Northrop Grumman Corporation
High Speed and High Accuracy
Blackbody Radiance Primary Standard

Richard Williams, Freddy Sevilla, Huy Ha, Steve Moisant
Northrop Grumman Corporation

Adriaan Carter, Timothy Jung
Jung Research and Development

Dave Higham, Nelson Palmer, Craig Thompson
Orbital ATK

CALCON, 26 August, 2015
Outline

• Problem Statement
• Blackbody Design Features Overview
• Thermal Performance Test Results and Discussion
• Emissivity Models and Results
• Conclusion
Problem Statement

• Root question: How does one maintain a calibrated IR radiance source for IR sensor calibration?

• Radiance accuracy requirements:
  – Temperature uncertainty of less than 20 mK.
  – Emissivity greater than 0.9995 over the 2.5 um to 5.0 um wavelength range.

• NIST traceability – at least in temperature over the operating temperature range.

• Low operational cost:
  – Change temperature and stabilize quickly.
  – Easily maintained calibration and with NIST traceability.
Outline

- Problem Statement
- Blackbody Design Features Overview
- Thermal Performance Test Results and Discussion
- Emissivity Models and Results
- Conclusion
Vacuum Shell and External Hardware

Length = 36”
Width = 34”
Height = 38.5”
Weight ~250lbs

SPRT
Fluid In/Out
Vacuum Gauges
IR Radiance Port
Pump Port ISO 160 This end.
Backfill Valve
• High flow rate fluid is used to provide temperature control and uniformity.
• Easily replaced Standard Platinum Resistance Thermometers (SPRTs) are used to measure the fluid temperature.
Required Fluid Flow Rate was Computed

- Fluid flow rate is above Reynolds number to maximize fluid to metal Heat Transfer Coefficient (HTC).
• The exhaust fluid from the Blackbody Cavity Assembly is circulated through the Thermal Guard to generate a near isothermal environment.
Outline

• Problem Statement
• Blackbody Design Features Overview
  • Thermal Performance Test Results and Discussion
• Emissivity Models and Results
• Conclusion
The high fluid flow rate and the fluid temperature controller allow for rapid temperature ramping.

The temperature stabilizes to 15 mK control in 15 to 20 minutes.
Blackbody Temperature Stability

- The fluid temperature controller can control the fluid temperature to about 10 mK or less.
At a set point of 450 K, the estimated heat loads on the Blackbody Cavity Assembly when the shutter is closed are:

- The radiative heat load on the outside = 0.14 W
- The radiative heat load through and around the shutter = 0.06 W
- The conductive heat load through the mechanical supports = 0.56 W.

At a blackbody setpoint temperature of 450 K:
- The Thermal Guard is about 1.1 K cooler than the Blackbody.
- The Inner Shutter Blade is about 21 K cooler.
• Blue curve shows the effects of the heat loads described on the previous slide on the thermal fluid, when the shutter is closed.

• Red curve shows a similar effect, except for when the shutter is open.

• SPRT temperature readings vs. temperature are consistent with expectations.
With the shutter closed effect subtracted from the shutter open effect, this curve represents the radiative heat load on the fluid.

Using these data, the computed radiative blackbody heat load vs. temperature, and the known fluid thermal characteristics, the fluid flow rate can be estimated.
PRTs were embedded into the wall of the blackbody cavity to measure changes in cavity wall temperature as a function of shutter position.

The PRTs were located where the heat load on the cavity wall is the highest.
The change in cavity wall temperature vs. fluid input temperature allows the computation of the fluid to metal Heat Transfer Coefficient (HTC).

The largest contributor uncertainty, by a factor of more than 3 than all the others at a relative value of 20%, was the estimation of the radiative heat load on the cavity wall at the PRT location.
The deduced HTC data are fit with a continuous line in order to allow for a thermal model that is continuous with temperature.
• With the deduced HTC, standard values for the conductivity of aluminum, and an assumed zero thermal impedance across the 6 um black coating, the relationship between the Fluid Exhaust SPRT and the surface temperature of the blackbody cavity rear wall.
The simple shape allows for an analytical computation of the blackbody cavity emissivity factor.
• With the computed emissivity enhancement factor, the cavity surface reflectance can be converted into a blackbody cavity effective emissivity.

• The emissivity comfortably meets the 0.9995 requirement over the 2.5 um to 5.0 um wavelength range.
• Rays emanating from the radiometer detector are used to model the effective reflectance of the Blackbody Cavity from the radiometer’s point of view.

• Reflectance of blackbody cavity chosen to be at 3.7 um
The reflectance of the cavity was simulated at a wavelength of 3.7 μm to be 0.99976.

\[\text{Emissivity} = 1 - \frac{\text{reflected power}}{\text{input power}} = 1 - \frac{1.8976E - 2 W}{4.4146E - 6 W} = 0.99976\]
Ray Trace Emissivity Calculation

### Analytical Emissivity Results

<table>
<thead>
<tr>
<th>Cavity Gain Uncertainty Effect</th>
<th>Surface Reflectance Uncertainty Effect</th>
<th>Effective Emissivity Combined Uncertainty Range (2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-σ upper limit</td>
<td>0.999705 (+0.00017%)</td>
<td>0.999852 (+0.015%)</td>
</tr>
<tr>
<td>Estimated Value</td>
<td>0.999704</td>
<td>0.999704</td>
</tr>
<tr>
<td>2-σ lower limit</td>
<td>0.999702 (-0.00017%)</td>
<td>0.999555 (-0.015%)</td>
</tr>
</tbody>
</table>

### Ray Trace Model Emissivity Results

<table>
<thead>
<tr>
<th>Black Total Reflectance</th>
<th>Effective Cavity Emissivity Radiometer Point of View</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005</td>
<td>0.99988</td>
</tr>
<tr>
<td>0.010</td>
<td>0.99976</td>
</tr>
<tr>
<td>0.015</td>
<td>0.99964</td>
</tr>
</tbody>
</table>

- Both the analytical and ray trace modeling of emissivity are in close agreement.
Summary and Conclusions

• A primary grade IR radiance standard was developed
  – Temperature Range: 230 K to 450 K
  – Temperature Stability (Standard Deviation): 10 mK (k=2)
  – Potential Temperature Bias Maximum (Type B Uncertainty): 8 mK
  – Wavelength Range: 2.5 um – 5.0 um
  – Emissivity Minimum: 0.99955 ± 0.00015 (k=2)

• Features were incorporated to reduce operational costs
  – Rapid temperature changes to reduce sensor testing costs.
  – Easy and quick temperature calibration to reduce calibration costs.

• A derivation of the performance characteristics of a primary standard quality radiance blackbody cavity was demonstrated.