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On-Orbit Absolute Radiance Standard for the Next Generation of IR Remote Sensing Instruments

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ABSTRACT

The next generation of infrared remote sensing satellite instrumentation, including climate benchmark missions will require better absolute measurement accuracy than now available, and will most certainly rely on the emerging capability to fly SI traceable standards that provide irrefutable absolute measurement accuracy. As an example, instrumentation designed to measure spectrally resolved infrared radiances with an absolute brightness temperature error of better than 0.1 K will require high-emissivity (>0.999) calibration blackbodies with emissivity uncertainty of better than 0.06%, and absolute temperature uncertainties of better than 0.045K (k=3). Key elements of an On-Orbit Absolute Radiance Standard (OARS) meeting these stringent requirements have been demonstrated in the laboratory at the University of Wisconsin (UW) and refined under the NASA Instrument Incubator Program (IIP). This work recently culminated with an integrated subsystem that was used in the laboratory to demonstrate end-to-end radiometric accuracy verification for the UW Absolute Radiance Interferometer. Along with an overview of the design, we present details of a key underlying technology of the OARS that provides on-orbit absolute temperature calibration using the transient melt signatures of small quantities (<1g) of reference materials (gallium, water, and mercury) imbedded in the blackbody cavity. In addition we present performance data from the laboratory testing of the OARS.

Keywords: Absolute Temperature Calibration, Blackbody, Climate Mission

1. INTRODUCTION

Future infrared remote sensing satellite instruments, especially those to be used for establishing a climate benchmark, will hinge upon the ability to fly absolute standards that provide the basis to meet stringent requirements on measurement accuracy. This next generation instrumentation will need to measure spectrally resolved infrared radiances with an absolute brightness temperature error of better than 0.1K (k=3). A key requirement for these future missions is to provide traceability to SI standards on-orbit.[1,2,3,4] This imposes stringent requirements on the instrument calibration blackbodies, and has given rise to a new philosophy to provide end-to-end instrument calibration verification on-orbit, using SI traceable standards.

A prototype climate benchmark instrument that includes this capability for on-orbit SI traceable calibration verification has been developed at the University of Wisconsin, under the NASA instrument Incubator Program (IIP). This instrument is called the Absolute Radiance Interferometer (ARI),[5,6] and it includes the On-orbit Absolute Radiance Standard (OARS) for end-to-end calibration verification. Under the IIP, the ARI calibration performance was demonstrated in the laboratory to an on-orbit equivalent of 0.1 K (k=3). A significant development under the IIP includes the OARS, which uses the transient melt signatures from multiple phase transition cells to provide temperature calibration to sensors imbedded in the blackbody cavity. The OARS also uses a Heated Halo to provide on-orbit blackbody cavity emissivity measurements.[7]

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This paper begins with the establishment of key requirements for both the internal blackbody used in conjunction with a space view for instrument calibration, and the OARS source used for calibration verification. This is followed by a description of the OARS design, including a discussion of the phase transition cell implementation and performance. We will then discuss the integration and testing of the OARS, and its use for end-to-end testing of the University of Wisconsin ARI. We conclude by describing alternate implementations of the phase transition cell technology that is suitable for more general applications.

2. TOP-LEVEL BLACKBODY REQUIREMENTS

The flow-down requirement on blackbody performance for the ARI instrument is determined by performing a perturbation analysis on the instrument calibration equation.[5] Table 1 lists the parameter values and uncertainties that were used to establish the instrument blackbody and OARS verification source specifications. The left plot in Figure 1 provides the Brightness Temperature error verses Scene Temperature at various wavenumber values for the ARI (dashed) and OARS (solid). The plot on the right combines these uncertainties and compares them with the required 0.1 K instrument level performance. Of particular note is the 45 mK uncertainty required for the instrument blackbody and OARS. This level of accuracy is obtained on-orbit and is traceable to SI standards by using melt signatures from three different miniature phase transition cells.

Table 1. Parameter Values and Uncertainties (k=3) Used for Calibration Uncertainty Analysis

Temperatures	Value	Uncertainty
Cold calibration reference (space target)	4 K	0 K
Hot calibration referance (internal calibration target)	295 K	0.045 K
Verification target: On-orbit Radiance Standard (OARS)	220-320 K	0.045 K
Reflected radiance (cold calibratin reference)	290 K	0 K
Reflected radiance hot calibratin reference)	290 K	4 K
Reflected radiance OARS calibratin reference)	290 K	4 K
Emissivities		
Cold calibration reference (space target)	1	0.0006
Hot calibration referance (internal calibration target)	0.999	0.0006
Verification target: On-orbit Radiance Standard (OARS)	0.999	0.0006*

In the table it has been assumed that the OARS emissivity and associated uncertainty is determined from pre-launch TVAC testing with a very high emissivity source, providing emissivity uncertainties of: 0.0006 at 200 cm-1; 0.0004 at 800 cm-1; 0.0002 at 1400 cm-1; 0.0001 at 2000 cm-1; and 0.000075 at 2600 cm-1.

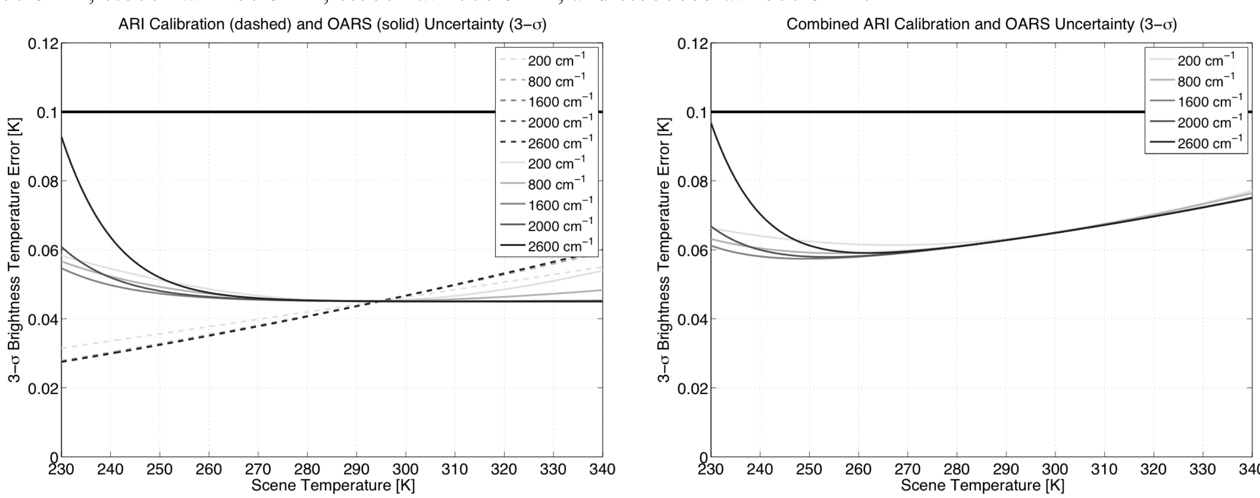

Figure 1. The plot on the left shows the brightness temperature error for the ARI instrument (dashed lines) calibrated with its internal ambient blackbody and a space view, and the OARS verification source (solid lines), for on-orbit conditions at several wavenumbers. The plot on the right is the combination of the errors shown at left, and represents the level of ARI instrument verification that can be provided by the OARS on-orbit.

3. ON-ORBIT ABSOLUTE RADINCE STARDARD (OARS) – KEY FEATURES

A section view schematic of the OARS space flight design is shown in Figure-2. The light-trapping cavity shape is coated with Aeroglaze Z306 diffuse black paint. The heated cavity temperature is measured with five Thermometrics SP60 thermistors, with absolute temperature calibration provided by three imbedded phase transition cells (mercury, water, and gallium). The cavity is cold-biased via coupling to a cold heat sink (cold radiator). The Heated Halo located in front of the cavity is used for measuring cavity emissivity to within an accuracy of 0.0006 (k=3). This technology was also part of the IIP and is discussed in detail by Gero et al.[8,9] The OARS design is a derivative of an earlier UW development for NASA's Geostationary Imaging Fourier Transform Spectrometer (GIFTS).[10-15] The phase transition technology was originally demonstrated at UW under internal funding, using a prototype GIFTS blackbody and controller. This work laid the foundation for the advancement of this technology under the IIP, under which the OARS was brought from TRL 3 to 6.

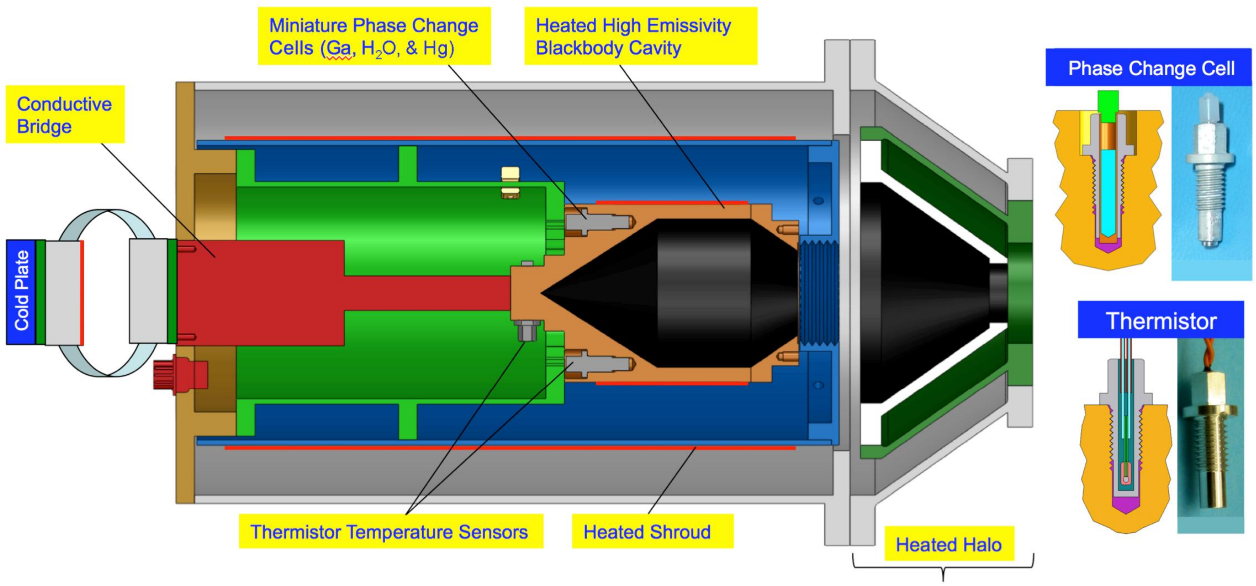

Figure 2. Section view schematic of the OARS space flight design showing the blackbody cavity and the imbedded thermistor temperature sensors and phase transition cells, which are broken out in more detail at right. Multilayer insulation is not shown.

The concept for using miniature phase transition cells to calibrate imbedded blackbody cavity thermistors is illustrated in Figure 3, which shows a typical transient temperature response (signature) from one of the blackbody cavity thermistors during a gallium (<1 gram) melt event.[16] At the start of the melt process the blackbody cavity is brought to thermal stability in the constant temperature mode about 50 mK under the expected phase change temperature. Then the blackbody controller is switched into constant power mode using a power level that would bring the cavity to about 100 mK above the expected phase change temperature. If no gallium were present the cavity would follow an exponential temperature rise to a new equilibrium temperature. However, even in the presence of a small quantity of gallium the cavity heater power goes into melting the gallium when it reaches the melt temperature – creating a melt plateau. As the time taken to pass through the melt plateau increases, the mid melt temperature more closely approaches the theoretical melt temperature to the reference material. This is illustrated, again for gallium, in Figure 4. Note that the procedure for obtaining a melt signature does not require any more sophistication than what is available from a high quality temperature controller.

It has been shown that the asymptotic characteristic curve used to fit the mid melt temperature versus melt duration data shown in the right plot of Figure 4 is unique and invariant for a given melt material and design implementation. This allows the melt behavior for a given system to be fully characterized, and was used as a metric in the validation of the housing design that underwent extensive accelerated lift testing designed to simulate 7 years on orbit.[17]

A thermistor temperature sensor is calibrated using this scheme by measuring its resistance during the mid melt plateau. With the aid of the characteristic curve a calibration temperature can be assigned and associated with this resistance. If three different reference melt materials are used, then three pairs of calibration temperature and measured resistance are available for each thermistor to determine the traditional three (A, B, and C) Steinhart-Hart calibration coefficientes. Extensive testing has shown that each of the calibration temperatures associated with the different melt materials can be established to within 5 mK using this transient signature approach. The thermal design of the blackbody and the long duration of the melt transient lead to a very isothermal condition in the cavity during a melt. The gradients between the melt materials and the thermistors to be calibrated are less than 2 mK.

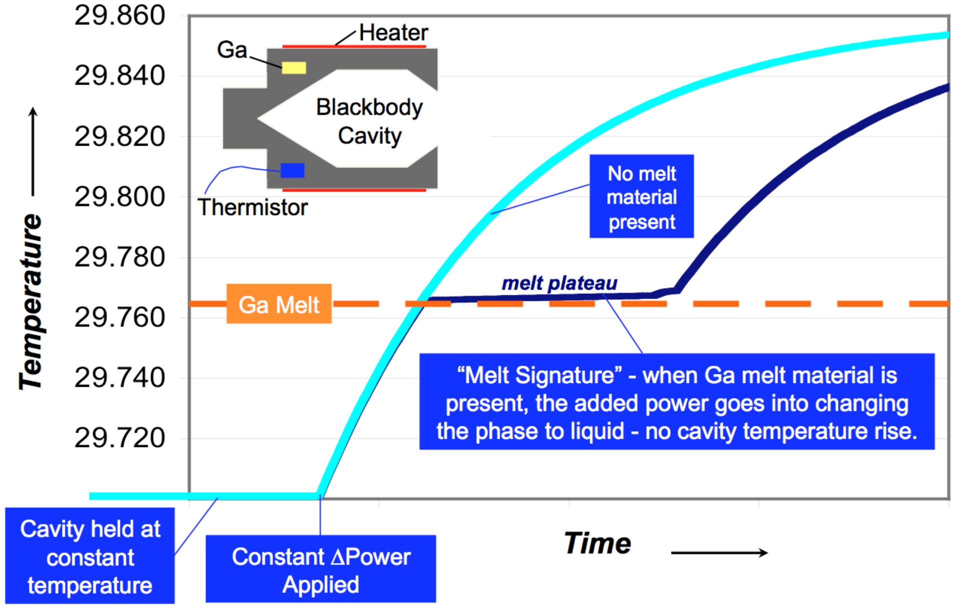

Figure 3. Sequence of events during a typical melt of gallium confined in a phase transition cell and imbedded into an OARS as illustrated in Figure 2. After initial stabilization in the constant temperature mode, a constant power is used to transition through the melt plateau, which is discernable to within 5 mK (k=3).

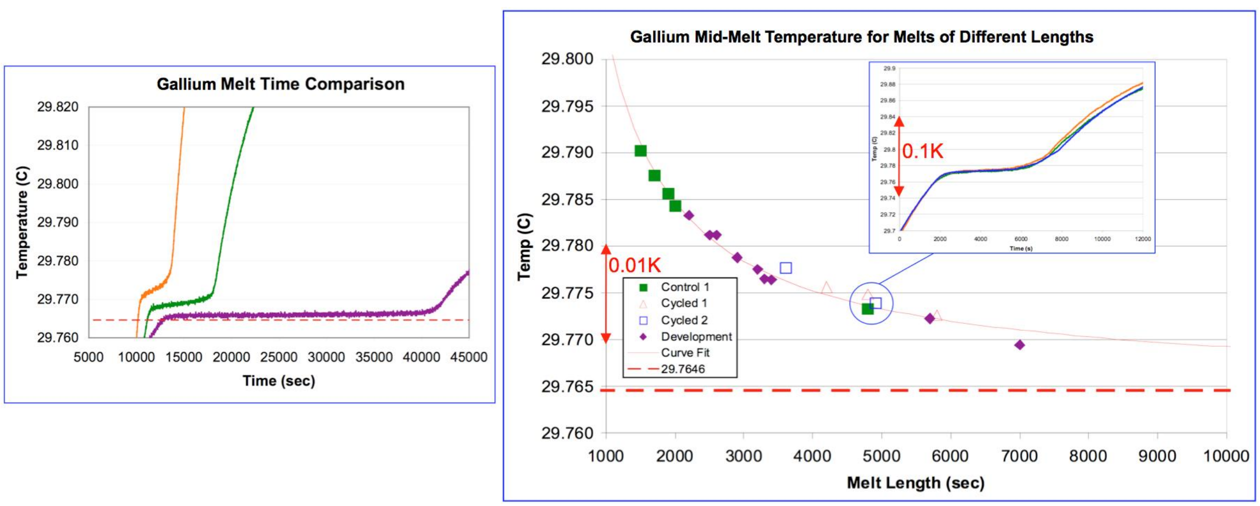

Figure 4. The plot on the left shows three different melts of different duration. The longer the melt the closer the plateau approaches the theoretical melt temperature. The large plot at right illustrates this by plotting mid-melt temperature vs. melt length – each data point corresponds to a single melt. This characteristic asymptotic behavior has shown to be invariant for a given physical configuration. The inset plot at upper right shows the three melt signatures associated with the circled data points, indicating great reproducibility.

Figure 5 provides a summary of the different melt materials that have been characterized and undergone accelerated life testing in the laboratory.[17,18] Three materials are targeted for a typical climate benchmark mission (mercury, water, and gallium), providing a wide range of calibrated temperature (-40 °C to +30 °C). The three materials listed on the lower half of the table were investigated for use on a demonstration in microgravity where three materials will be used but the test hardware has a limit of -13 °C. The materials chosen are water+AgI (where the AgI is used to prevent supercool freeze temperatures), gallium-tin eutectic, and gallium.

	Material	Melt Point [°C]	Liq. >>Solid	LME Possible	Signatures (TEC)	Acc. Life Test - Unsealed	Acc. Life Test - Welded		Signatures (Blackbody)
							Abbreviated	Full	
Original IIP	Gallium	29.7	Expands	Yes	X	X	X	X	X
	Water	0.0	Expands	No	X	X	X	X	X
	Mercury	-38.9	Contracts	Yes	X	X	X	X	X
ISS	Gallium-Indium	16.5	Expands	Yes	X				
	Gallium-Tin	20.5	Expands	Yes	X		X		X
	Water + AgI	0.0	Expands	No	X		X		X

Figure 5. A table summarizing the accelerated life test status of six different phase change reference materials all housed in phase transition cells.

4. (OARS) INTEGRATION AND TEST

Figure 6 shows a section view of the laboratory version of the OARS that was built and demonstrated through end-to-end testing of the ARI system under the IIP. For this laboratory version the temperature controlled shroud uses a fluid loop to maintain the cold-biased temperature environment for the cavity. Cavity temperatures from -60 to +60 are possible with this design. Four Thermometrics SP60 thermistors and three phase transition cells (mercury, water, and gallium) are imbedded in the cavity.

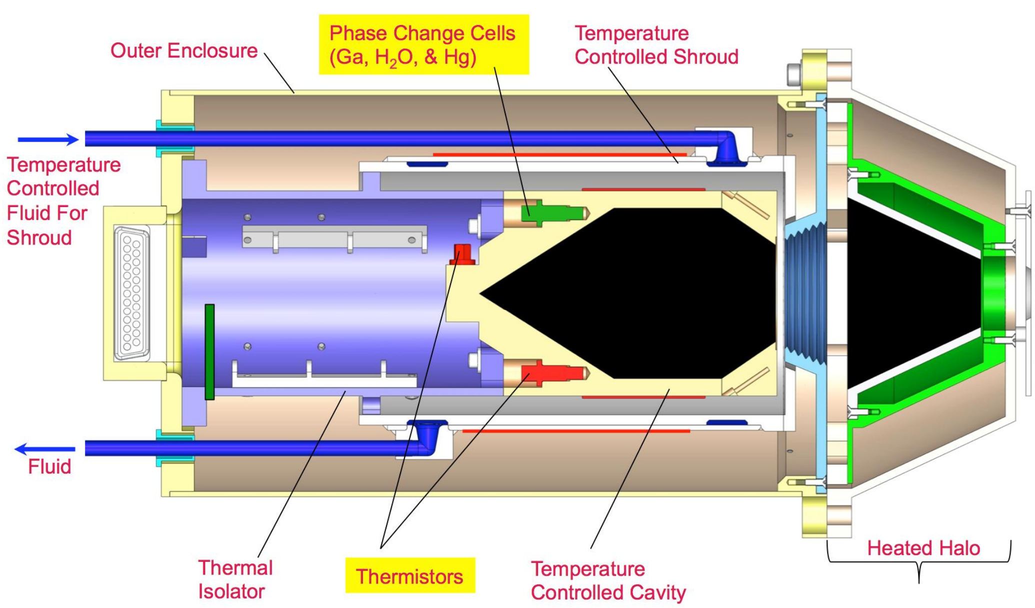

Figure 6. A section view of the laboratory version of the OARS that was developed under the IIP for calibration verification of the ARI instrument. The temperature controlled shroud uses a fluid loop to maintain temperature.

Prior to installation into the OARS, the thermistors were calibrated in a thermal chamber using the temperature metrology system illustrated in Figure 7. Temperature calibration probes with accuracies of ±5 mK (k=3) are imbedded in an aluminum calibration block along with the thermistors. This assembly is heavily insulated from the chamber to allow a high degree of isothermality to be achieved at each calibration temperature. At each calibration temperature, thermistor resistances are read with a Fluke 8508A Reference Multimeter to an equivalent temperature accuracy of better than ±0.5 mK (k=3). Nine thermistor temperature-resistance calibration points from -60 to 60 °C are used for two overlapping 4-term regression fits of the Steinhart-Hart thermistor equation (five points are used in each fit). The three phase change cells that were used in the OARS underwent a full characterization and rigorous accelerated life test prior to installation.

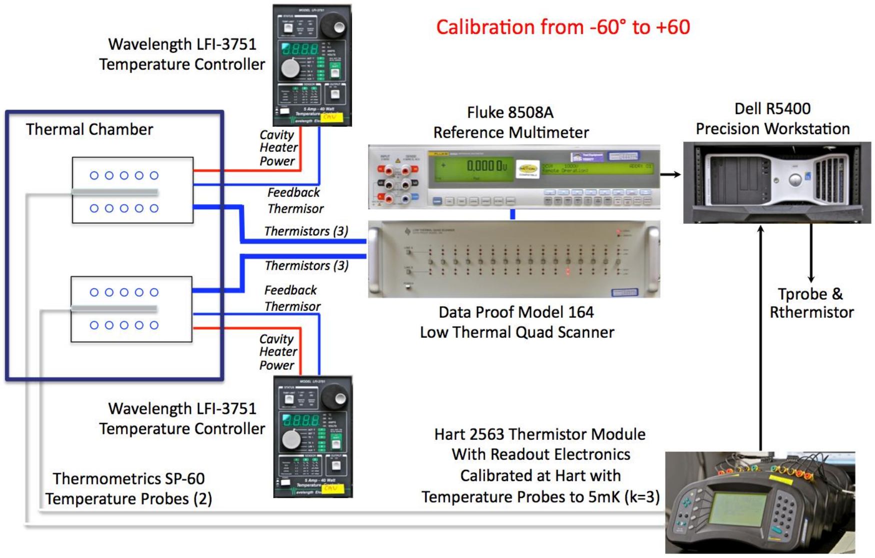

Figure 7. The temperature metrology system used for the calibration of the OARS thermistors consists of two precision Hart temperature probes that provide absolute accuracies of ±5 mK (k=3), and a Fluke 8508A reference multimeter for measuring thermistor resistance to an equivalent temperature of better than 0.5 mK (k=3).

Figure 8 illustrates the component pieces of the OARS before it was assembled. The cavity slips into the inner shield isolator assembly, which then mounts inside the outer case. The heated halo and halo insulator then mount to the front of the outer case.

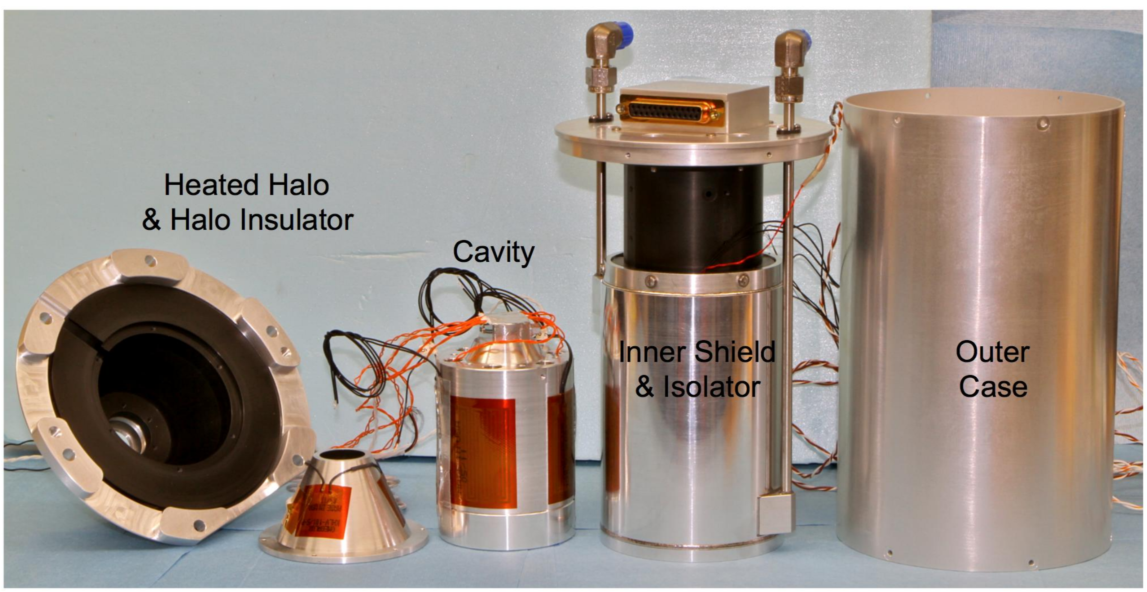

Figure 8. Component pieces of the OARS before it was assembled to the configuration illustrated in Figure 6.

Figure 9 shows the fully integrated ARI climate benchmark prototype instrument that was used to demonstrate end-to-end radiometric performance equivalent to 0.1 K (k=3) on-orbit.[5] The left panel shows the front end where a scene select mirror sequentially views the sky, the traditional hot and ambient instrument calibration blackbodies, and the OARS that provides end-to-end calibration verification. The right panel shows the view into the back of the instrument where the fore optics, Michelson interferometer, and aft optics with associated infrared detectors have been highlighted. For a spaceflight implementation, the hot and ambient blackbodies would be replaced by ambient blackbody and space views respectively. On-orbit the OARS would be run through a repeating stair-step temperature profile over a wide range of earth scene temperatures (-50 to 50°C). Visible in the left photo of Figure 9 are the fittings on the OARS for the fluid lines that connect to the temperature controlled shroud, providing the cold-bias temperature for the blackbody cavity. In a space flight implementation this fluid loop would be replaced with a thermal coupling to a spacecraft radiator or instrument cold plate.

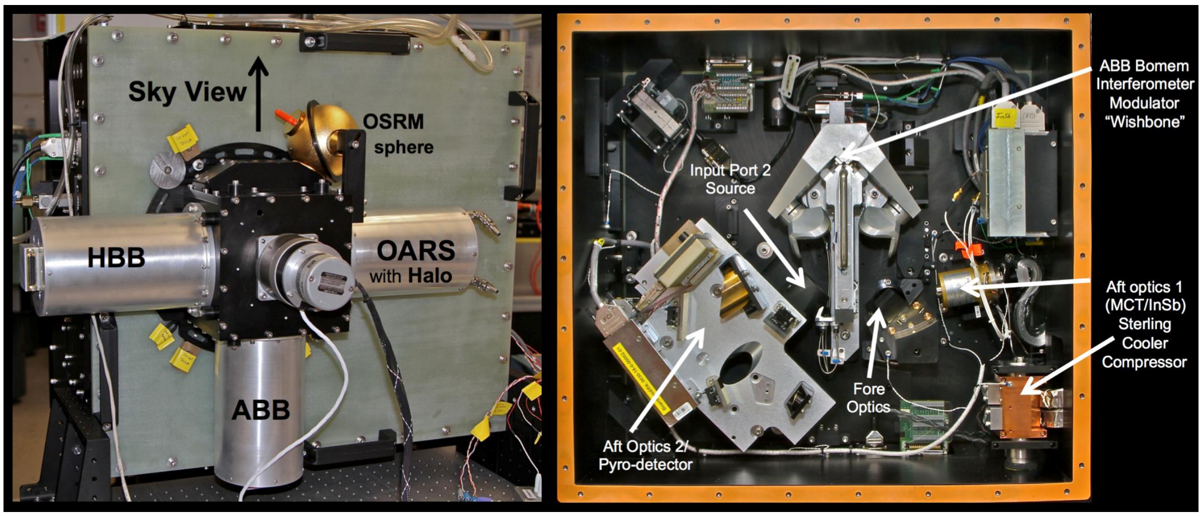

Figure 9. The Absolute Radiance Interferometer. At left the front-end is shown where a scene mirror provides views of the sky, the traditional instrument calibration blackbodies (hot and ambient), and the OARS, that is used for end-to-end calibration validation. The scene mirror feeds the Michelson interferometer through the fore optics, located on the back-side of the instrument, along with the aft optics and associated IR detectors (right photo).

Examples of melt behavior using the integrated OARS are shown in Figure 10. Melt signatures from each of the three materials fall very close to the characteristic curve. Calibration temperatures can be established to well within ±5 mK (k=3). As demonstrated in earlier work[16,17] the characteristic curve for each material and implementation is very stable over time, even after exposure to rigorous deep thermal cycling and warm temperature soaks.

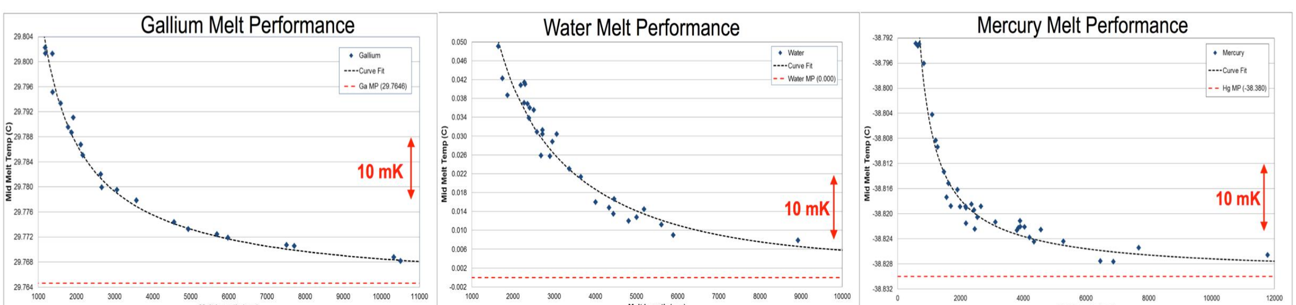

Figure 10. Examples of melt behavior for mercury, water, and gallium obtained from the integrated OARS.

When the OARS is used as a validation source there are very low temperature gradients in the blackbody cavity due to the configuration of the temperature controlled shroud that can be operated close to (and just under) the cavity set point. Figure 11 shows an example of this for the OARS running at -40 °C. This figure shows a plot of temperature from three cavity thermistors over a period of 24 hours. The location of these thermistors is shown in the cavity diagram at the right of the plot. The combined temperature gradient and 24-hour stability are within 10 mK. This is excellent performance considering the 60 °C gradient between the cavity and the laboratory temperature. The effective radiometric temperature of the OARS blackbody is derived from the thermistor temperature measurements as indicated in the equation shown under the cavity diagram. The thermistor weighting takes into account the linear temperature distribution from the cone/cylinder intersection to the cone apex, and the instrument field of view geometry at the cavity cone.

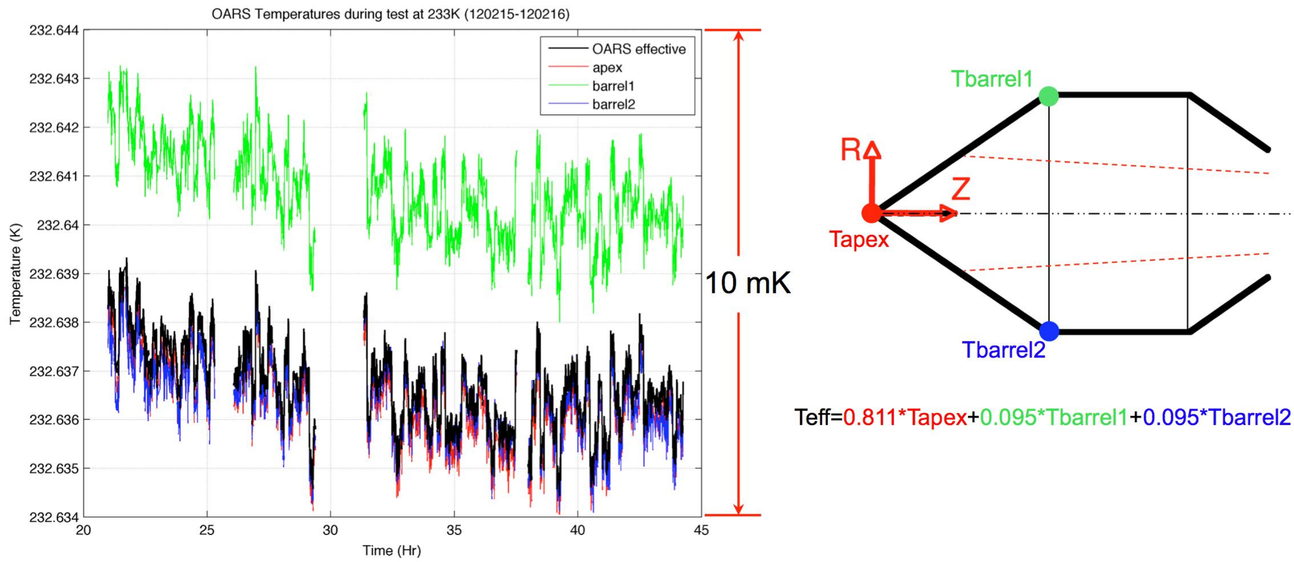

Figure 11. OARS thermistor readings over a 24 hour period with the blackbody cavity controlled at -40°C.

The overall OARS blackbody temperature uncertainty budget is shown in Figure 12. This budget includes uncertainty contributions from the temperature calibration standard, the readout electronics, the temperature transfer process during calibration, the cavity temperature uniformity (during use), the long-term stability, and the determination of the thermistor weighting factors used to calculate the blackbody effective radiometric temperature. The budget indicates a total blackbody temperature uncertainty of 45 mK (k=3) for both the laboratory and space flight implementations. This meets the requirements set forth in section 2 above.

Temperature Uncertainty	Laboratory OARS & ARI Cal Sources	On-Orbit OARS & ARI Cal Sources	Comments for On-Orbit OARS
Temperature Calibration Standard (Thermometrics SP60 Probe with Hart Scientific 2560 Thermistor Module)	0.005	0.005	Phase Change Calibration Uncertainty
Blackbody Readout Electronics Uncertainty			
Readout Electronics Uncertainty (at delivery)	0.001	0.000	Combined with above for On-orbit
Blackbody Thermistor Temperature Transfer Uncertainty			
Gradient Between Temperature Standard and Cavity Thermistors	0.010	0.007	
Calibration Fitting Equation Residual Error	0.002	0.015	
Cavity Temperature Uniformity Uncertainty			
Cavity to Thermistor Gradient Uncertainty (1/3 of total max expected gradient)	0.025	0.025	
Thermistor Wire Heat Leak Temperature Bias Uncertainty*	0.008	0.008	
Paint Gradient (assumes fulll alue at nominal HBB Temp and conservative viewing geometry)	0.018	0.018	
Long-term Stability			
Blackbody Thermistor (8 years of drift assuming 100 C)	0.005	0.010	Short Term Stabiity
Blackbody Controller Readout Electronics	0.000	0.005	Short Term Stabiity
Effective Radiometric Temperature Weighting Factor Uncertainty			
Monte Carlo Ray Trace Model Uncertainty in Determining Teff (1/3 of total max expected gradient)	0.030	0.025	Improved with better modeling
*(conservatively assumed to be the full value calculated for the effect in the worse case thermal environment and making conservative thermal coupling assumptions)	0.045	0.045	

Figure 12. OARS Blackbody Temperature Uncertainty Budget

5.0 OTHER IMPLEMENTATIONS

The phase transition cell technology can be integrated into an extended area calibration source such as found on many infrared spaceflight instruments, with little impact on existing designs, and can be used within significant spacecraft constraints. There is minimal mass impact and very little addition to system complexity because the technology can rely on existing blackbody and instrument-level thermal capabilities to transition through a phase change. With a modest investment very large gains in accuracy can be obtained. Implementing the phase transition cell technology significantly lowers blackbody temperature uncertainty because periodic on-orbit absolute calibration checks can be made with very high accuracies, in contrast to the current situation where these accuracies must rely only on pre-launch ground calibration.

ACKNOWLEDGEMENTS

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