Low-Background Temperature Calibration of Infrared Blackbodies

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Introduction

The stability of blackbody sources and their ability to be modeled accurately make them well suited for radiometric calibration activity. However, the implementation of the blackbody in industry or the laboratory may, and often does result in blackbody performance that deviates from ideal. The Low Background Infrared (LBIR) facility at the National Institute of Standards and Technology (NIST) was established in 1989 to fulfill the national need for calibrations in the infrared wavelength region in a low 20 K to 80 K background environment (Datla *et al.*). The calibration capability is based on the ability to measure infrared power absolutely using Absolute Cryogenic Radiometers (ACRs) (Foukal *et al.*, Datla *et al.*). Four ACRs are maintained at the LBIR facility, two of one model, the ACR I, for measuring powers from 5 nW to 250 µW, and two of a more sensitive model, the ACR II, for measuring powers from 40 pW to 100 µW (Carter *et al.*). Power measurements of 500 pW with 4 pW standard deviation (Type A uncertainty) are now routinely achieved with the ACR II. The four ACRs are periodically compared against the NIST primary national optical power measurement standard, the High Accuracy Cryogenic Radiometer (HACR) for verification of their accuracy (Gentile *et al.*). The results of the most recent intercomparisons are presented below.

Since 2001, 8 blackbodies were calibrated against the ACRs, which demonstrated a significant spread in blackbody performance. These 8 blackbodies incorporated 5 different blackbody designs. Some blackbodies were designed with the goal of achieving near perfect blackbody performance. These blackbodies showed excellent performance and were easy to calibrate. Blackbodies that demonstrated relatively poor calibrations were typically designed with priority given to other performance requirements such as temperature ramp rate, spectral filter use between the cavity opening and the defining aperture of the system, or very low power output. This does not mean that blackbodies can not be designed to meet both industrial process requirements and high calibration quality. In most cases simple changes to those with poor calibration performance could have resolved the most significant problems without changing the desired industrial process performance. These issues are discussed to show that the quality of a delivered blackbody calibration report is a result of the combined performance of the customers blackbody and the ACR together, not just the optimal performance capabilities of the LBIR calibration facility.

Low Background Calibration Facilities

The LBIR facility performs calibration activity in a high vacuum, low temperature 20 K to 80 K background environment created in either one of two cryogenic-vacuum chambers. Both chambers are approximately 2 m in length and have cryo-shrouds that enclose a cylindrical volume that is about 1.5 m in length and about 0.5 m diameter. At test conditions the chambers are typically operated at $1.3*10^{-7}$ Pascal and the closed-cycle He refrigerators used to cool the cryo-shrouds to anywhere between 15 K and 80 K. Inside the chambers, the ACRs are mounted on liquid He cryostats which are cooled to 2 K by pumping the liquid He down to 2670 Pascal.

Absolute Cryogenic Radiometer Performance

A QED-150 trap detector was used as the transfer standard in this study in a way that was similar to previous intercomparisons (Lorentz *et al.*). This is a three Si photodiode reflectance trap detector. The optical path within the detector includes five reflections so that the total reflection at 632.8 nm should be less than 0.4%. To determine an absolute responsivity, the optical power from an intensity stabilized He-Ne laser was measured using first the NIST primary optical power measurement standard, the High Accuracy Cryogenic Radiometer (HACR) and then again later by the newer HACR II. The external responsivity of the trap was measured to be .502448 A/W by the HACR at the beginning of intercomparison effort, and 0.502457 A/W by the HACR II at the end. The uncertainty associated with the calibrated responsivity of each measurement is 0.02 %.

The light source for the intercomparison was a polarized, stabilized He-Ne laser with a maximum power output of 1.5 mW. The laser was transmitted into the cryogenic-vacuum chamber through a Brewster angle window and a 1 cm diameter hole in the cryo-shroud. The ACR under test was placed 1 m from the 1 cm hole in the cryo--shroud so that the ACR only received 20 µW to 30 µW of background radiation through the hole in the shroud. A QED-150 trap detector that was calibrated with the HACR was used to measure the laser power just in front of the Brewster angle window. The trap detector was then removed from the beam path to allow the power to be measured by the ACR inside the chamber. The effective transmission of the HeNe laser from trap detector location in front of the Brewster window to the location of the ACR 1.5 m away was measured in a separate experiment. Table 1 shows the intercomparison results as the ratio of radiometric power measured in the calibrated QED-150 trap to that measured in the ACR. In summary, the intercomparison shows that on average the LBIR ACRs agree with HACR to 0.003 %, with a standard deviation of 0.08 % (Type A). The total uncertainty of the individual intercomparisons is dominated by the Brewster window transmission measurements uncertainty. Greater detail of the intercomparison effort will be presented along with the evaluation of the non-equivalence in the ACRs.

Table 1 Ratio of radiometric power measured in the calibrated QED-150 trap to that measured in the ACR.

ACR Name	$R_{trap/ACR}$	Total Uncertainty
ACR I(a)	1.000658	.036%
ACR I(b)	1.000532	.038%
ACR II(a)	0.999753	.060%
ACR II(b)	0.998922	.040%

Blackbody Calibrations and Overall Performance

Using these ACRs, the performance of the 8 blackbodies calibrated since 2001 can be accurately assessed and compared. The blackbodies calibrated at the LBIR facility are typically cryogenic-vacuum blackbodies that operate with cavity temperatures over the range of 180 K to 800 K. All but one of the blackbodies tested used aperture wheels to vary the size of the defining aperture in front to the blackbody cavity. All of the blackbodies had space between the defining aperture and the cavity for a shutter, 1 or 2 filters wheels, or a chopper. Calibrations of the blackbodies were typically performed entirely within the cryogenic vacuum chambers at $1.3*10^{-7}$ Pascal in a 20 K to 30 K background environment.

The blackbodies were calibrated for radiance temperature using the Stefan-Boltzmann law, length measurements of the optical geometry of the calibration configuration and power measurements made by the ACRs. Expected ACR signals were computed from a simple geometric optical model that uses the radii of the blackbody and ACR defining apertures, the distance between those apertures, and the contact thermometry on the blackbody cavity. Then, all of the defining and non-limiting apertures and baffles are then used to compute diffraction corrections (Shirley *et al.*) for the power measurements actually made by the ACR. The geometrically modeled and diffraction corrected power measurements are then compared to make a radiance temperature calibration curve for that blackbody.

The results of the calibrations for the 5 different blackbody designs show an informative pattern of blackbody behavior. Blackbodies that were designed for rapid temperature ramping demonstrated the most problems. The blackbody cavity that demonstrated the largest difference between measured radiance temperature and the contact thermometry showed a temperature error that varied from 6 % at 200 K to 3 % at 600 K. It is unlikely that this was a sensor calibration error because there were two co-located sensors that measured nearly the same value and an independent experiment confirmed the radiance temperature difference. By comparison, blackbody cavities that were designed to have good thermal conductivity within the cavity showed agreement between radiance temperature and contact thermometry that varied from 0.1 % to 0.5 % at all temperatures.

Often evidence of thermal problems within a blackbody cavity is demonstrated by the temperatures sensors themselves. In one particular blackbody, the thin walls of the cavity conducted so little heat that the cavity temperature as measured by the contact thermometry dropped by 0.3 K when the shutter was opened. Furthermore, two calibrated sensors at dissimilar locations showed a temperature difference of 6 K at a cavity temperature of 400 K. The obvious and subtle causes of these and other calibration issues will be presented in more detail.

References

Datla, R. U., Croarkin, M. C., Parr, A. C., Cryogenic Blackbody Calibrations at the National Institute of Standards and Technology, *Journal of Research of the National Institute of Standards and Technology, 99*, 77-87, 1994.

Foukal, P. V., Hoyt C. C., Kochling, H., Miller, P. J., Cryogenic absolute radiometers as laboratory irradiance standards, remote sensing detectors, and pyroheliometers, *Applied Optics, 29*, 988-993, 1990.

Datla, R. U., Stock, K., Parr, A. C., Hoyt, C. C., Miller, P. J. Foukal, P. V., Characterization of an absolute cryogenic radiometer as a standard detector for radiant power measurements, *Applied Optics, 31*, 7219-7225, 1992.

Carter, A. C., Lorentz, S. R., Jung, T. M., Datla, R. U., ACR II: Improved Absolute Cryogenic Radiometer for Low Background Infrared Calibrations, *Applied Optics, 44,* 871-875, 2005.

Gentile, T. R., Houston, J. M., Cromer, C. L., Realization of a scale of absolute spectral response using the National Institute of Standards and Technology high-accuracy cryogenic radiometer, *Applied Optics, 35*, 4392-4403, 1996.

Lorentz, S. R., Datla, R. U., Intercomparison between the NIST LBIR Absolute Cryogenic Radiometer and an Optical Trap Detector, *Metrologia 30*, 341-344. 1993.

Shirley, E. L., Terraciano, M. L., Two innovations in diffraction calculations for cylindrically symmetrical systems, *Applied Optics, 40*, 4463-4472, 2001.