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

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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 CO2, H2O, 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 3rd 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 emissivity 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

Slide 6

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Radiometric Calibration of AERI
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
AERI Front-end Assembly

Interferometer Assembly with Blackbodies

Front-end Port for Scene Mirror Assembly

Detector with Stirling Cooler

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**

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Absolute</th>
<th>Reprod.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Non-linearity Correction</td>
<td>0.2%</td>
<td>0.05%</td>
</tr>
<tr>
<td><em>(addressed briefly here)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blackbody Calibration</td>
<td>0.9%</td>
<td>0.18%</td>
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<tr>
<td><em>(main topic of this talk)</em></td>
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<tr>
<td>Spectral Calibration</td>
<td>0.2%</td>
<td>0.05%</td>
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<tr>
<td><em>(material in Dave Tobin’s talk applies)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>All numbers are 3σ (“not to exceed”)</strong></td>
<td>0.95%</td>
<td>0.20%</td>
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</table>
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

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

- \( N \) 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
- \( \text{Re}() \) is the real part of the complex ratio
AERI Calibration Error Estimates

Radiometric Requirement is 0.9% of Ambient Radiance

**Input Parameters**
- wn 770  Wavenumber, [cm-1]
- Thbb 333  Temp. of Hot Blackbody, [K]
- Tcbb 300  Temp. of Cold Blackbody, [K]
- Tstr 305  Temp. of Structure Reflecting into BB’s, [K]
- Ehb 0.999  Emissivity of HBB, [-]
- Ecbb 0.999  Emissivity of CBB, [-]

**Uncertainties (3 sigma)**
- ΔThbb 0.10  [K]
- ΔTcbb 0.10  [K]
- ΔTstr 5  [K]
- ΔEhb 0.001  [-]
- 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**

<table>
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<tr>
<th>wn</th>
<th>770</th>
<th>Wavenumber, [cm⁻¹]</th>
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<tr>
<td>Thbb</td>
<td>333</td>
<td>Temp. of Hot Blackbody, [K]</td>
</tr>
<tr>
<td>Tcbb</td>
<td>300</td>
<td>Temp. of Cold Blackbody, [K]</td>
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<tr>
<td>Tstr</td>
<td>305</td>
<td>Temp. of Structure Reflecting into BB’s, [K]</td>
</tr>
<tr>
<td>Ehbb</td>
<td>0.999</td>
<td>Emissivity of HBB, [-]</td>
</tr>
<tr>
<td>Ecbb</td>
<td>0.999</td>
<td>Emissivity of CBB, [-]</td>
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**Uncertainties (3 sigma)**

<table>
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<tr>
<th>wn</th>
<th>2200</th>
<th>Wavenumber, [cm⁻¹]</th>
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</thead>
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<tr>
<td>Thbb</td>
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<td>Temp. of Hot Blackbody, [K]</td>
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<td>0.999</td>
<td>Emissivity of HBB, [-]</td>
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<tr>
<td>Ecbb</td>
<td>0.999</td>
<td>Emissivity of CBB, [-]</td>
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**Uncertainties (3 sigma)**

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<td>0.999</td>
<td>Emissivity of HBB, [-]</td>
</tr>
<tr>
<td>Ecbb</td>
<td>0.999</td>
<td>Emissivity of CBB, [-]</td>
</tr>
</tbody>
</table>

**Longwave: 770 cm⁻¹**

**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

- Aperture (6.90 cm)
- Blackbody Cavity
- Circumferential Heater
- Case
- Thermal Insulation
- Cavity Structural Support (thermal isolator)
- Electrical Connector
- Handle
- Sense Thermistors (3) (dedicated feedback thermistor is located at base of cone section)
AERI Blackbody

- Heater Winding
- Thermistor
- Cavity Aperture (6.9 cm)
- Cavity Support (Thermal Isolator)

Thermistor Installation

- Leads
- Shrink Tubing
- 46041 Thermistor
- Epoxy (3M 2216)
- Thermal Grease (Wakefield 126)
- Blackbody Cone
**AERI Blackbody Temperature Calibration Overview**

**AERI BB System**

**Resistance Calibration**

**Temperature Calibration**

**Temperature Calibration**

\[ T = 1 / \left( A + B \cdot \ln(R) + C \cdot (\ln(R))^3 \right) \]
## Temperature Uncertainty Budget

### Temperature and Resistance Reference Uncertainty

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
<th>± peak error [K]</th>
<th>RSS [K]</th>
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<tr>
<td>26</td>
<td>Temperature Calibration Standard (Guildline PRT)</td>
<td>0.030</td>
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<tr>
<td>32</td>
<td>Calibration Resistors</td>
<td>0.007</td>
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<tr>
<td>33</td>
<td>Resistor Readout Electronics Residual Error</td>
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<tr>
<td></td>
<td><strong>RSS</strong></td>
<td><strong>0.032</strong></td>
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### Thermistor Temperature Transfer Uncertainty

<table>
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<tr>
<td>26</td>
<td>Temperature Gradient Between PRT and Thermistors</td>
<td>0.020</td>
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<tr>
<td>28</td>
<td>Calibration Fitting Equation Residual Error</td>
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<tr>
<td></td>
<td><strong>RSS</strong></td>
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### Cavity Temperature Non-uniformity Uncertainty

<table>
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<th>#</th>
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<th>RSS [K]</th>
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</thead>
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<tr>
<td>37</td>
<td>Azimuthal Gradients Due to Free Convection</td>
<td>0.050</td>
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<tr>
<td>37</td>
<td>Longitudinal Gradients Due Primarily to Conduction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>Radial Gradients Due to Conduction, Convection, and Radiation</td>
<td>0.050</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Paint Gradient</td>
<td>0.030</td>
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<tr>
<td></td>
<td><strong>RSS</strong></td>
<td><strong>0.058</strong></td>
<td>0.058</td>
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</tbody>
</table>

### Long-term Stability

<table>
<thead>
<tr>
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<th>Description</th>
<th>± peak error [K]</th>
<th>RSS [K]</th>
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</thead>
<tbody>
<tr>
<td>30</td>
<td>Thermistor</td>
<td>0.050</td>
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<tr>
<td>34</td>
<td>Resistance Measurement Electronics</td>
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<tr>
<td></td>
<td><strong>RSS</strong></td>
<td><strong>0.058</strong></td>
<td>0.058</td>
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</table>

### Effective Radiometric Temperature Weighting Factor Uncertainty

<table>
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<tr>
<th>#</th>
<th>Description</th>
<th>± peak error [K]</th>
<th>RSS [K]</th>
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</thead>
<tbody>
<tr>
<td>36</td>
<td>Monte Carlo Ray Trace Model Uncertainty in Determining Teff</td>
<td>0.030</td>
<td></td>
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<tr>
<td></td>
<td><strong>RSS</strong></td>
<td><strong>0.095</strong></td>
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</tbody>
</table>

XX Indicates slide number where more detailed information is presented
AERI Blackbody Temperature Calibration- Probe Traceability & Configuration

- Insures Excellent Thermal Coupling Between PRT and Blackbody Thermistors

UW SSEC Guideline 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

Typical AERI Thermistor Calibration Deviation From YSI Nominal

Calibration reduces AERI thermistor uncertainty to < 0.038 K

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

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

Data from BB S/N 24
Temperature Gradient Due to Paint Thickness

\[ \Delta T = 0.0075 \text{ K} \] results from \( (T_h - T_a) = 40 \text{ C} \).

\[ \Delta T \] expected to be < 0.03 K for max. expected \( (T_h - T_a) = 120 \text{ C} \).

0.03 K is carried in the uncertainty budget.

\[ \Delta T = \frac{P}{A} \cdot \frac{t}{k} \]
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

Keithley Metrabyte EXP-GP 8 channel signal conditioning board

Blackbody Temperature Sensing (One Channel Shown)

Keithley Metrabyte DAS-HRES 16-bit A/D ISA-bus card

3 Thermistors

Ancillary Sensors

Signal Conditioning Electronics (Gain = 2.5)

Control Output

Analog Input

DAS-HRES

Industrial Computer

ABB

3 Thermistors

HBB

3 Thermistors
Calibration Resistor Traceability & Uncertainty

Uncertainty in Calibration Resistor Measurements Expressed as Equivalent Temperature Errors

- Calibration Resistor Uncertainty (Equivalent Temperature)
- Fluke Meter Uncertainty (Equivalent Temperature)

Temperature uncertainty 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

Calibration of AERI thermistor resistance measurement electronics uses precision resistors.
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

Fixed Resistor Reported Temperature History Since Deployment
2500 Ohm Resistor

Equivalent Temp of 249 K

Fixed Resistor Reported Temperature History Since Deployment
97 Kohm Resistor

Temperature Error Associated With Long-term Drift of the Electronics is < 0.030 K
## Emissivity Uncertainty Budget

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

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)

Indicates slide number where more detailed information is presented

\[ f = \frac{(1-Ep)(1-Ec)}{1-Ep-Cavity} \]

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

Aeroglace Z306 Paint Emissivity vs Number of Coats
(Paint samples measured by Labsphere in 11/96)

Uncertainty in emissivity measurement is <0.015*

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

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

$$R = \square \ast B(T_{\text{eff}}) + (1- \square)\ast B(T_{\text{refl}})$$

$$T_{\text{eff}} = w_1 \ast T_A + w_2 \ast T_B$$

B(T) = Planck radiance at T

\( w_1, \) 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)

Monte Carlo Prediction for AERI Normal Cavity Emissivity

Cavity Emissivity > 0.998

± 30% cavity factor uncertainty

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 Ice Blackbody in Down View

AERI Intermediate Temperature Blackbody in Sky view
AERI Instrument End-to-end Radiometric Calibration

Intermediate / Ice BB Test

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


Short Term Reproducibility < ± 5 mK Peak-to-Peak

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

Short Term Temperature Control < ±1 mK Peak-to-Peak
AERI Spectra Showing Reproducibility

Brightness Temp Overlay of 2 Observations
Intercomparison of Two MAERIs Measuring Sea Surface Temperature

16 Day Cruise

Daily Mean Difference in Measured SST Between MAERI-01 and MAERI-02

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

Track of the R/V Roger Revelle

Hawaii

New Zealand
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]