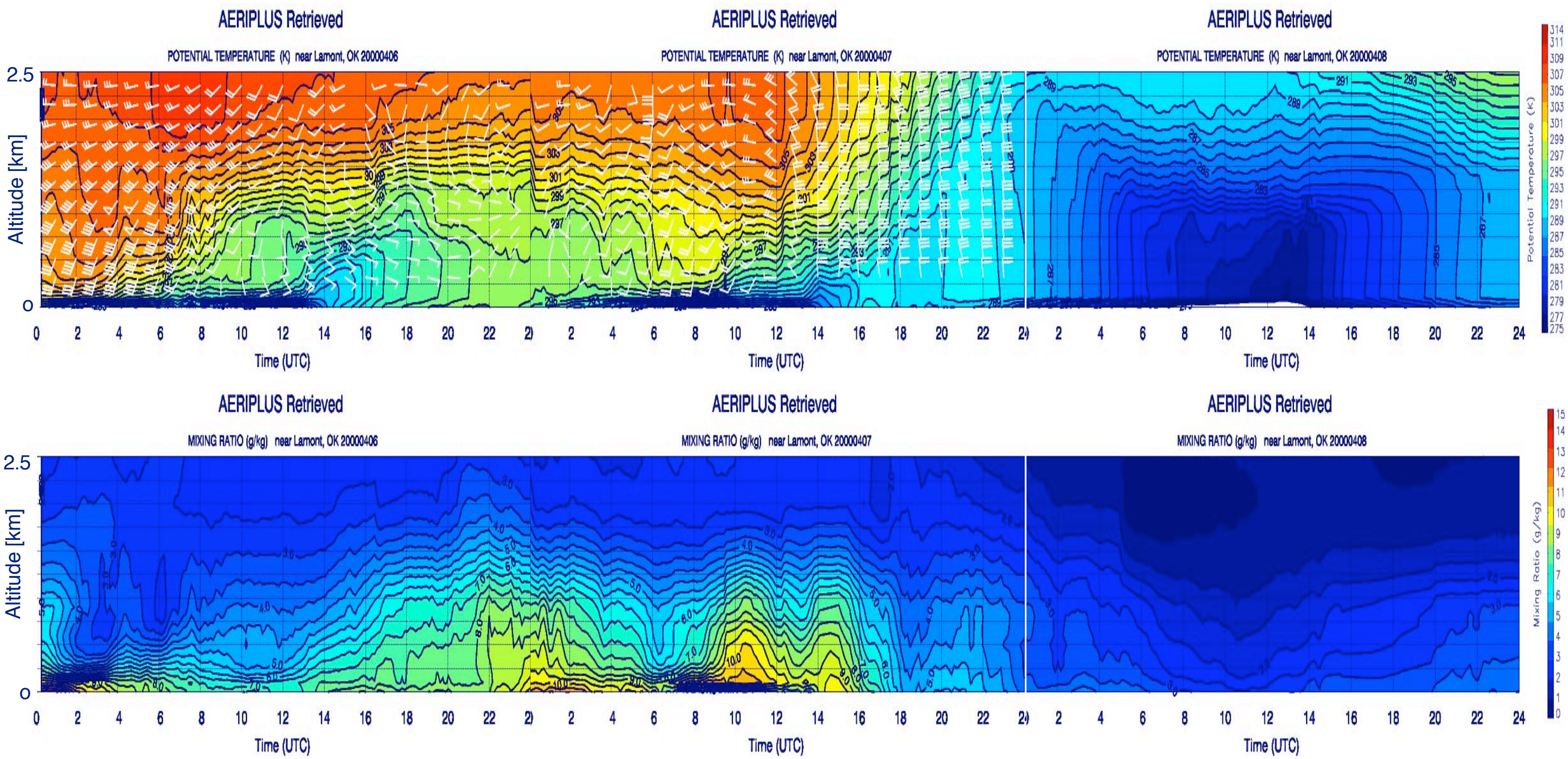
Operational at DOE ARM



AERI Provides Continuous Accurate High Resolution Radiometry in the Infrared

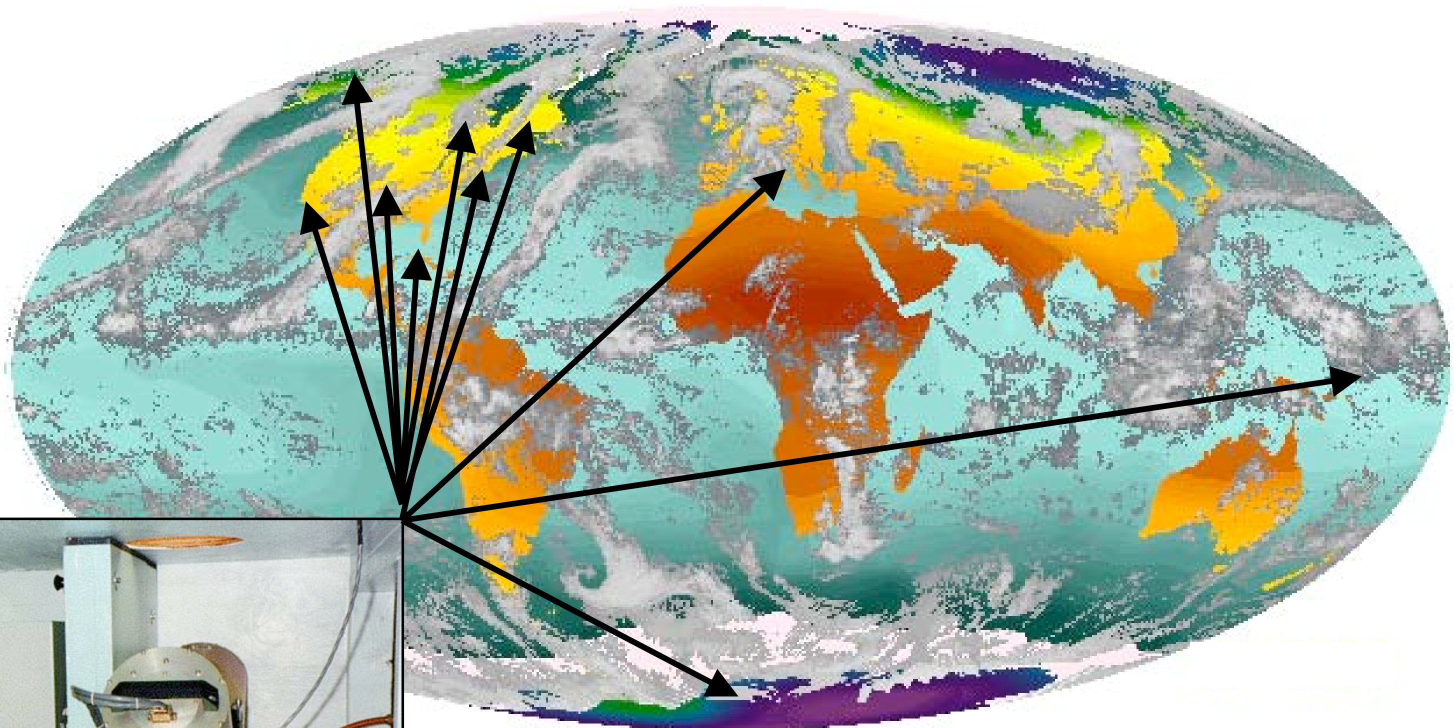
AERI is used to improve our understanding of atmospheric radiation transfer and cloud properties for climate studies, and for weather applications.

AERI Provides Continuous Atmospheric Profiling of Temperature and Water Vapor



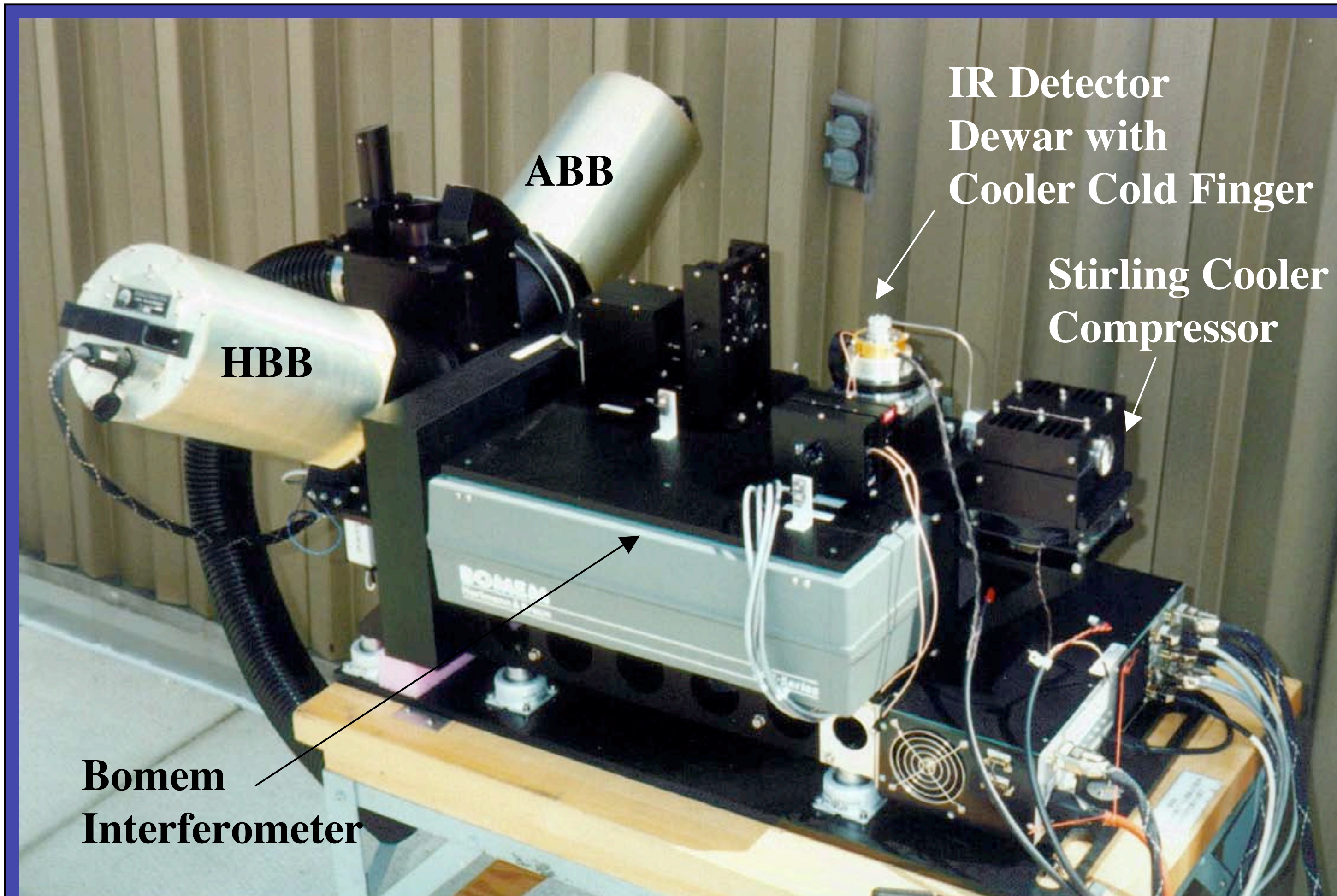
THE UNIVERSITY of WISCONSIN MADISON

AERI Systems Around The World



- UW AERI - 2 (AERIBAGO, SSEC)
- DOE AERI - 7 (Kansas/Oklahoma, Alaska, S. Pacific)
- U-Miami M-AERI - 3 (Florida)
- Bomem AERI - 4 (Italy, California, Maryland, Canada)
- U Idaho P-AERI - 1 (Antarctica)

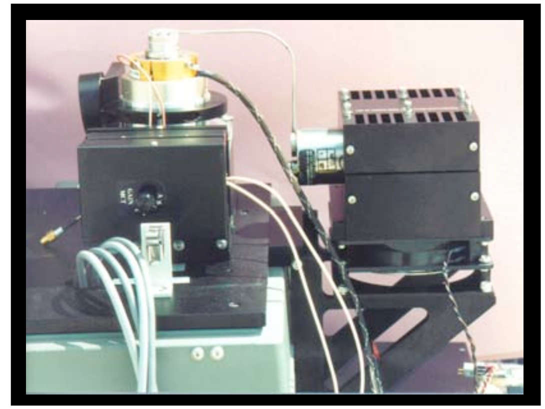
AERI Interferometer Assembly



THE UNIVERSITY of WISCONSIN MADISON

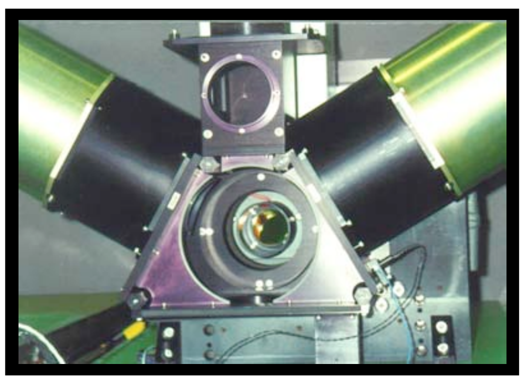
AERI Front-end Assembly

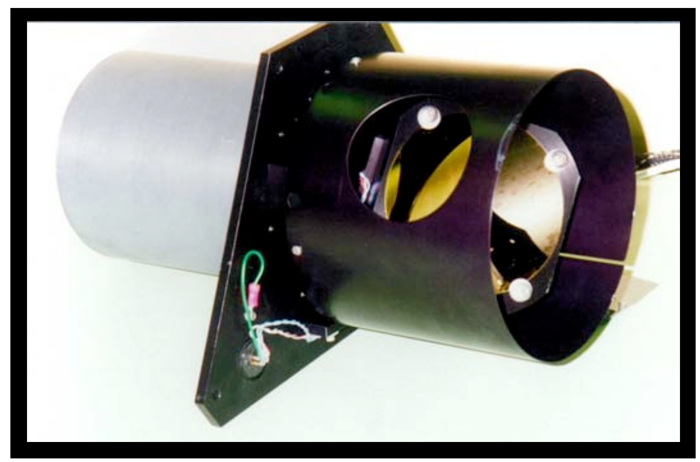
Interferometer Assembly with Blackbodies



Detector with Stirling Cooler

Front-end Port for Scene Mirror Assembly



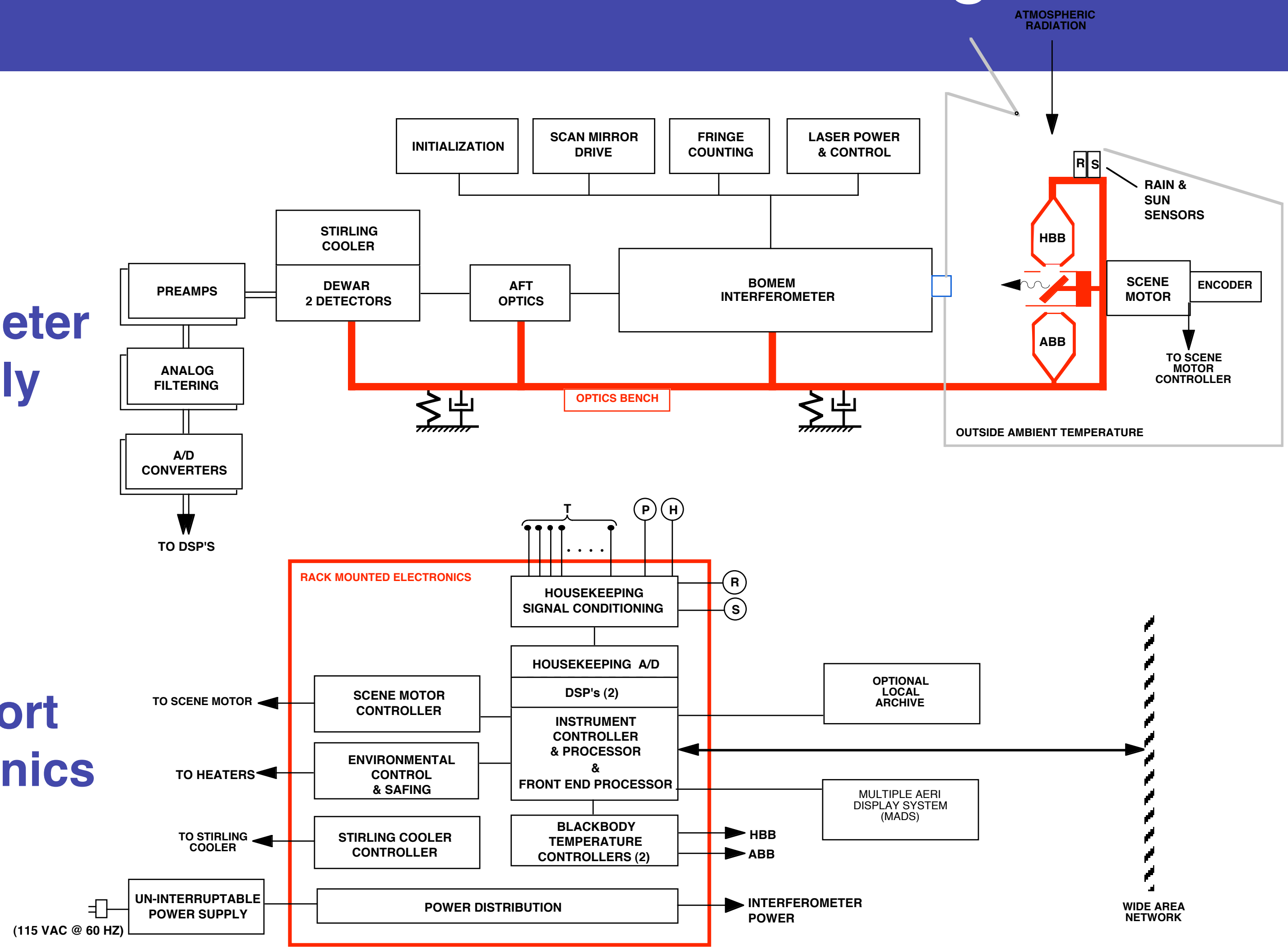


Scene Mirror Assembly

AERI Functional Block Diagram

Interferometer Assembly

Support Electronics



AERI Radiometric Accuracy Requirements

- Absolute Accuracy: better than 1%*
- Reproducibility: better than 0.2%*

*expressed as % of ambient radiance

Radiance Uncertainty Requirements and Budget

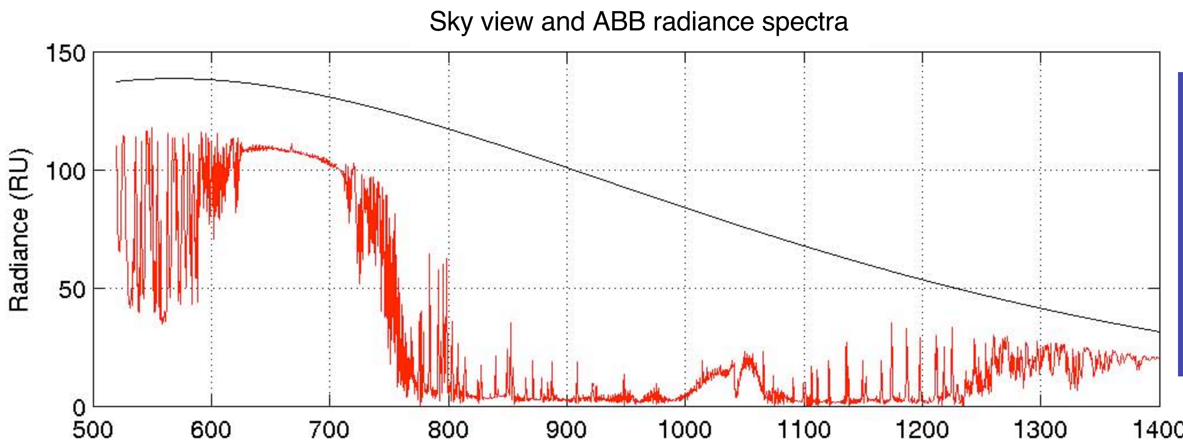
- **Top Level Requirements**
  - Absolute Accuracy: **< 1.0% of ambient radiance**
  - Reproducibility: **< 0.2% of ambient radiance**

- **Budget Goals for Key Contributors**

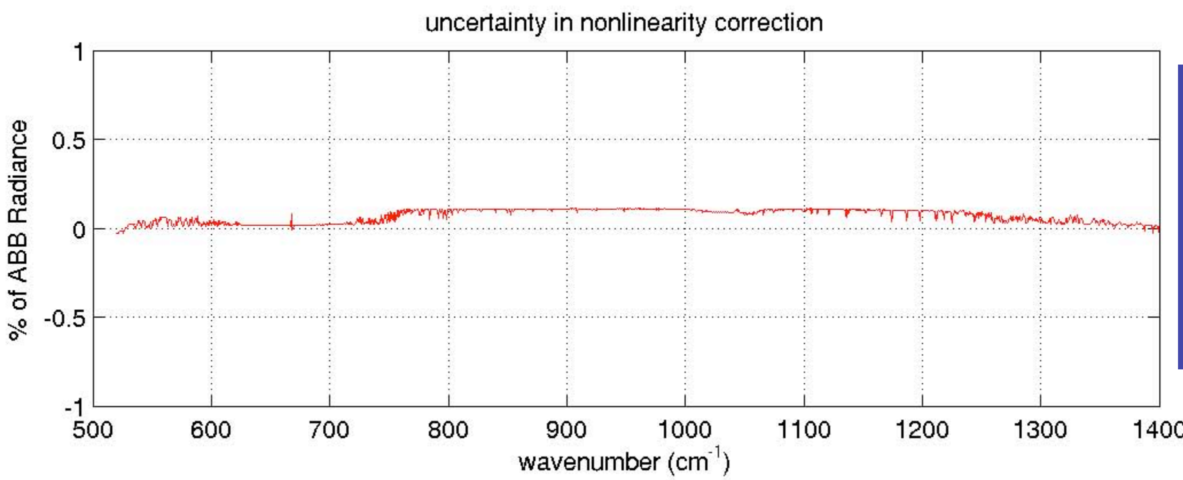
	Absolute	**Reprod.**
Detector Non-linearity Correction *(addressed briefly here)*	**0.2%**	**0.05%**
Blackbody Calibration *(main topic of this talk)*	**0.9%**	**0.18%**
Spectral Calibration *(material in Dave Tobin's talk applies)*	**0.2%**	**0.05%**
	0.95%	**0.20%**

All numbers are 3σ ("not to exceed")

AERI Non-linearity Correction and Uncertainty



Maximum Detector Non-linearity correction is order 1%



Uncertainty in correction is estimated to be < 0.10%

The non-linearity correction is physically based with one adjustable and one modeled parameter

Instrument Calibration Model and Predicted Radiometric Performance

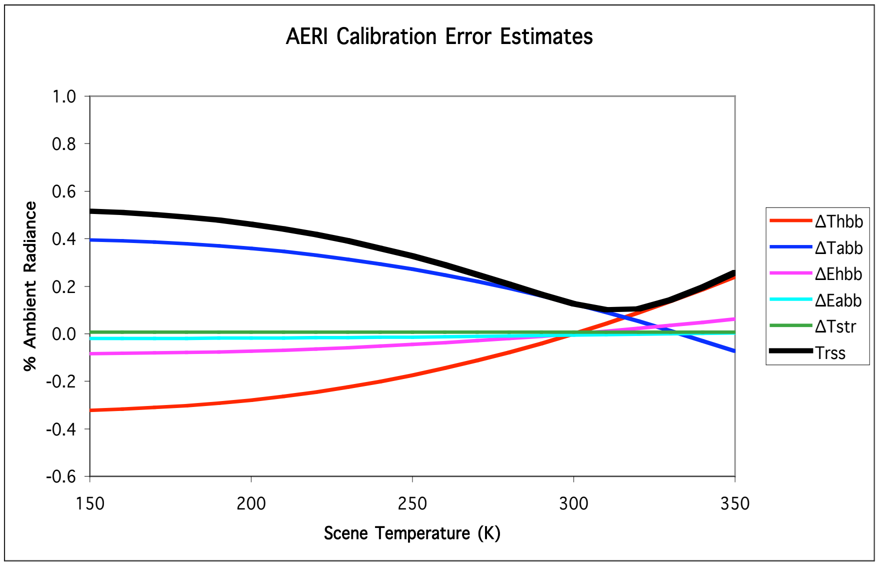
AERI Instrument Calibration Equation

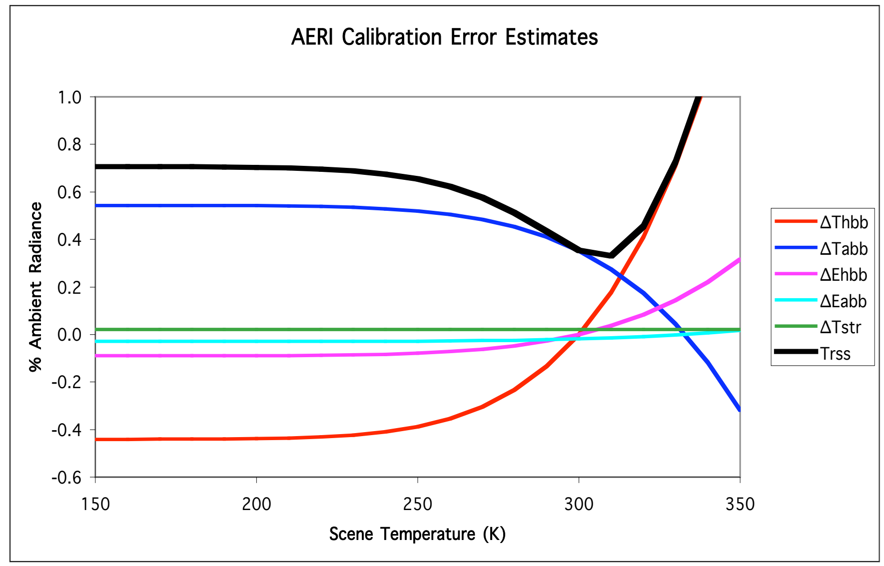
$$N = \left(B_H - B_A\right)\mathrm{Re}\left[\frac{C_S - C_A}{C_H - C_A}\right] + B_A$$

- N is the calibrated spectral radiance
- B_H is the effective Planck emission for the hot blackbody
- B_A is the effective Planck emission for the ambient blackbody
- C_S is the complex spectrum for the sky view
- C_H is the complex spectrum for the hot blackbody view
- C_A is the complex spectrum for the ambient blackbody view
- Re() is the real part of the complex ratio

AERI Calibration Error Estimates

Radiometric Requirement is 0.9% of Ambient Radiance





Input Parameters			Uncertainties (3 sigma)		
wn	770	Wavenumber, [cm-1]			
Thbb	333	Temp. of Hot Blackbody, [K]	ΔThbb	0.10	[K]
Tcbb	300	Temp. of Cold Blackbody, [K]	ΔTcbb	0.10	[K]
Tstr	305	Temp. of Structure Reflecting into BB's, [K]	ΔTstr	5	[K]
Ehbb	0.999	Emissivity of HBB, [-]	ΔEhbb	0.001	[-]
Ecbb	0.999	Emissivity of CBB, [-]	ΔEhbb	0.001	[-]

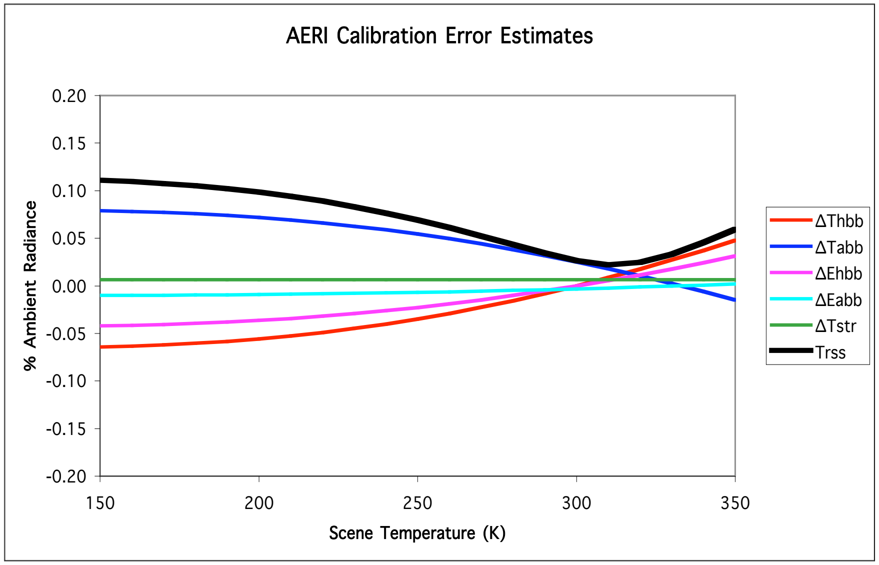
Input Parameters			Uncertainties (3 sigma)		
wn	2200	Wavenumber, [cm-1]			
Thbb	333	Temp. of Hot Blackbody, [K]	ΔThbb	0.10	[K]
Tcbb	300	Temp. of Cold Blackbody, [K]	ΔTcbb	0.10	[K]
Tstr	305	Temp. of Structure Reflecting into BB's, [K]	ΔTstr	5	[K]
Ehbb	0.999	Emissivity of HBB, [-]	ΔEhbb	0.001	[-]
Ecbb	0.999	Emissivity of CBB, [-]	ΔEhbb	0.001	[-]

Longwave: 770 cm-1

Shortwave: 2200 cm-1

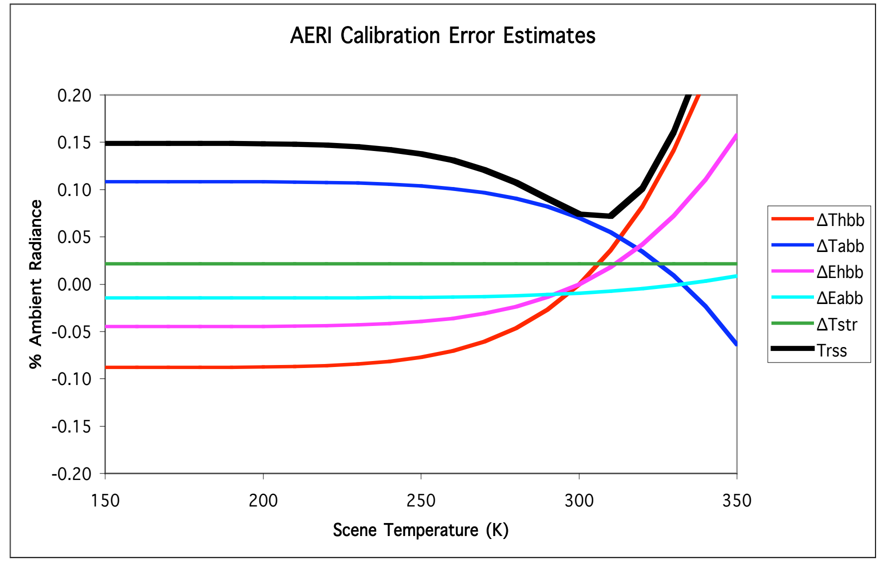
AERI Reproducibility Error Estimates

Radiometric Requirement is 0.18% of Ambient Radiance



Input Parameters			Uncertainties (3 sigma)		
wn	770	Wavenumber, [cm-1]			
Thbb	333	Temp. of Hot Blackbody, [K]	ΔThbb	0.02	[K]
Tcbb	300	Temp. of Cold Blackbody, [K]	ΔTcbb	0.02	[K]
Tstr	305	Temp. of Structure Reflecting into BB's, [K]	ΔTstr	5	[K]
Ehbb	0.999	Emissivity of HBB, [-]	ΔEhbb	0.0005	[-]
Ecbb	0.999	Emissivity of CBB, [-]	ΔEhbb	0.0005	[-]

Longwave: 770 cm-1



Input Parameters			Uncertainties (3 sigma)		
wn	2200	Wavenumber, [cm-1]			
Thbb	333	Temp. of Hot Blackbody, [K]	ΔThbb	0.02	[K]
Tcbb	300	Temp. of Cold Blackbody, [K]	ΔTcbb	0.02	[K]
Tstr	305	Temp. of Structure Reflecting into BB's, [K]	ΔTstr	5	[K]
Ehbb	0.999	Emissivity of HBB, [-]	ΔEhbb	0.0005	[-]
Ecbb	0.999	Emissivity of CBB, [-]	ΔEhbb	0.0005	[-]

Shortwave: 2200 cm-1

Blackbody Design and Calibration

Blackbody Requirements

❑ Blackbody System Requirements

- ➢ Temperature knowledge: ± 0.10 K
- ➢ Temp. gradient knowledge: better than 0.10 K
- ➢ Emissivity: > 0.998
- ➢ Emissivity knowledge: better than ± 0.1%

❑ Instrument Imposed Requirements

- ➢ BB Aperture: 6.9 cm
- ➢ Envelope: 18 cm dia. X 30 cm long
- ➢ Operating Temperature: 213 K to 333 K
- ➢ Period between cal. views: < 10 minutes

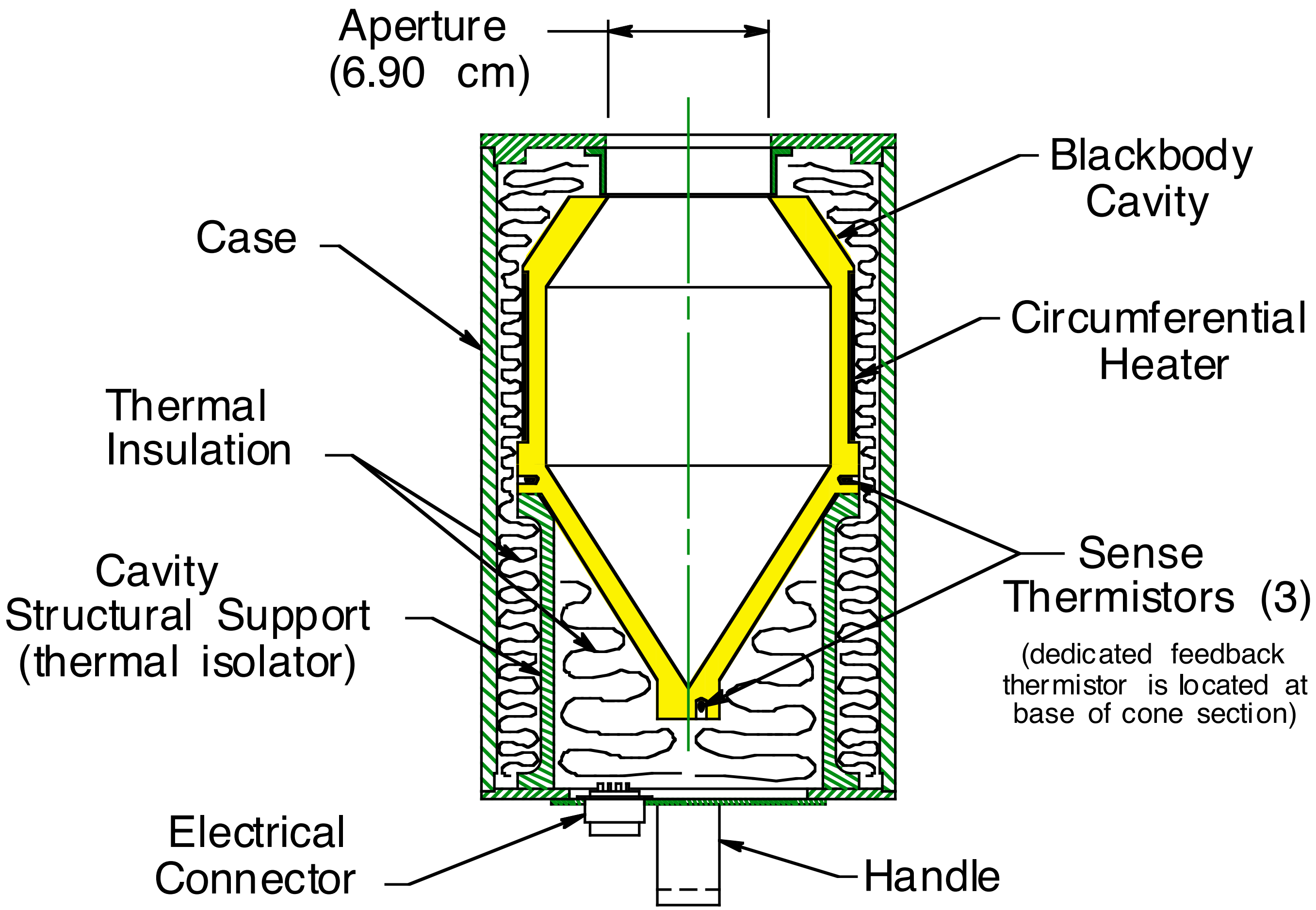
Top-level Design Choices

- **Cavity Approach**
  - Provides high emissivity (cavity factor near 40)
  - Emissivity enhancement due to cavity is well characterized
  - Cavity walls provide good conduction (low gradients)
  - Easy to manufacture

- **Chemglaze Z306 Black Paint**
  - Provides high emissivity that is well characterized and stable
  - Provides a hardy diffuse surface

- **YSI 46041 Super-stable Thermistors**
  - Very stable (< 0.01°C drift after 100 months at 70°C)
  - Easy to couple thermally to blackbody cavity
  - Reasonably rugged

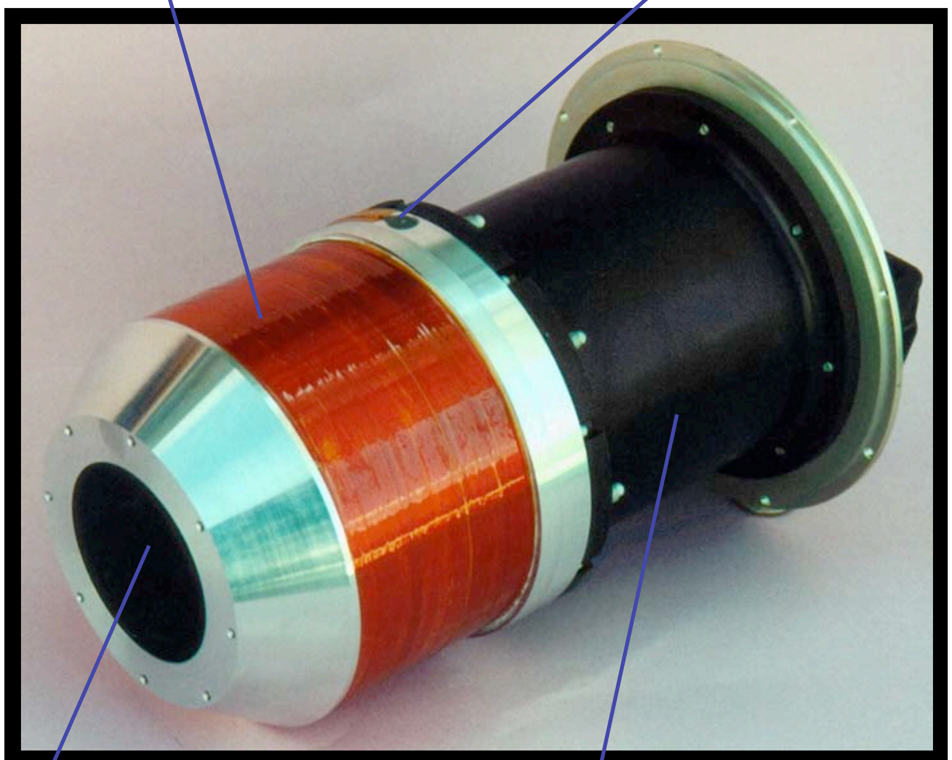
AERI Blackbody

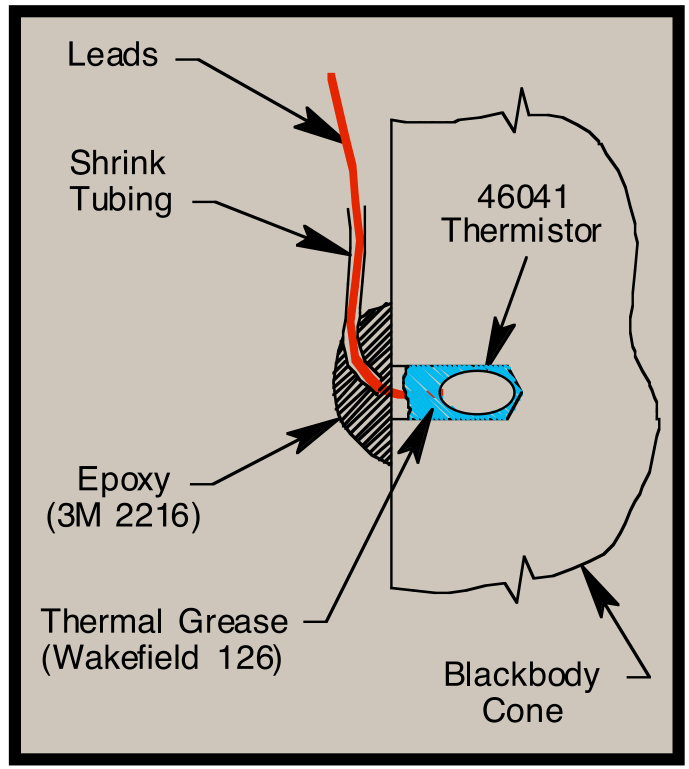


AERI Blackbody

Heater Winding

Thermistor



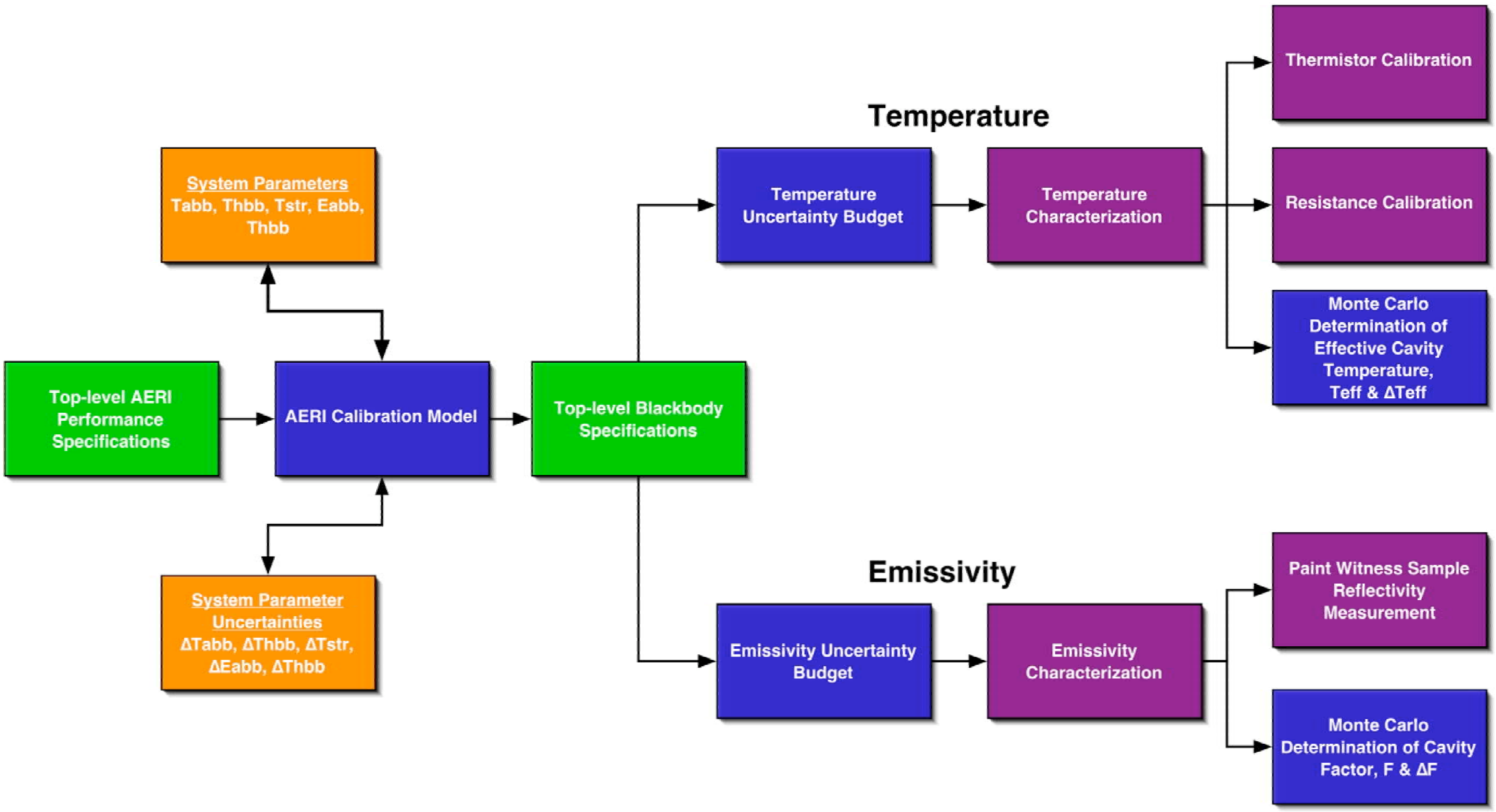


Cavity Aperture
(6.9 cm)

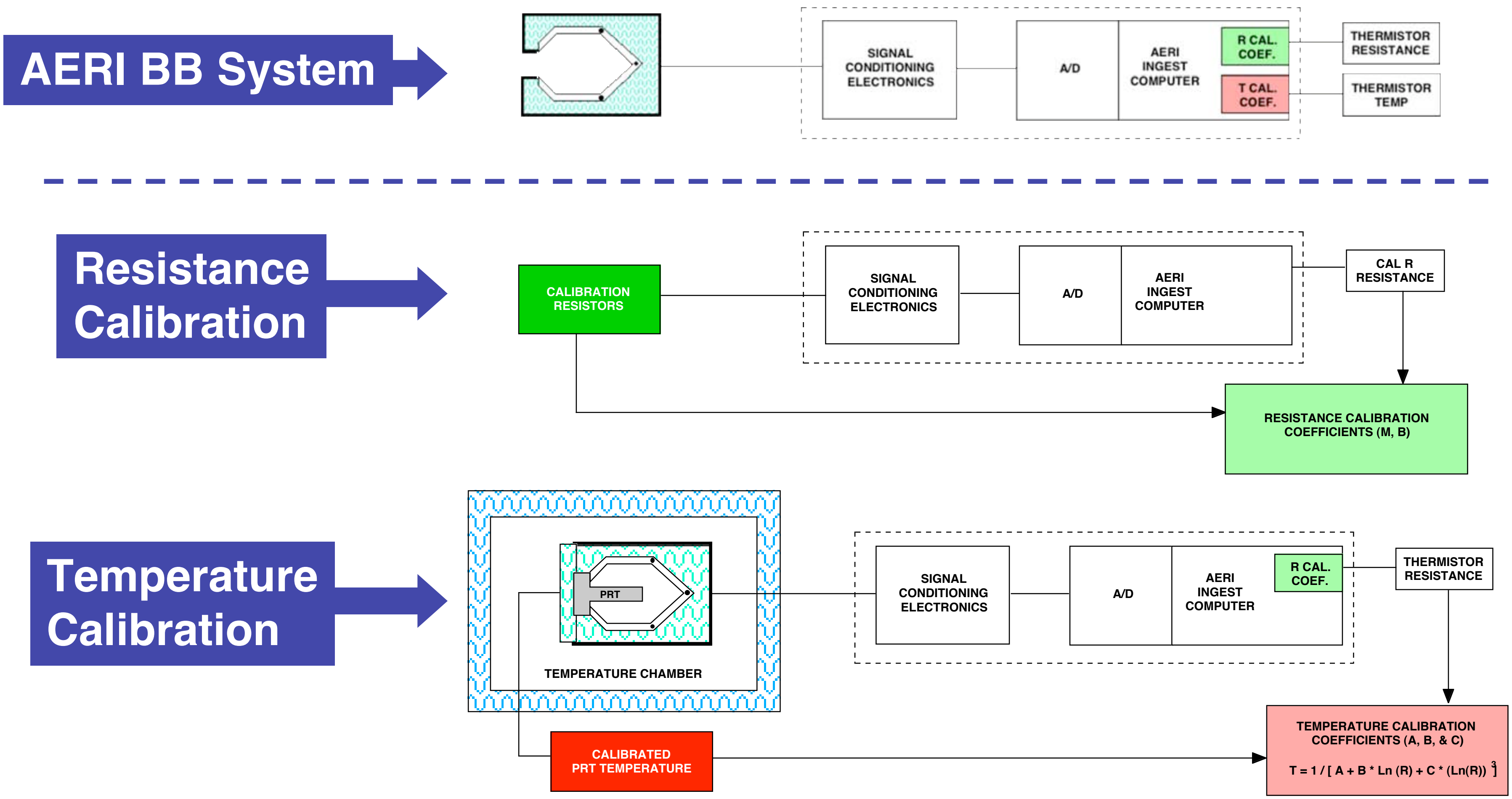
Cavity Support
(Thermal Isolator)

Thermistor Installation

AERI Blackbody Calibration Roadmap



AERI Blackbody Temperature Calibration Overview

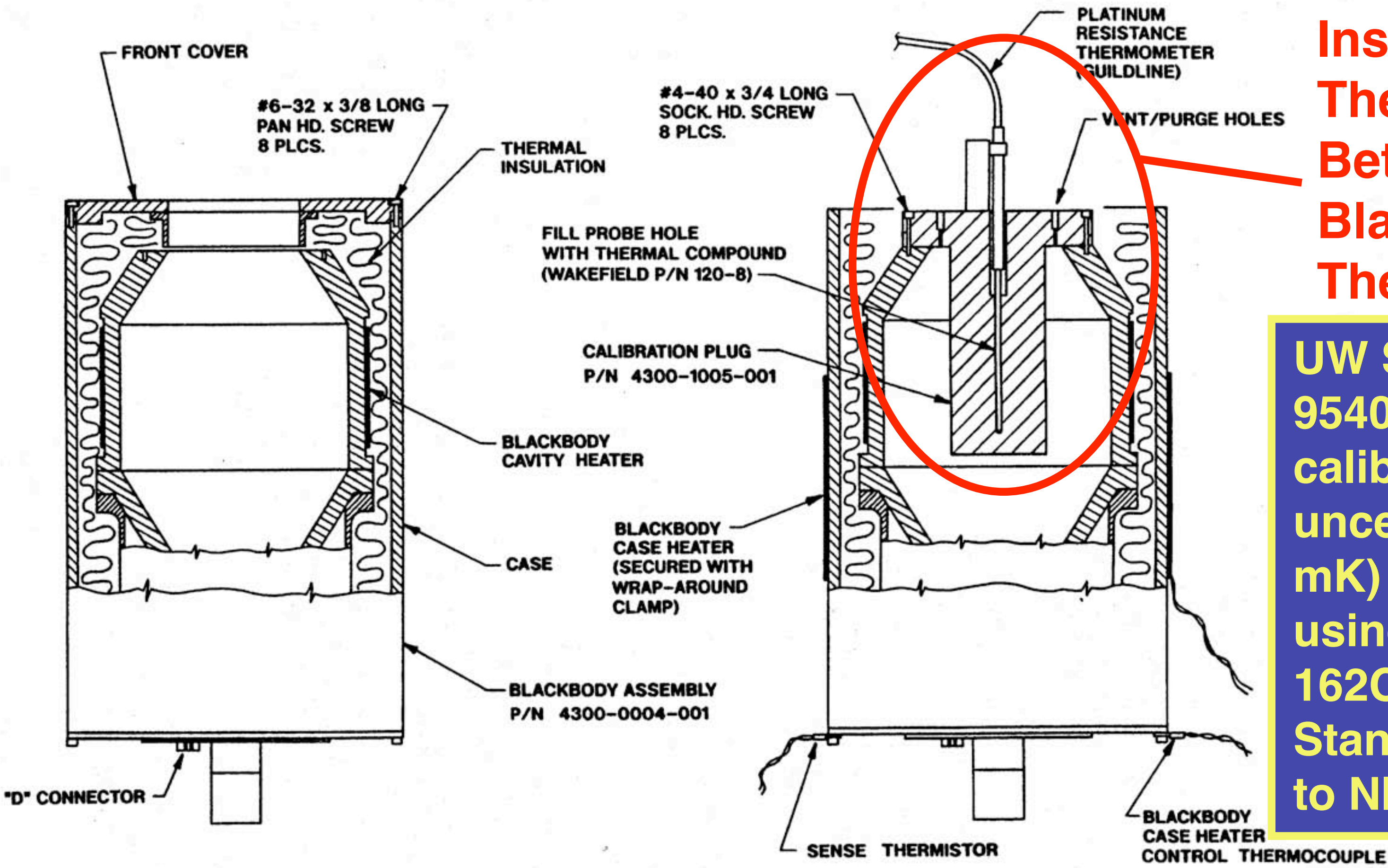


Temperature Uncertainty Budget

Slide	Item	± peak error [K]	RSS [K]
	Temperature and Resistance Reference Uncertainty		
26	Temperature Calibration Standard (Guildline PRT)	0.030	
32	Calibration Resistors	0.007	
33	Resistor Readout Electronics Residual Error	0.007	
	RSS	0.032	0.032
	Thermistor Temperature Transfer Uncertainty		
26	Temperature Gradient Between PRT and Thermistors	0.020	
28	Calibration Fitting Equation Residual Error	0.003	
	RSS	0.020	0.020
	Cavity Temperature Non-uniformity Uncertainty		
37	Azumuthal Gradients Due to Free Convection		
37	Longitudinal Gradients Due Primarily to Conduction		
37	Radial Gradients Due to Conduction, Convection, and Radiation	0.050	
29	Paint Gradient	0.030	
	RSS	0.058	0.058
	Long-term Stability		
30	Thermistor	0.050	
34	Resistance Measurement Electronics	0.030	
	RSS	0.058	0.058
	Effective Radiometric Temperature Weighting Factor Uncertainty		
36	Monte Carlo Ray Trace Model Uncertainty in Determining Teff	0.030	0.030
			0.095

XX Indicates slide number where more detailed information is presented

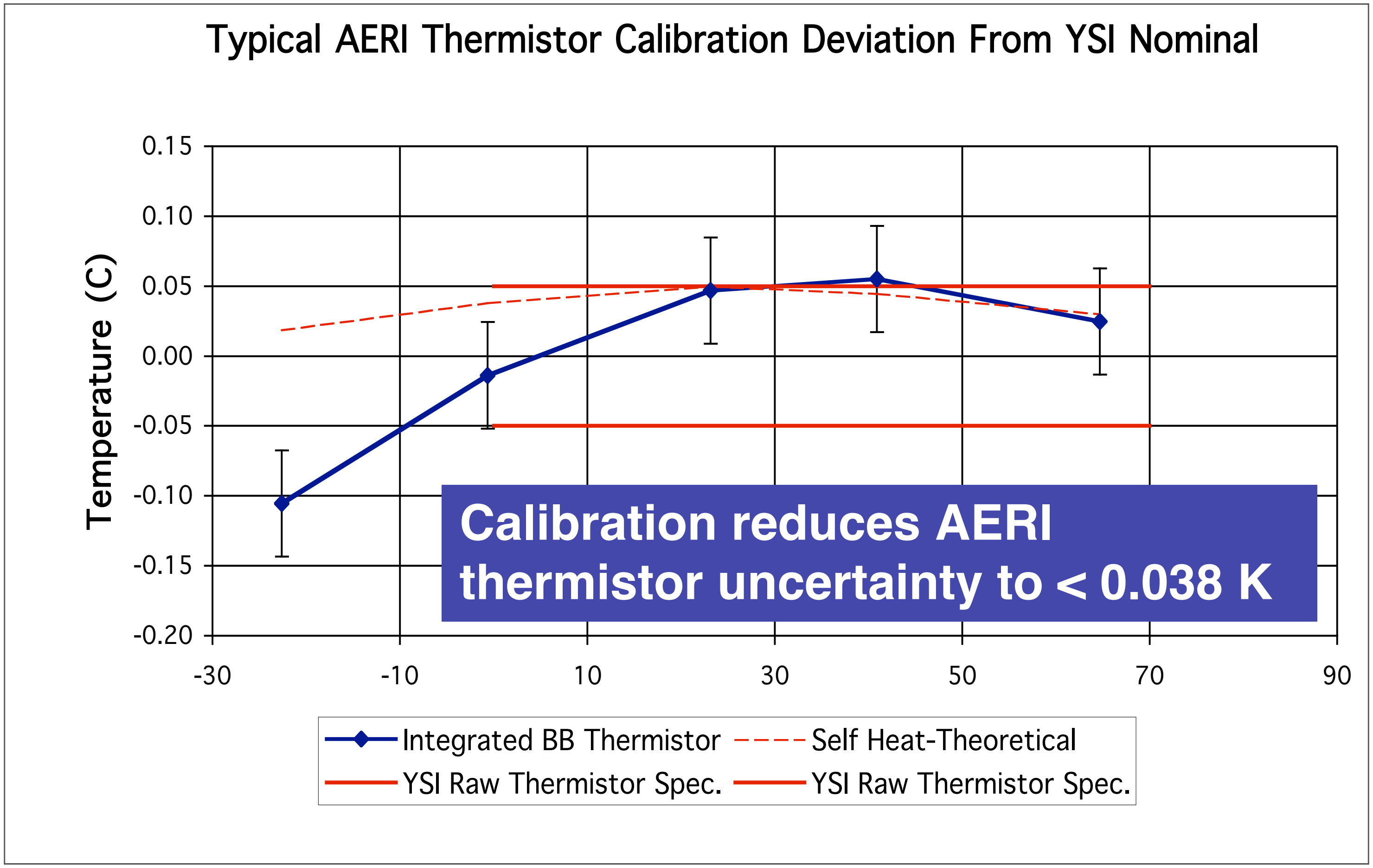
AERI Blackbody Temperature Calibration-Probe Traceability & Configuration



UW SSEC Guildline 9540 PRT is calibrated (with an uncertainty of 30 mK) at the factory using a Rosemont 162CE SPRT Primary Standard Traceable to NIST.

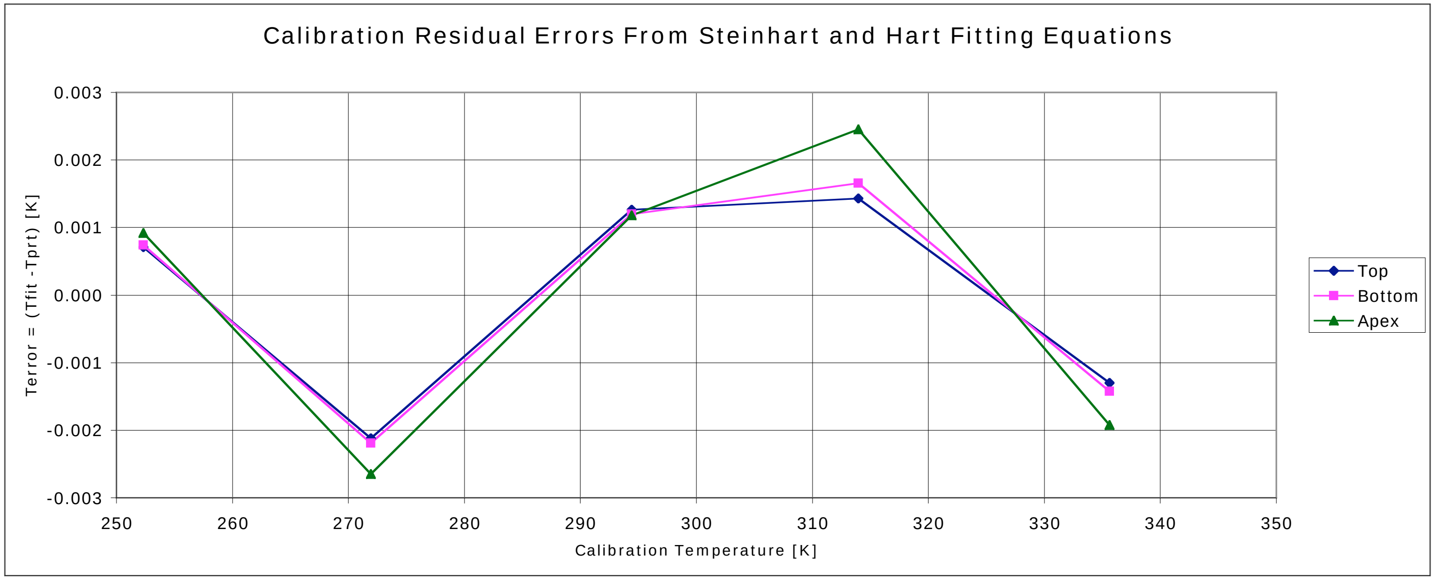
Standard Configuration **Calibration Configuration**

AERI Thermistor Calibrations Reduce Uncertainty From YSI Nominal Specification



Data from AERI Blackbody S/N 34

Thermistor Calibration Residual Errors From Regression Fit of Steinhart and Hart Equations



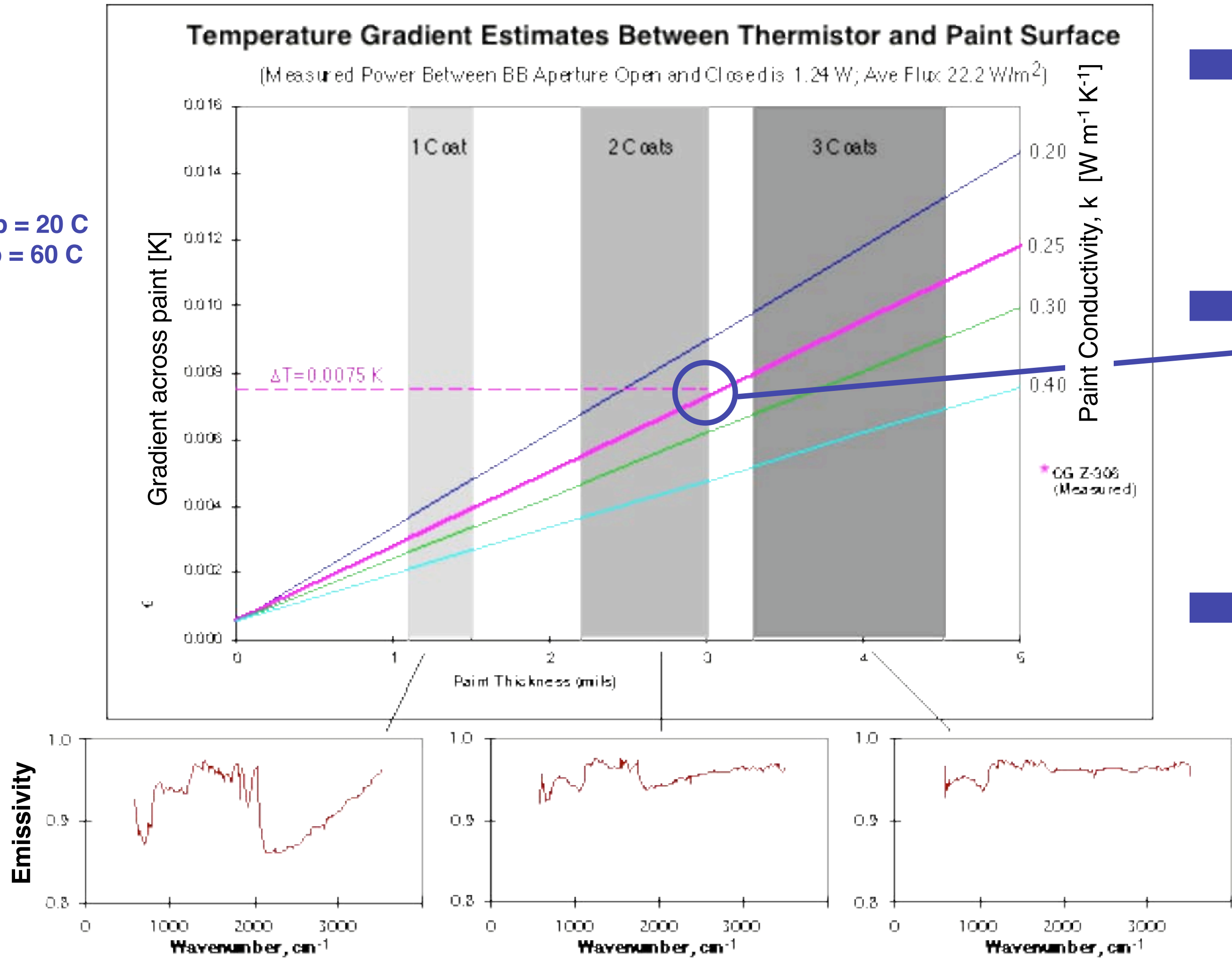
Residual Error From Fitting Equations < 3 mK

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

Data from BB S/N 24

Temperature Gradient Due to Paint Thickness

Tamb = 20 C
Thbb = 60 C



ΔT=0.0075 K results from (Th-Ta)=40 C.

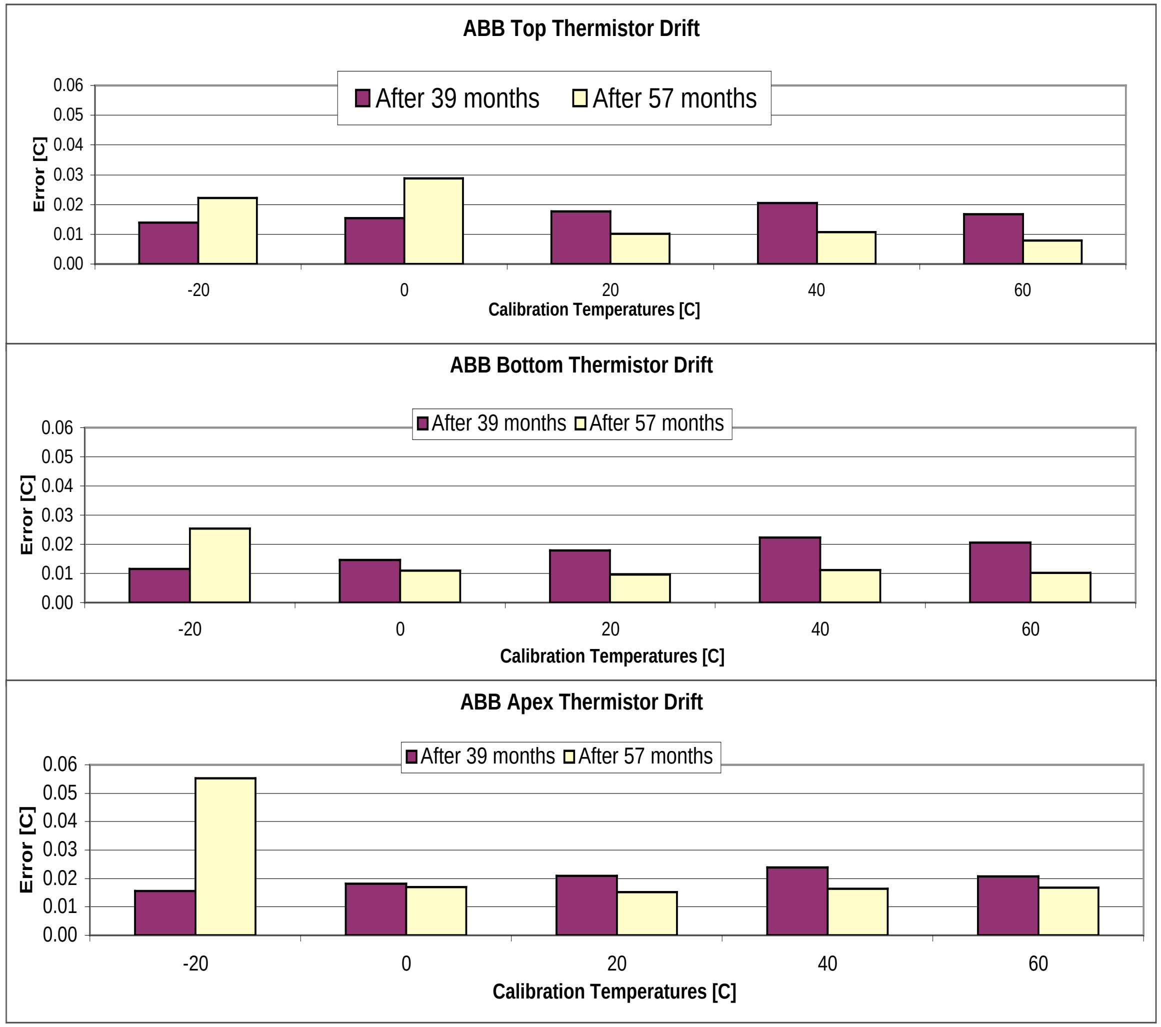
ΔT expected to be < 0.03 K for max. expected (Th-Ta)=120 C.

0.03 K is carried in the uncertainty budget

$$\Delta T=(P/A)*(t/k)$$

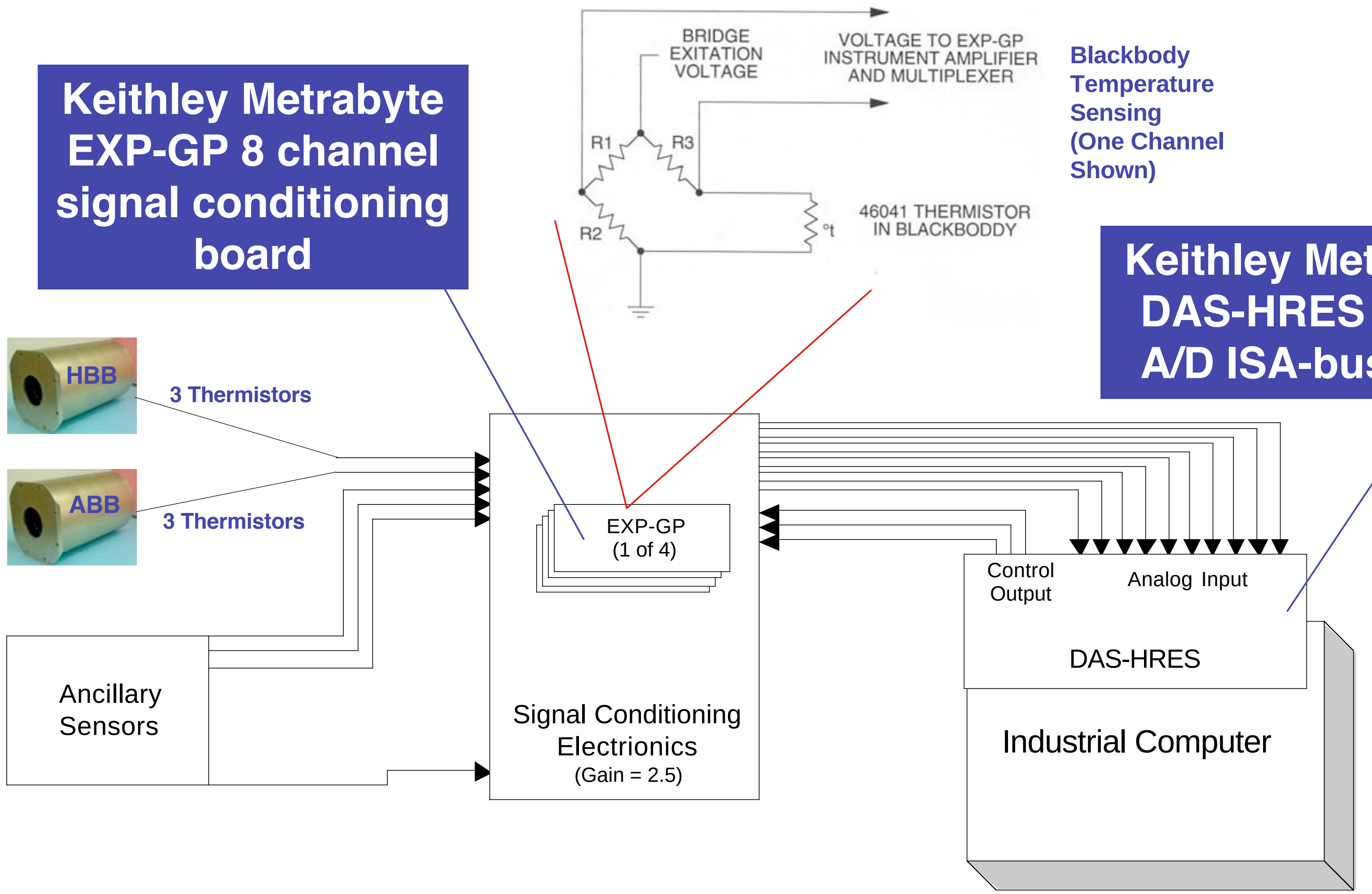
Typical Long-term Blackbody Thermistor Drift

Long-term Thermistor Drift < 0.05 K

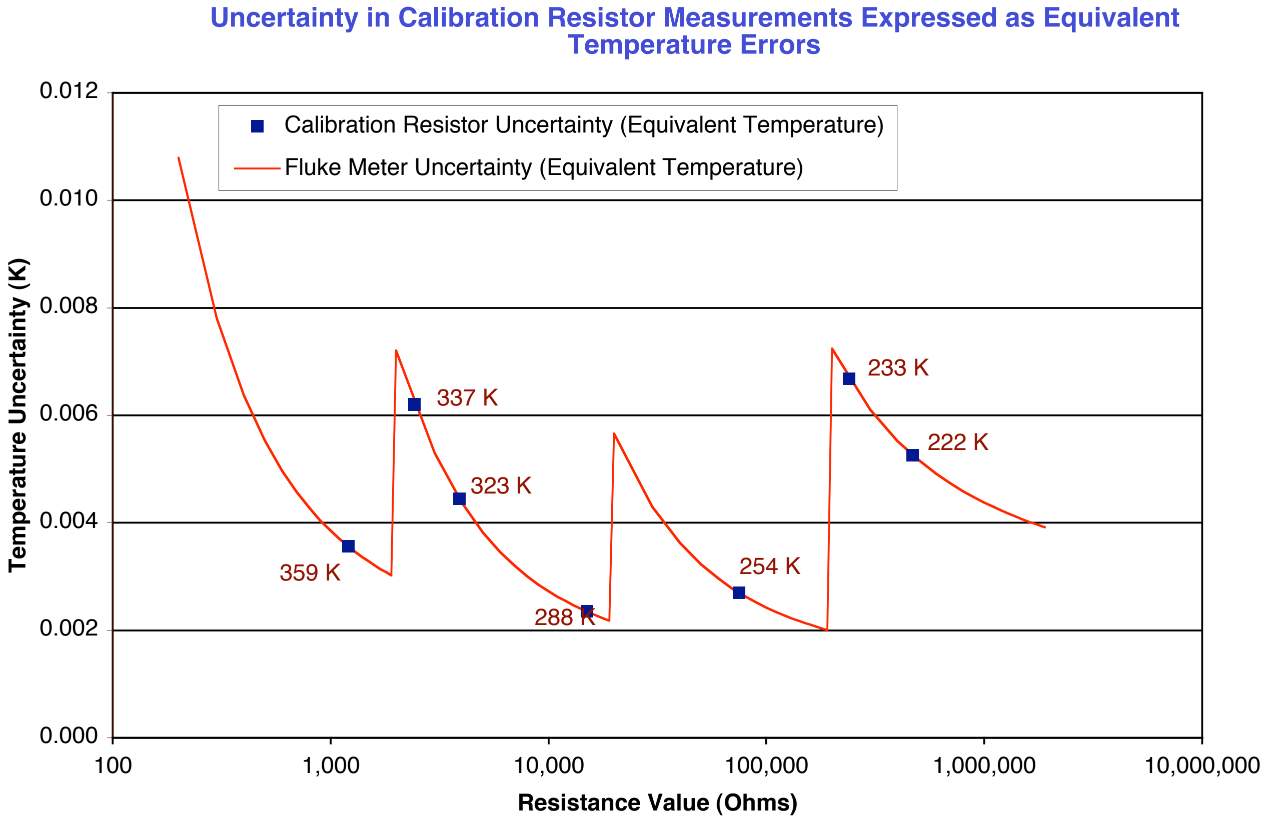


Data from AERI Blackbody S/N 24

AERI Thermistor Resistance Measurement Electronics



Calibration Resistor Traceability & Uncertainty

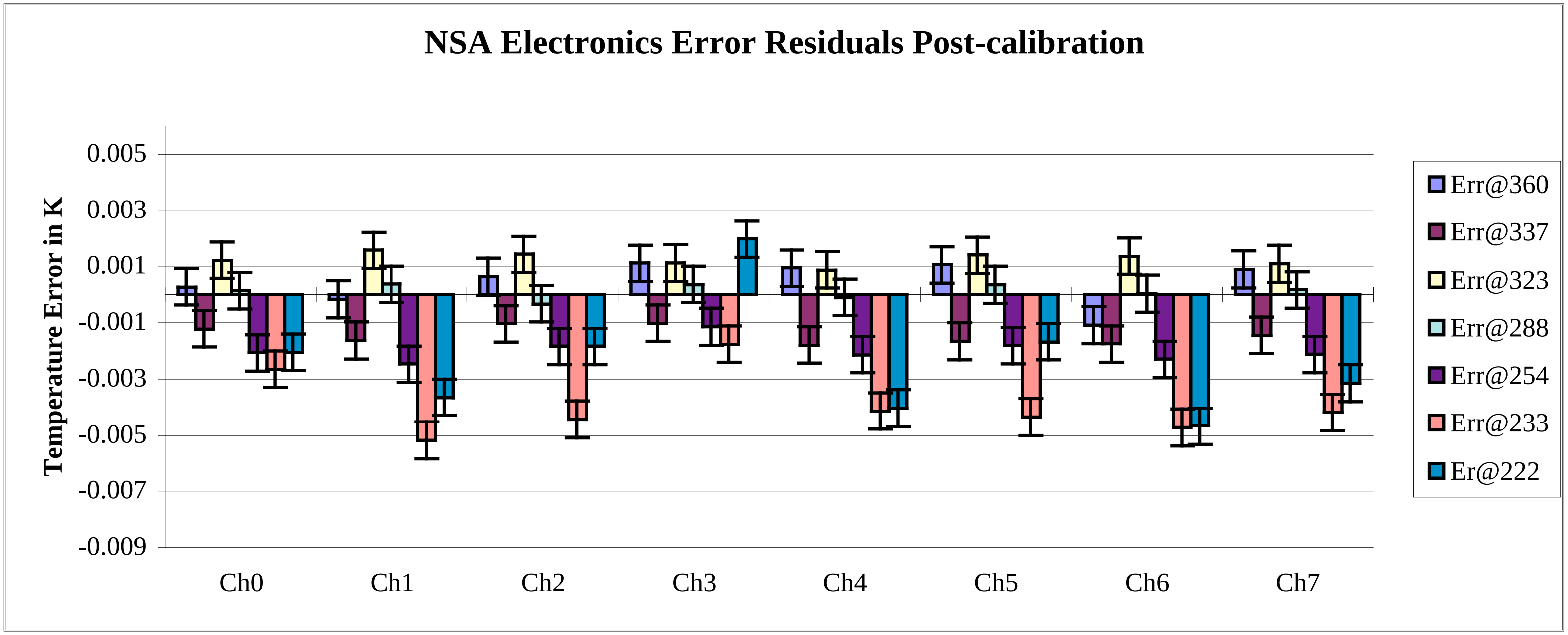


Calibration of AERI thermistor resistance measurement electronics uses precision resistors

Temperature error associated with calibration resistor uncertainty is < 7 mK

UW SSEC 8842A Fluke Meter Calibrated at Factory using a Fluke 5700A-W/03 Calibrator Primary Standard Traceable to NIST

AERI Electronics Post Calibration Residuals

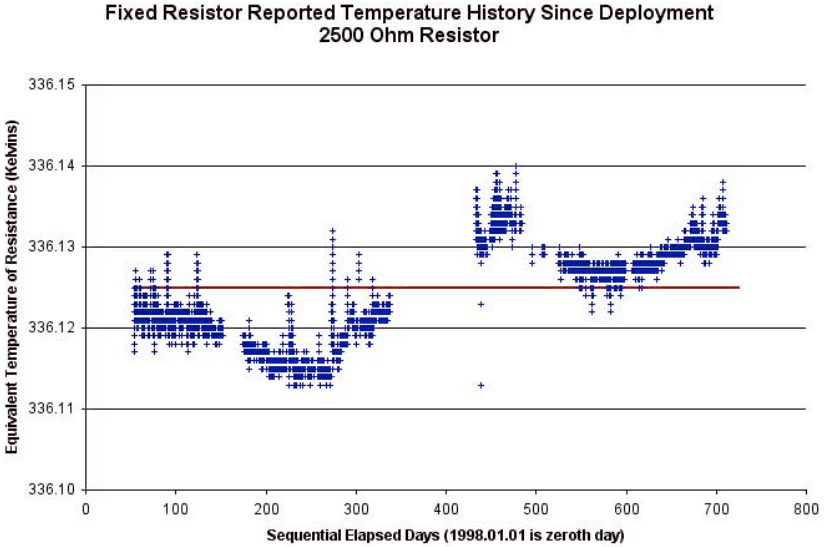


Equivalent temperature error following AERI electronics calibration is < 7 mK

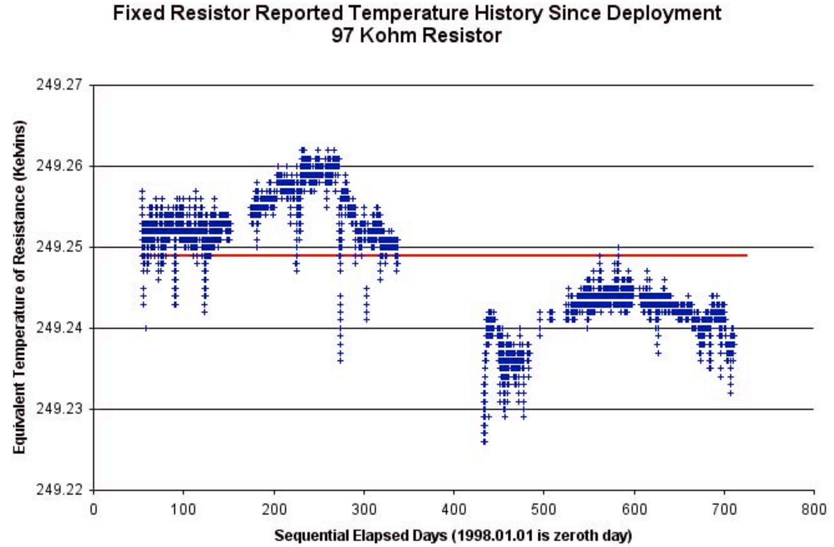
Residuals arise from linear fit in the Count Domain Transformed to the Temperature Domain

AERI Electronics Long-term Drift

Equivalent Temp of 336 K



Equivalent Temp of 249 K



Temperature Error Associated With Long-term Drift of the Electronics is < 0.030 K

Emissivity Uncertainty Budget

Slide		Uncertainty (3 sigma)	Note	for Ep=0.94 f=39	ΔEc	ΔEc (3 sigma)
36	**Paint Witness Sample Measurement**	1.5% Ep	[1]	ΔEp=0.0141	(1/f)*ΔEp	0.00036
36	**Paint Application Variation**	1.0% Ep	[2]	ΔEp=0.0094	(1/f)*ΔEp	0.00024
36	**Long-term Paint Stability**	2.0% Ep	[3]	ΔEp=0.0188	(1/f)*ΔEp	0.00048
39	**Cavity Factor**	30% f	[4]	Δf=11.7	(1-Ep)/f^2*Δf	0.00046
					RSS	0.00080

Notes:

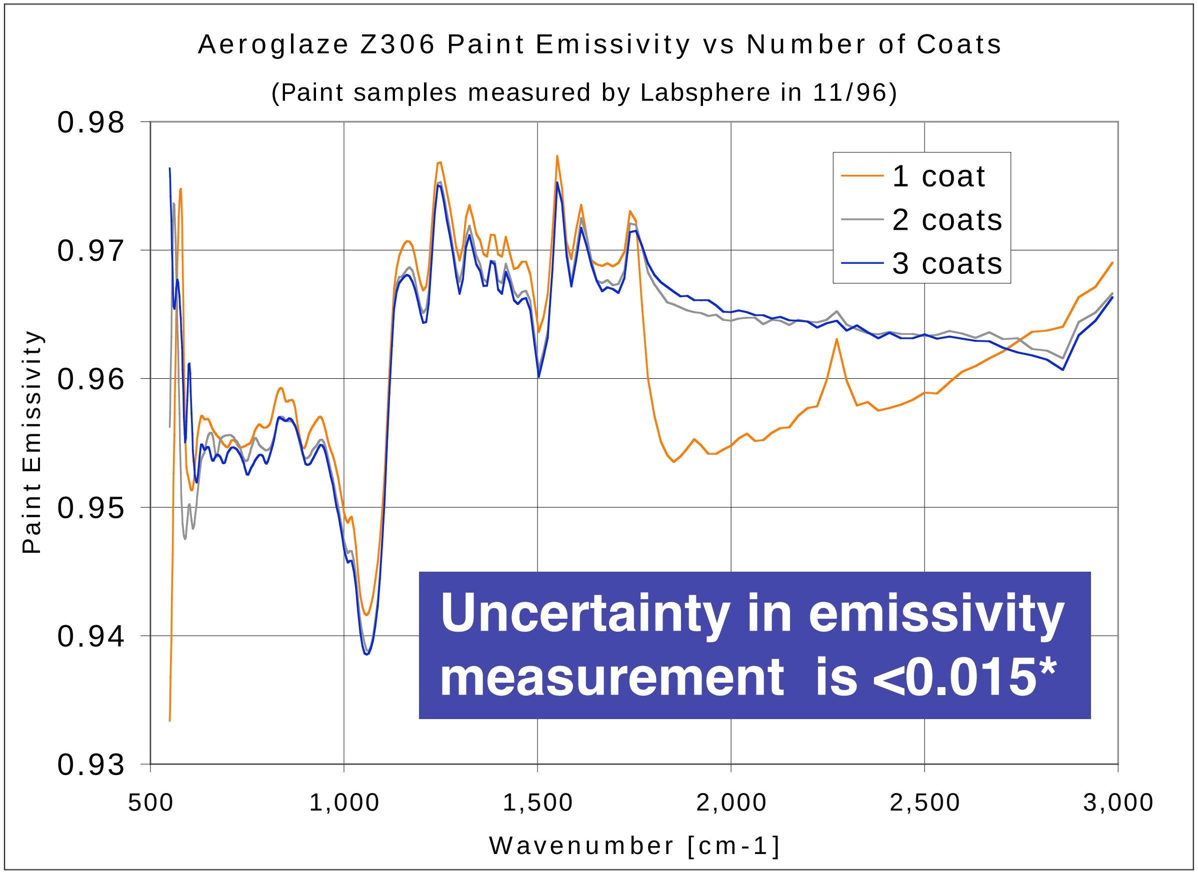
[1] Factor of 4 higher than NIST* for 2 sigma. Another factor of 1.5 to get to 3 sigma.
[2] Worst case difference between 1 and 3 coats
[3] 2 x above
[4] Accounts of Cavity Model Uncertainty

* NIST Stated accuracy is 4% of Reflectivity (2 sigma)

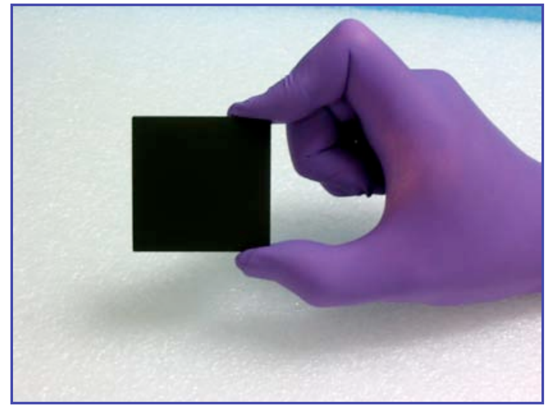
XX **Indicates slide number where more detailed information is presented**

f=(1-Ep)/(1-Ec)
f=Cavity Factor
Ep=Emissivity of Paint
Ec=Emissivity of Cavity

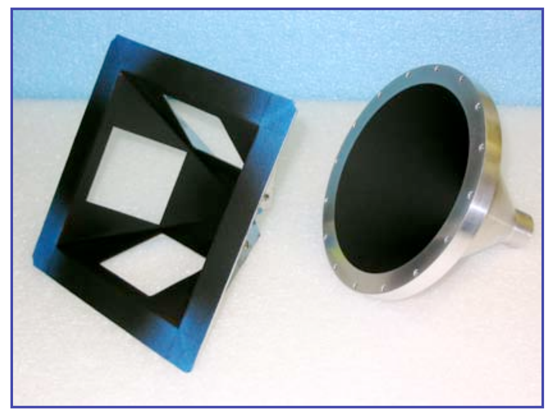
Paint Emissivity Measurement



**Labsphere does not state accuracy for high emissivity samples. Stated value is conservative. By comparison, NIST stated accuracy for this measurement is < 0.004.*



Blackbody Paint Witness Sample



Witness Sample Holder "Mimics" Blackbody Cone Geometry

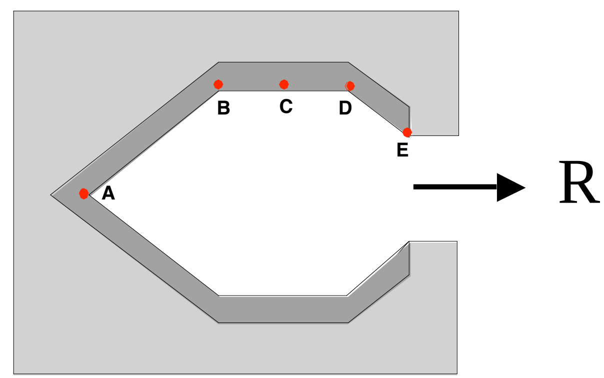
Emissivity Characterization From Monte Carlo Modeling

- Emissivity better than 0.998
- Emissivity knowledge: better than 0.001

$$R = \epsilon * B(T_{eff}) + (1-\epsilon)*B(T_{refl})$$

$$T_{eff} = w_1 * T_A + w_2 * T_B$$

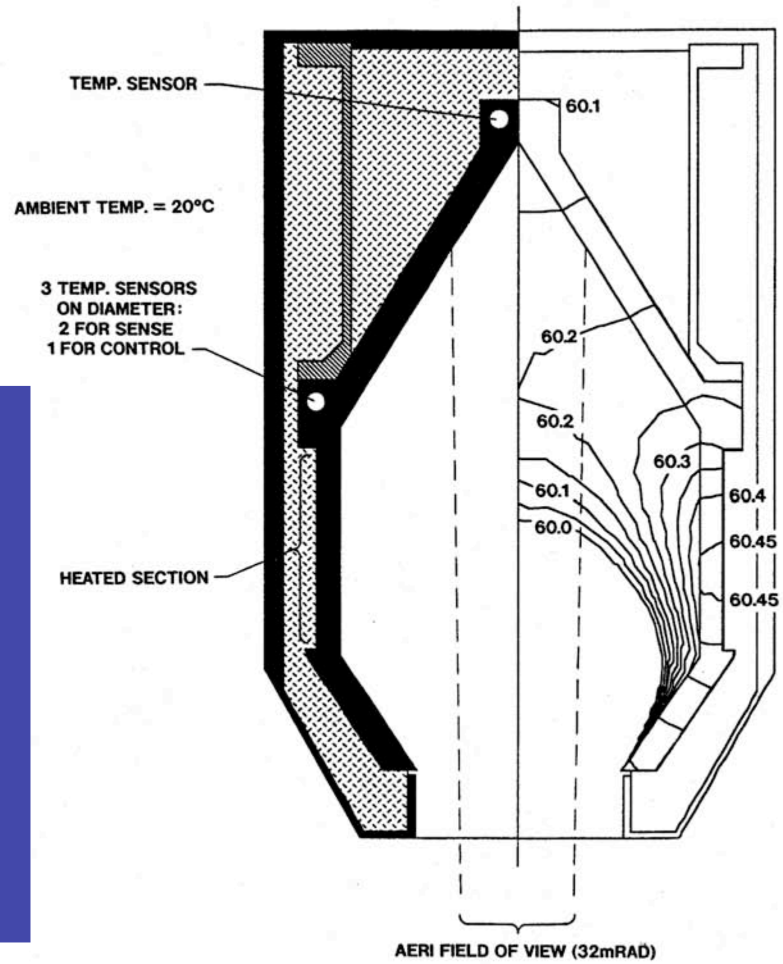
B(T) = Planck radiance at T



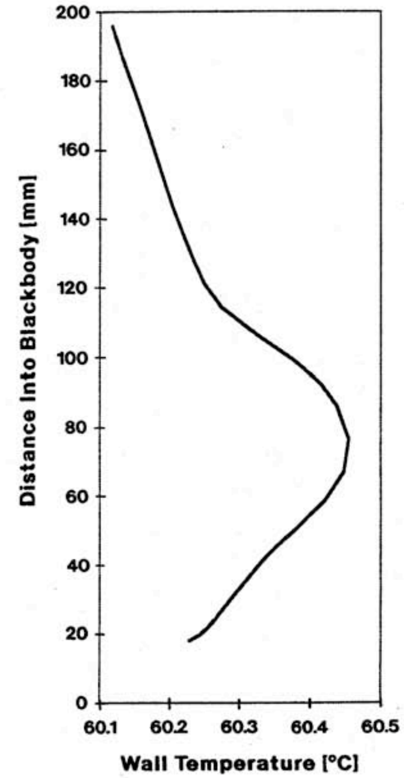
ϵ, w_1, and w_2 are computed using a Monte Carlo based cavity model

Model of Thermal Gradients in Blackbody

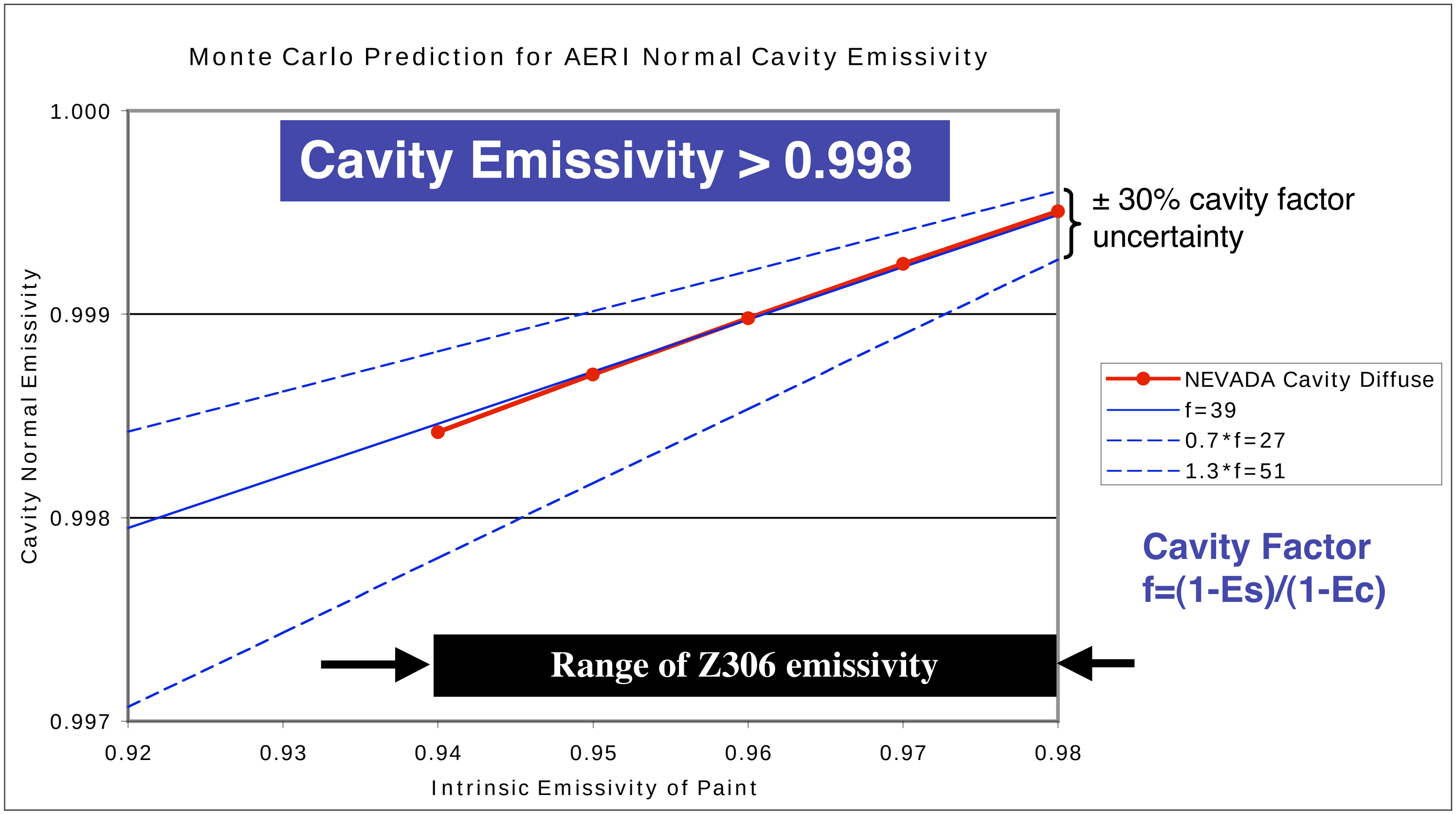
Temperature distribution used in Monte Carlo ray-trace determination of Teff



Tamb = 20 C
Thbb = 60 C

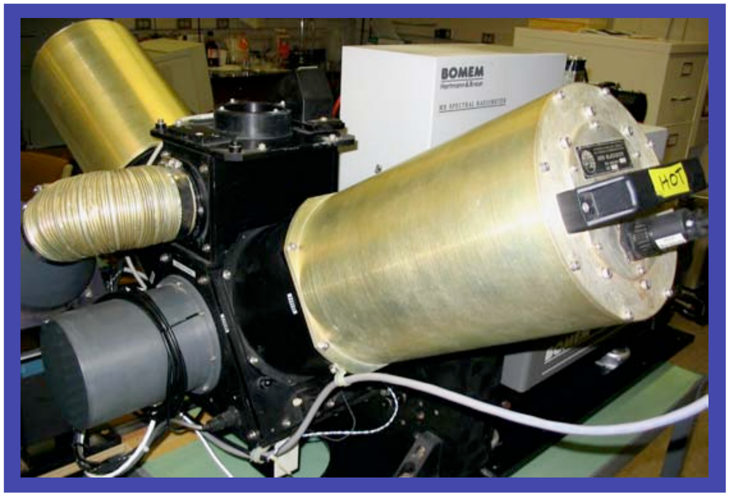


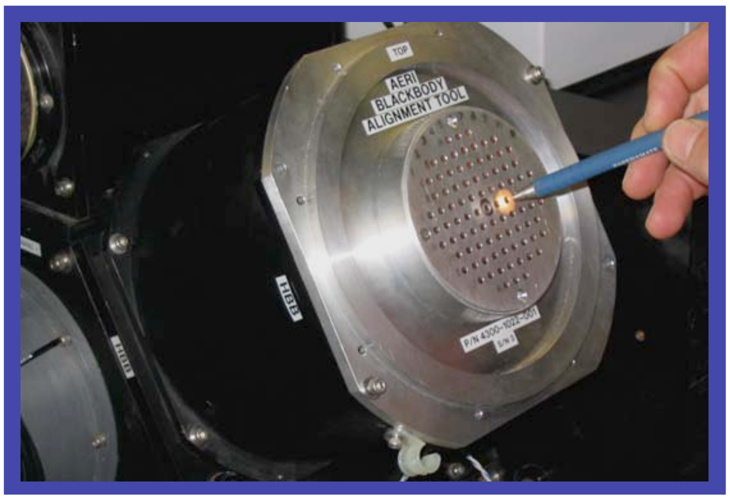
Monte Carlo Predictions of AERI Blackbody Cavity Emissivity (Diffuse Paint)

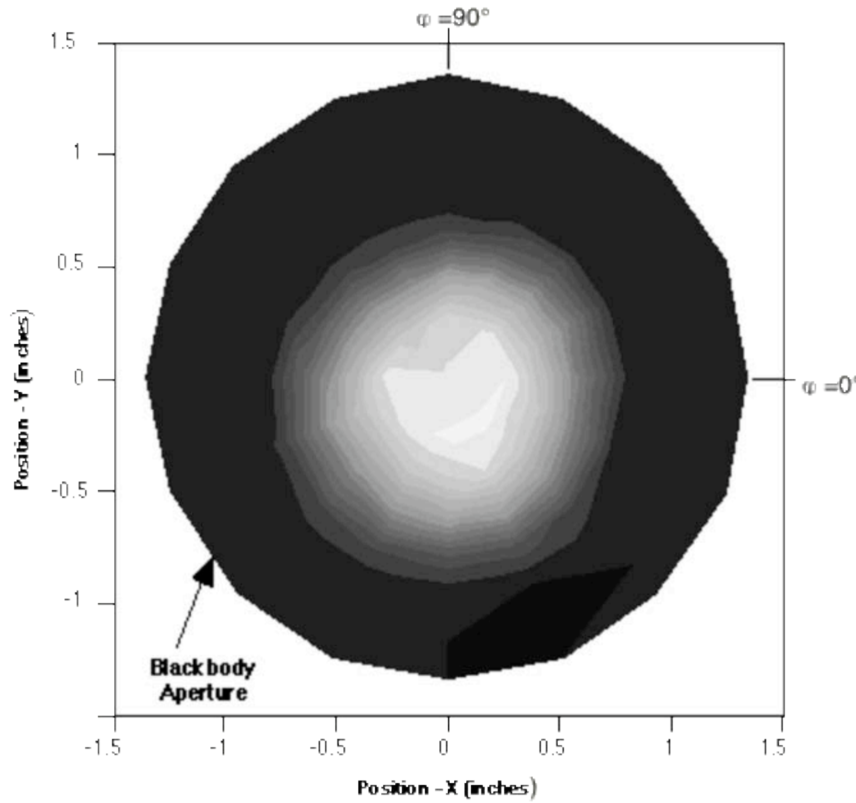


Deviations from the diffuse paint assumption equivalent to 20% specularity are within the cavity factor uncertainty of 30%.

AERI Radiometric FOV at Blackbody



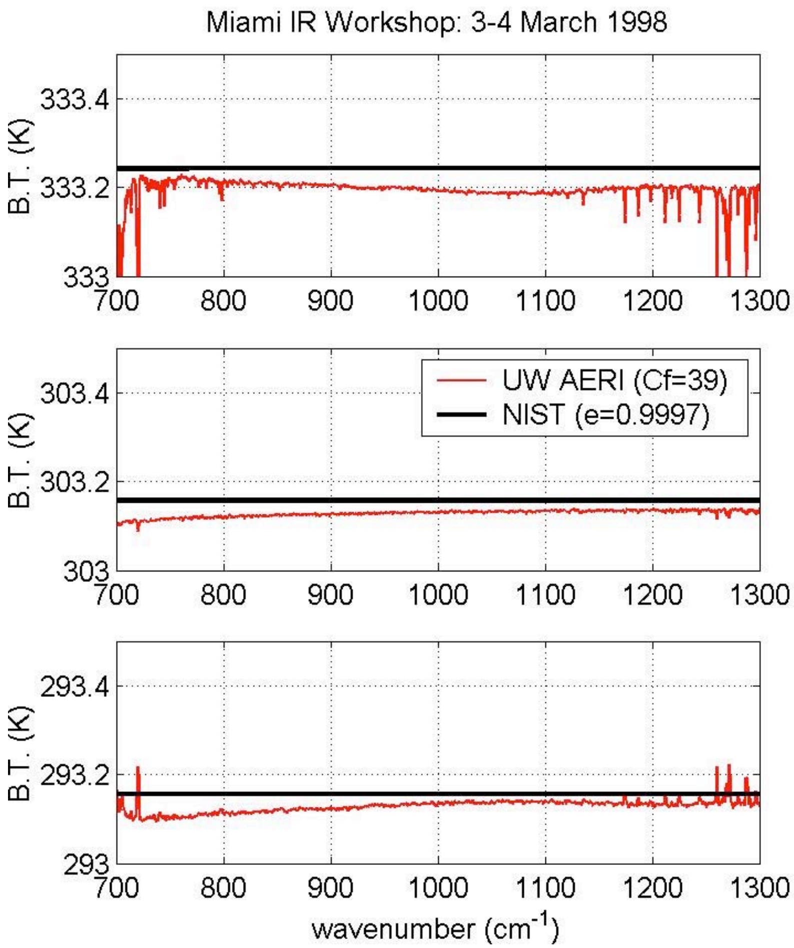




Radiometric Field-of-view is verified at the position of the blackbody aperture

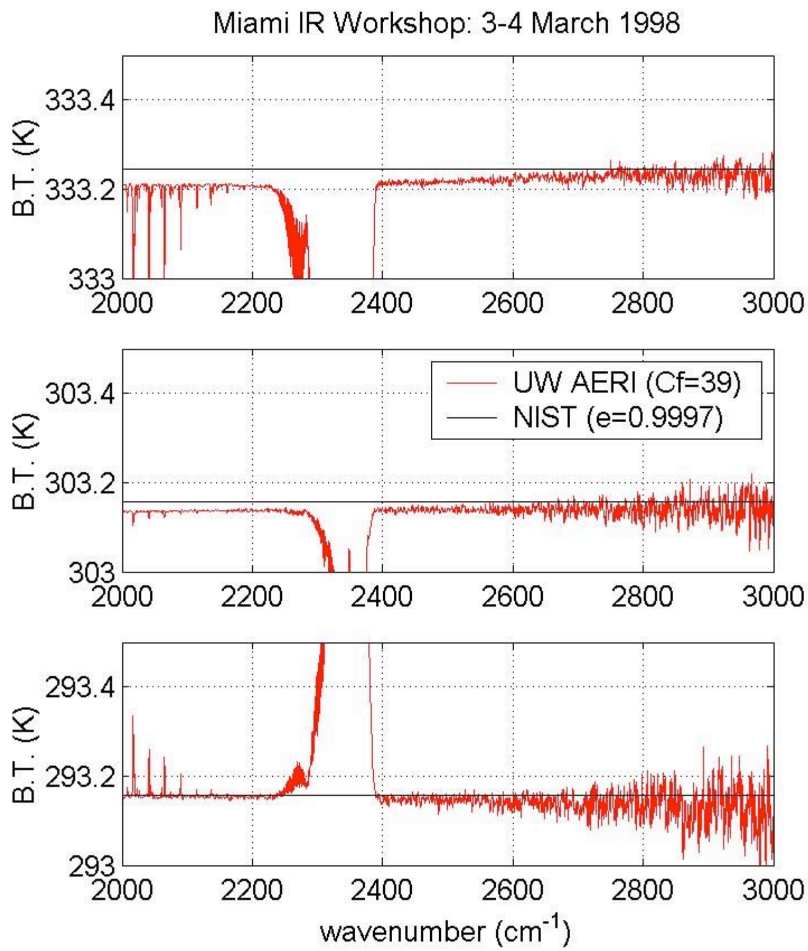
Instrument End-to-end Performance

AERI / NIST 3rd Generation Water-bath Based Blackbody Intercomparison - LW



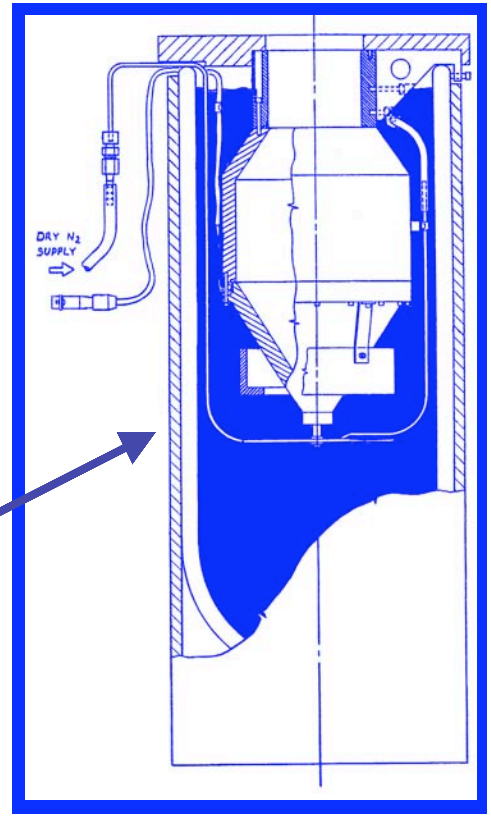
Max Error @ 333 K <0.055K
Max Error @ 303 K <0.050K
Max Error @ 293 K <0.050K

AERI / NIST 3rd Generation Water-bath Based Blackbody Intercomparison - SW

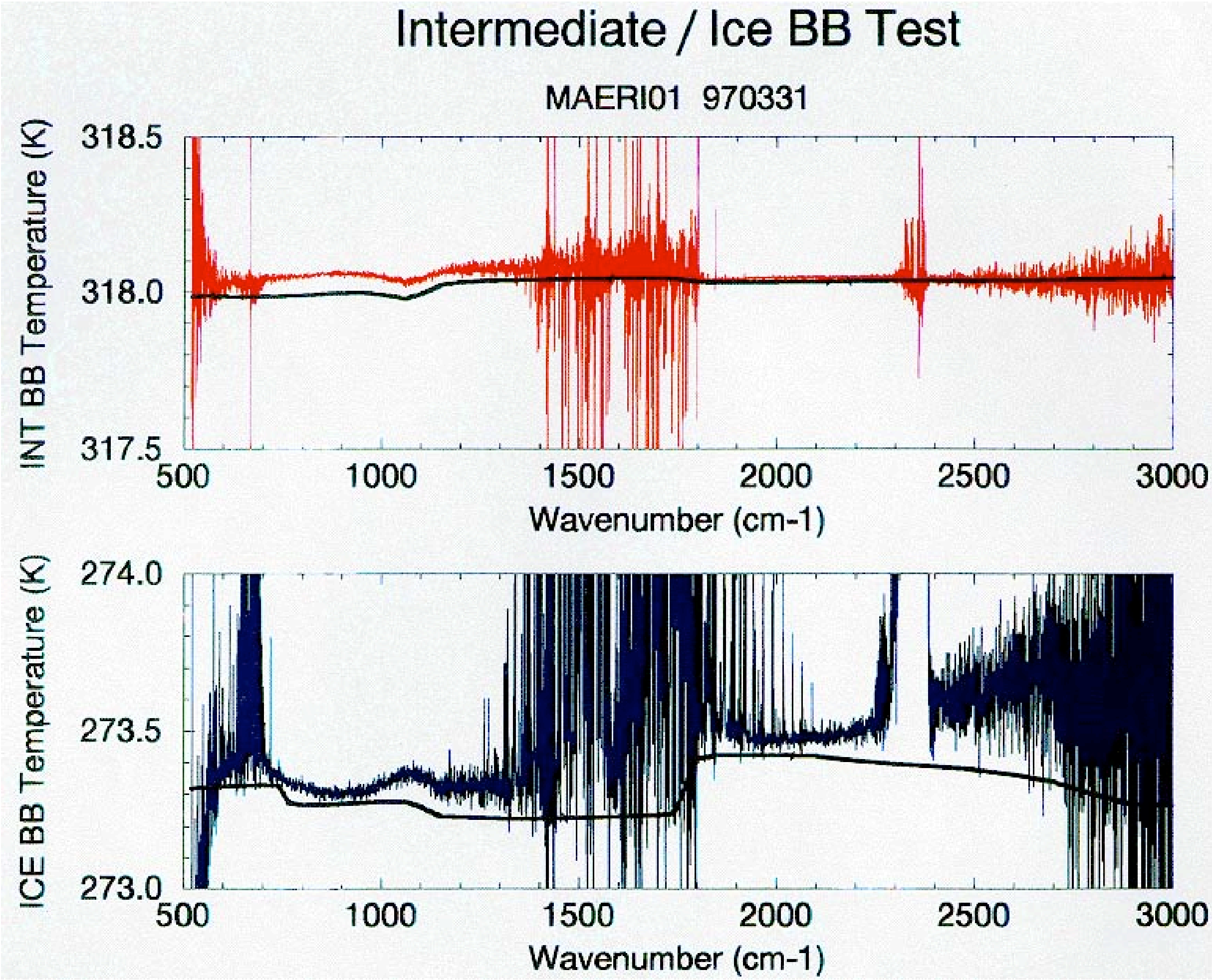


Max Error @ 333 K <0.035K
Max Error @ 303 K <0.025K
Max Error @ 293 K <0.035K

AERI Instrument End-to-end Radiometric Calibration Configuration

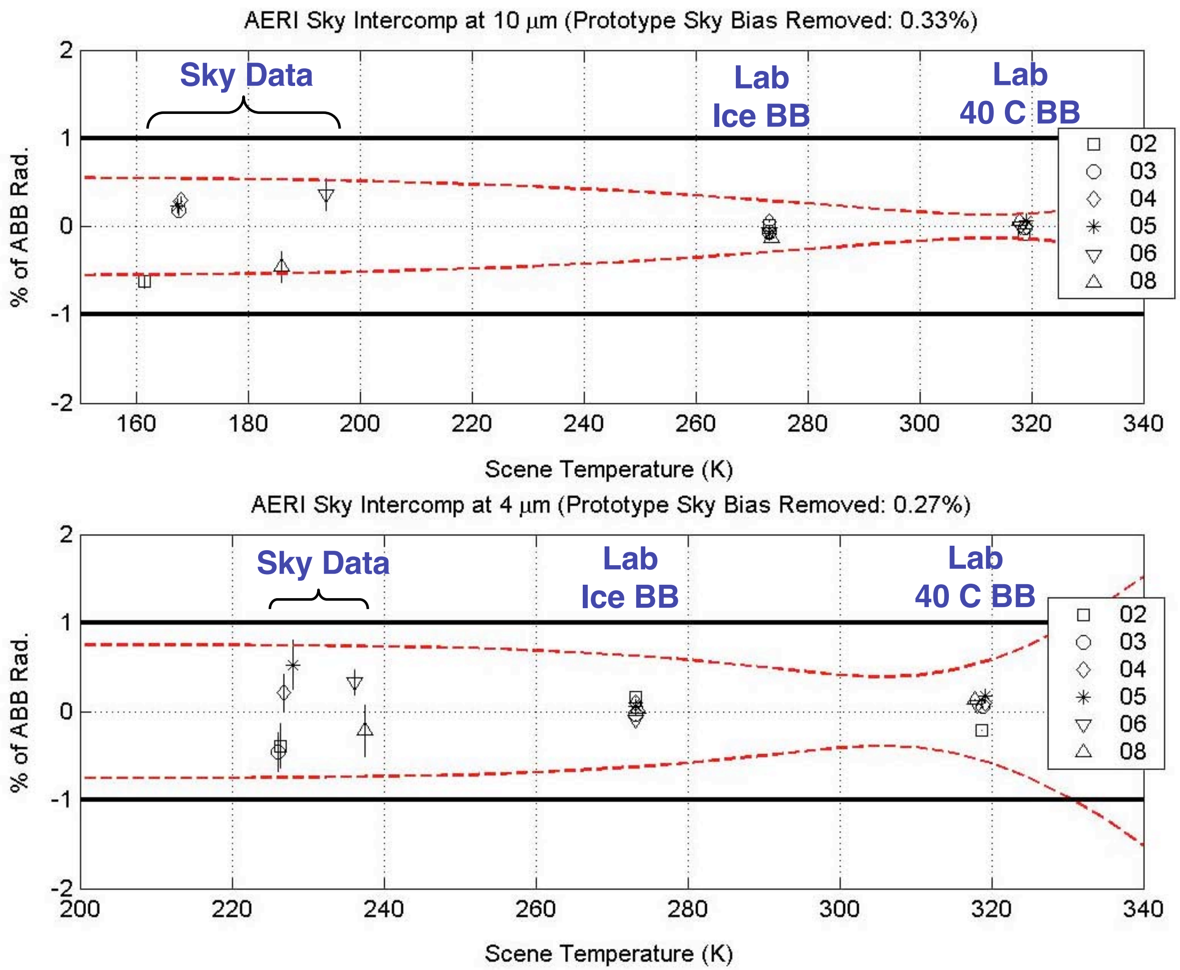


AERI Instrument End-to-end Radiometric Calibration



General Agreement Better Than 0.1 K

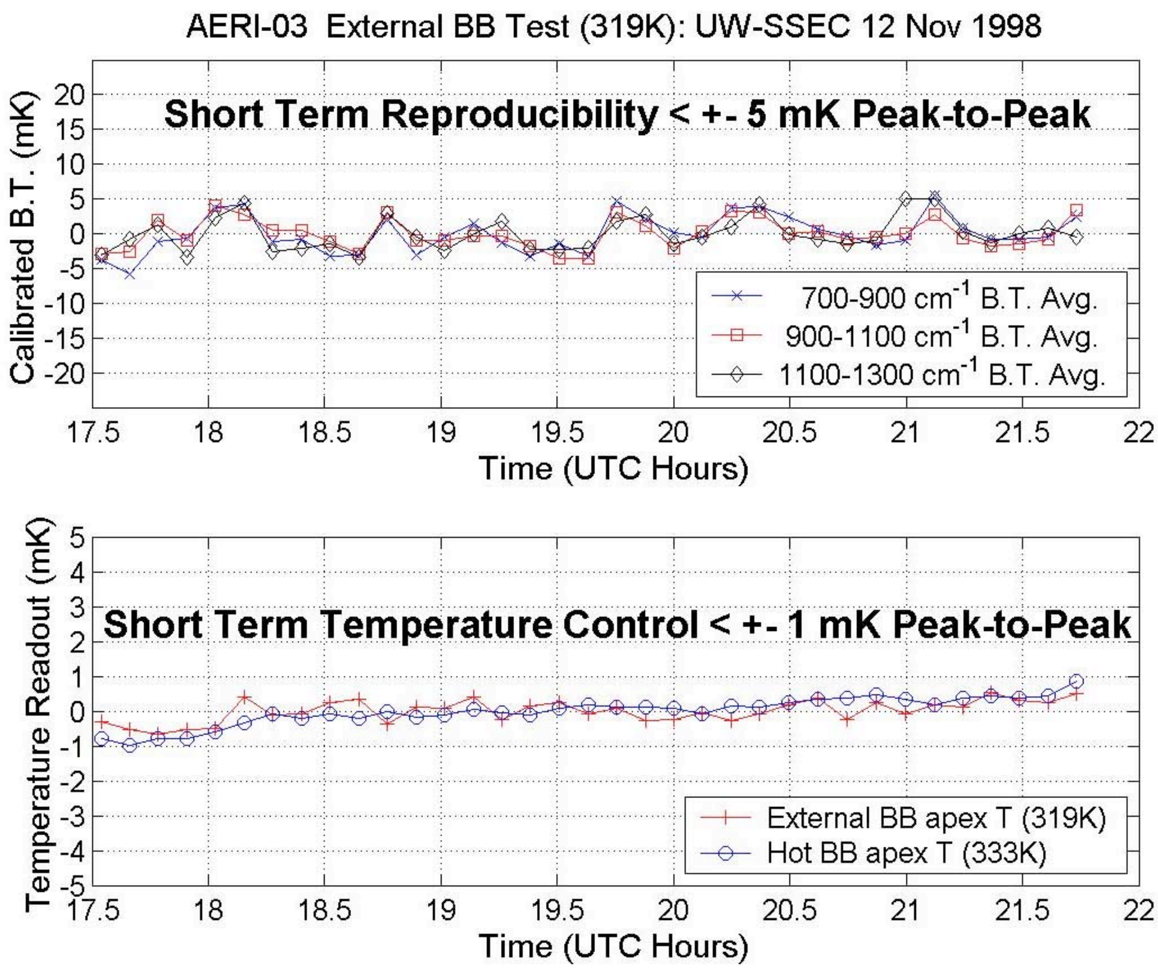
Calibration Variability Among 6 AERIs



AERI Radiometric Model Accurately Predicts Performance

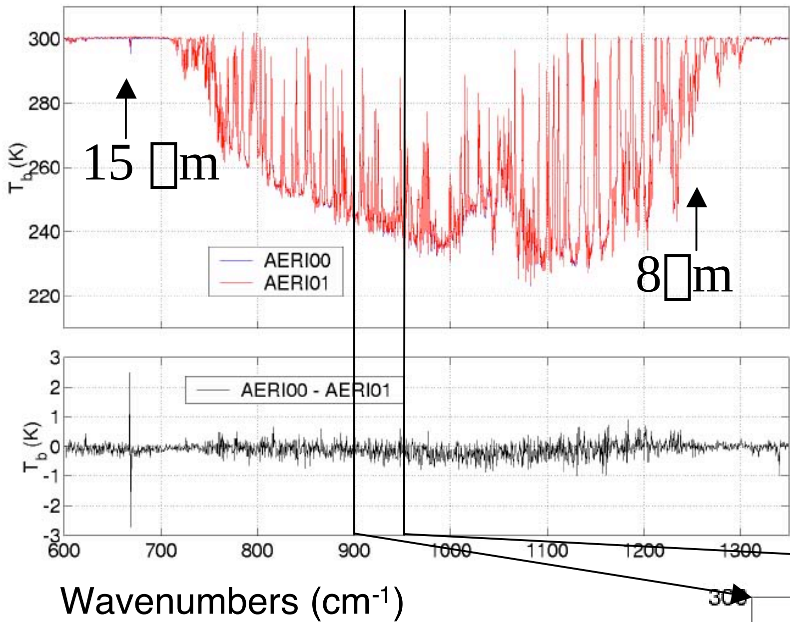
1% Specification
Calibration Model

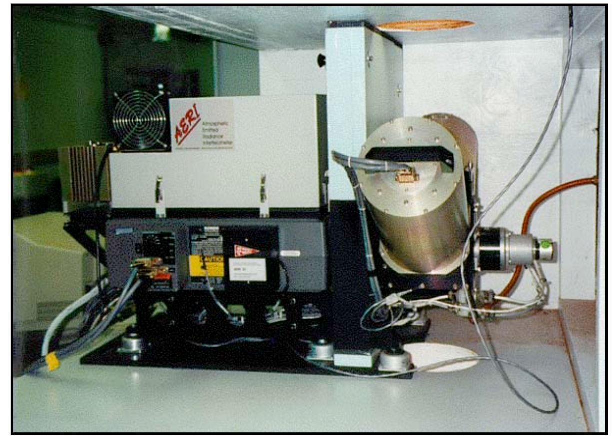
AERI Short Term Reproducability



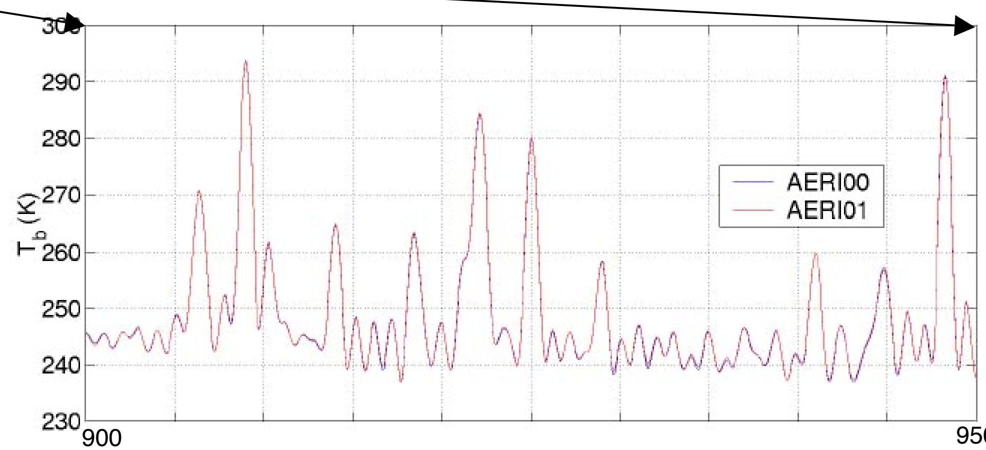
AERI stability better than 5 mK over a period of 4 hours

AERI Spectra Showing Reproducibility

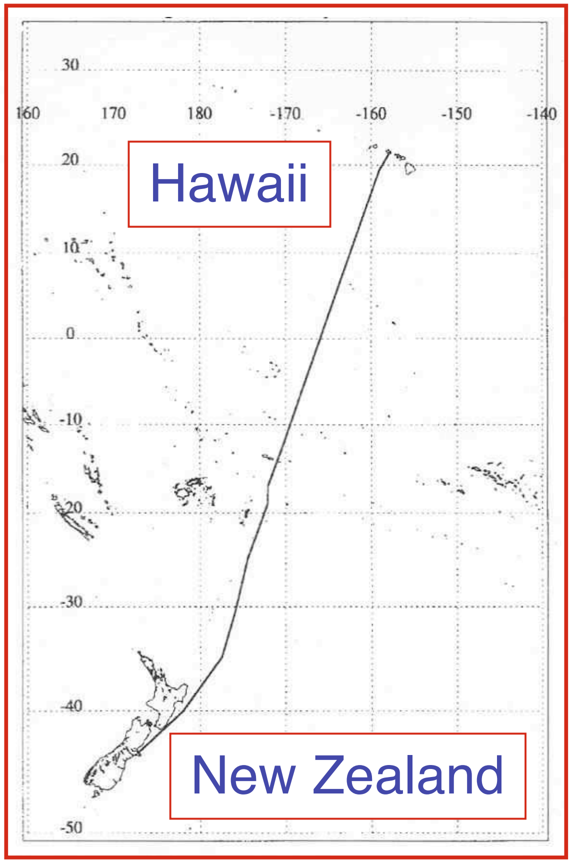




Brightness Temp Overlay of 2 Observations

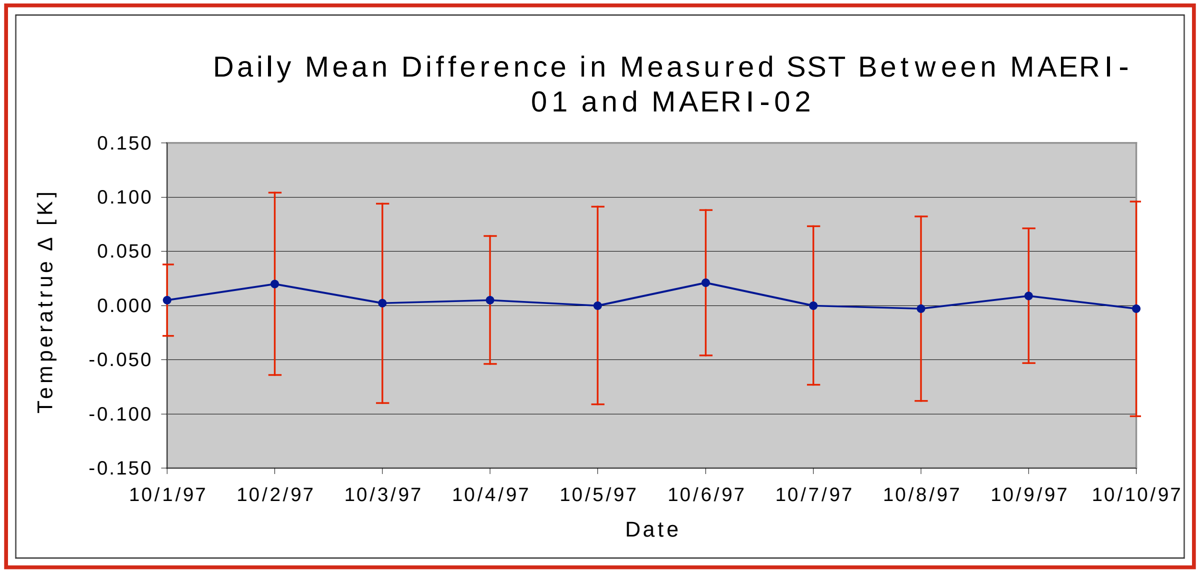


Intercomparison of Two MAERIs Measuring Sea Surface Temperature



Track of the R/V Roger Revelle
28 Sept. - 14 Oct. 1997

16 Day Cruise



Largest Daily Mean Difference: 0.020 K
Ten Day Mean Difference: 0.005 K

Summary

Summary

- The AERI is a robust well calibrated spectroradiometer with a demonstrated absolute radiometric accuracy better than 1% of ambient radiance, making it an especially valuable tool for climate and remote sensing applications.
- The AERI Calibration Blackbody performance and calibration methodology with Traceability to NIST have been verified.
- Success of the AERI has led to the use of the same concept for aircraft instruments (S-HIS and NAST) and for the advanced geostationary sounder (GIFTS). *[see Dave Tobin and John Elwell, CALCON 2003]*