NIST Low-background Infrared spectral calibration facility

S. R. Lorentz, S. C. Ebner, J. H. Walker and R. U. Datla

Abstract. The goal of the Low-background Infrared (LBIR) calibration facility at the National Institute of Standards and Technology is to provide the infrared user community with a calibration base for broadband and spectral radiant power measurements. The LBIR facility began broadband radiant-flux calibrations of infrared sources in 1990 using a cryogenic vacuum chamber to provide the low background at 20 K. A second cryogenic-vacuum chamber is being brought into service for spectral calibrations in the LBIR facility. This new spectral calibration chamber will house the spectral instrument and be the centre for the spectral calibrations of sources and detectors and for the measurement of optical properties of materials. The LBIR spectral instrument is composed of a KRS-5 prism predisperser for order-sorting, followed by a grating monochromator. This calibration capability is currently being developed in three areas: spectral calibration of infrared detectors for use in low-background applications; spectral resolution of radiation from black-body sources such as cavities and other geometries such as spheres and plates; and characterization of optical components of interest to the community such as filters and window materials. This work will be carried out over the spectral range 2 µm to 30 µm.

1. Introduction

The Radiometric Physics Division at the National Institute of Standards and Technology (NIST) has constructed facilities for the development and dissemination of standards in the infrared wavelength region. The Low-background Infrared (LBIR) facility comprises the primary national standard for broadband infrared power measurements. The LBIR currently provides measurements of broadband sources in a low-background 20 K environment. Generally, these sources are intended for use in cryogenic-vacuum test chambers performing calibrations of sensors used in space-based measurement and observation satellites. The facility has also performed emittance measurements of materials for use in the infrared. This paper reviews data from a representative broadband black-body calibration, and presents a discussion of the low-background spectral calibration capabilities that are now under construction.

2. Description of the LBIR facility

The apparatus used for the broadband calibration measurements is shown in Figure 1. The vacuum chamber is constructed from 304 stainless steel and is 60 cm in diameter and 152 cm long. A cryogenic shroud, cooled to 20 K, encloses the interior of the chamber, thus producing a low-background environment in which to perform calibrations and experiments. The shroud is cooled by a closed-cycle helium compressor which allows for continuous operation at cryogenic temperatures.

The standard reference detector used in the LBIR facility is the Absolute Cryogenic Radiometer (ACR) [1, 2]. The ACR is shown as an outline drawing in Figure 2. The ACR is an electrical-substitution radiometer capable of measuring radiant-flux levels from 20 nW to 200 µW with a combined standard uncertainty [3] of 1 % down to 0,1 % over that power range. The combined standard uncertainty is the combination of uncertainties arising from random and systematic effects at the level of two standard deviations. A conical-receiver-cavity design is employed in order to enhance the absorptivity of the blackened receiver. The receiver is spectrally flat from the ultraviolet to the far-infrared. The ACR is operated in an "active loop mode" where the temperature of the blackened receiver is continuously controlled. The temperature is sensed with a germanium resistance thermometer (GRT) and electrical power is applied with a resistive heater mounted on the receiver. Cryogenic operation of the ACR is achieved by a 3 L liquid-helium reservoir, which is pressure-controlled to lower the operating temperature of the ACR to 2 K. The natural time constant of the receiver is approximately 20 s at that temperature.

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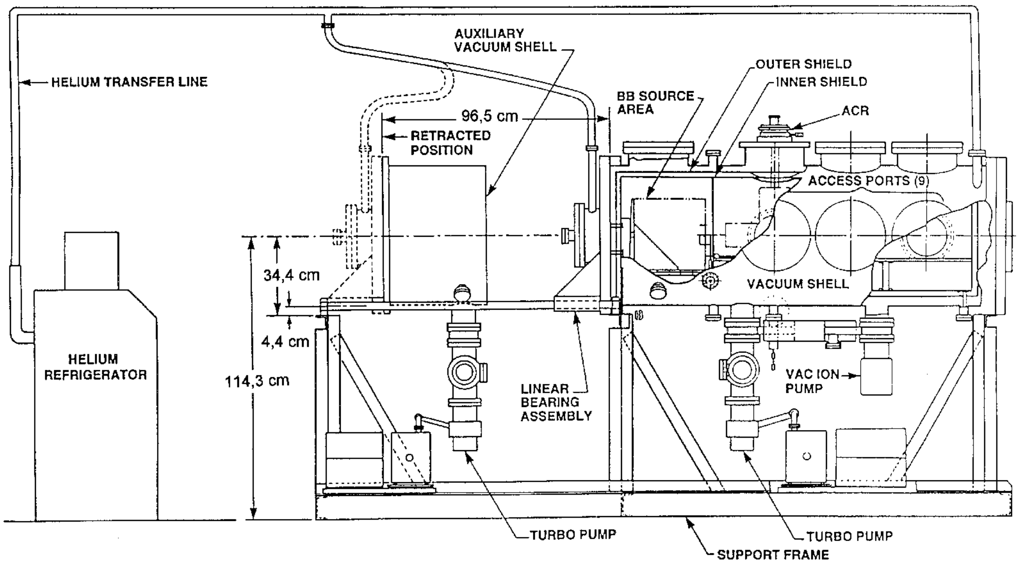

Figure 1. The Low-background Infrared (LBIR) chamber with partial cutaway showing the major features of the apparatus. Black-body source (BB source), Absolute Cryogenic Radiometer (ACR).

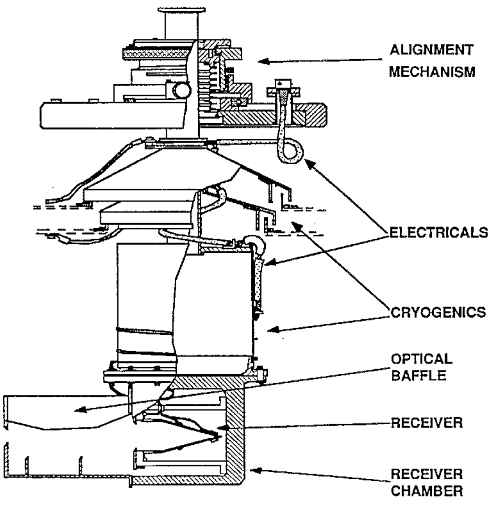

Figure 2. Cross-section of the Absolute Cryogenic Radiometer.

3. Broadband infrared source measurements

The LBIR facility has performed a variety of broadband black-body source calibrations for industrial and governmental laboratories since the facility began operation in 1990. Typical measurement requirements consist of determining the radiance temperature of the black-body source for a range of black-body temperatures and aperture sizes. The black-body calibrations are based on the total-flux measurements at the aperture of the ACR.

The radiance temperature is given by the following equation deduced from the Stefan-Boltzmann law and the geometrical factor to convert black-body radiance to irradiance at the ACR aperture [4]:

$$T = [P/(F_1 A_1 \sigma_m)]^{1/4},$$

where

$$F_1 = (1/2)\,[z - (z^2 - 4x^2y^2)^{1/2}],$$

$$x = r_2/S, \quad y = S/r_1, \quad z = 1 + (1 + x^2)\,y^2,$$

and $A_1 = \pi r_1^2$. P is the radiant power and σ_m is the Stefan-Boltzmann constant. The quantities r_1, r_2 and S are the radius of the black-body aperture, the ACR aperture, and the distance between the two apertures, respectively. However, at the infrared wavelengths where most of the radiant power exists for these cryogenic black bodies, the irradiance at the ACR aperture cannot be determined solely by geometrical optics. Diffraction effects at both limiting and nonlimiting apetures along the optical path between the black-body cavity and the ACR aperture affect the power transmitted to the ACR. Diffraction losses at each aperture along the optical path must be estimated.

Table 1 lists the diffraction corrections for a recent black-body calibration that was performed in the LBIR facility. The black-body assembly included an aperture wheel with a blank position and five apertures ranging in size from 0,2 mm to 6,4 mm in diameter. The calibration was performed over the black-body temperature range 60 K to 400 K. The diffraction corrections are listed as a function of black-body temperature and aperture size. The power at the ACR aperture ranged from 10 nW to 100 μW, as a function of temperature and aperture size. Values less than 10 nW were not measured since the expanded uncertainties would have exceeded 1 % or 2 % of the measured value. Figure 3 is a graph of the difference between the radiance temperature and the black-body-sensor platinum resistance thermometer (PRT) temperature for the largest aperture. The triangles represent data without the diffraction correction applied and the circles represent corrected data. The dashed

Table 1. Calculated diffraction corrections (percentages) to be applied to the measured radiant flux. The corrections are listed for each of the five black-body apertures versus the black-body temperature.

Nominal black-body temperature/K	Aperture diameter/mm				
	0,204	0,284	0,405	3,214	6,407
60				3,8	2,3
70				3,2	2,0
80				2,8	1,7
100				2,2	1,4
125				1,8	1,1
145				1,5	0,9
170			11,8	1,3	0,8
195		15,2	10,1	1,1	0,7
225	19,0	12,9	8,6	1,0	0,6
250	16,7	11,5	7,7	0,9	0,5
275	15,0	10,3	7,0	0,8	0,5
315	12,8	8,9	6,0	0,7	0,4
400	9,8	6,9	4,7	0,5	0,3

lines bounding the corrected data represent the expanded uncertainty at the 95 % confidence level. The importance of the diffraction corrections to the calibration measurements are clearly demonstrated in the graph. Considerable effort has been expended in the formulation of diffraction solutions that adequately represent the experimental situations. The systematic uncertainty in diffraction corrections is currently estimated to be ± 10 % of the correction value. Work is under way to reduce this uncertainty to a few percent of the correction value by experimental verification of diffraction corrections.

4. Spectral calibration capability

The LBIR facility is currently being enhanced to include the capability of performing spectral measurements and calibrations of infrared sources, detectors, filters and attenuators. A second cryogenic-vacuum chamber has been developed and this will be the centre for spectral calibration activity. This new spectral calibration chamber (SCC), similarly to the existing LBIR chamber, will provide a 20 K low-background environment in which to perform calibrations and carry out experiments.

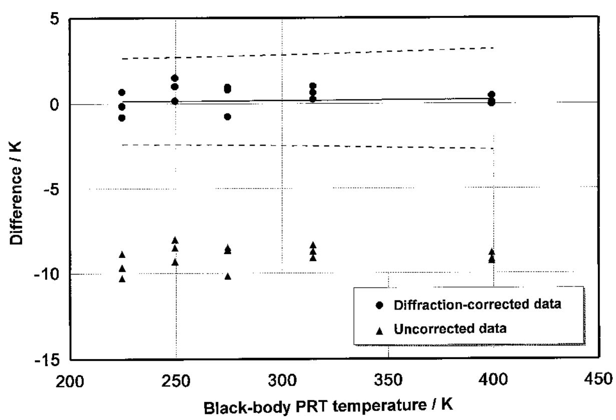

Figure 3. Difference (kelvins) versus the PRT temperature, where the difference is the radiance temperature deduced from the ACR power measurements minus the PRT temperature of the black body.

The LBIR spectral instrument, which will operate in the SCC, is composed of a KRS-5 prism predisperser, followed by a grating monochromator. A schematic drawing is given in Figure 4. The spectral coverage of the instrument is 2 μm to 30 μm, which is achieved using four different ruled gratings on a rotatable grating cube. The bandpass of the instrument is 1 % to 2 % with 500 μm entrance and exit apertures. The spectral instrument is vacuum-compatible and operates at the chamber temperature of 20 K. The prism predisperser is designed with a mirror assembly such that the prism and mirror can be interchanged, thereby removing the prism from the optical path. Also incorporated into the predisperser section of the instrument is a six-element filter wheel to be used for attenuators and filters. The filter wheel is intended to be used with filters for blocking, order sorting, or for spectral characterization.

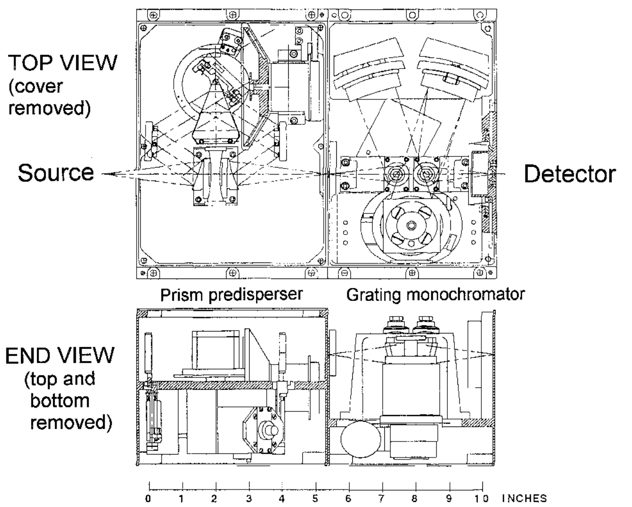

Figure 4. Schematic drawing of the LBIR cryogenic spectral instrument depicting top and end views.

The ACR will be used as the standard detector for the SCC facility. Due to the relatively long time constant of the ACR, approximately 20 s, it is prohibitively time-consuming to use the primary standard for entire spectral scans. Instead, transfer-standard detectors will be used to acquire the bulk of the data and the ACR will be used to establish the absolute scale of the measurements. One type of transfer-standard detector under development is an impurity-band-conductor detector such as arsenic-doped silicon. These detectors have an operating temperature of 10 K and are suitable for a low-

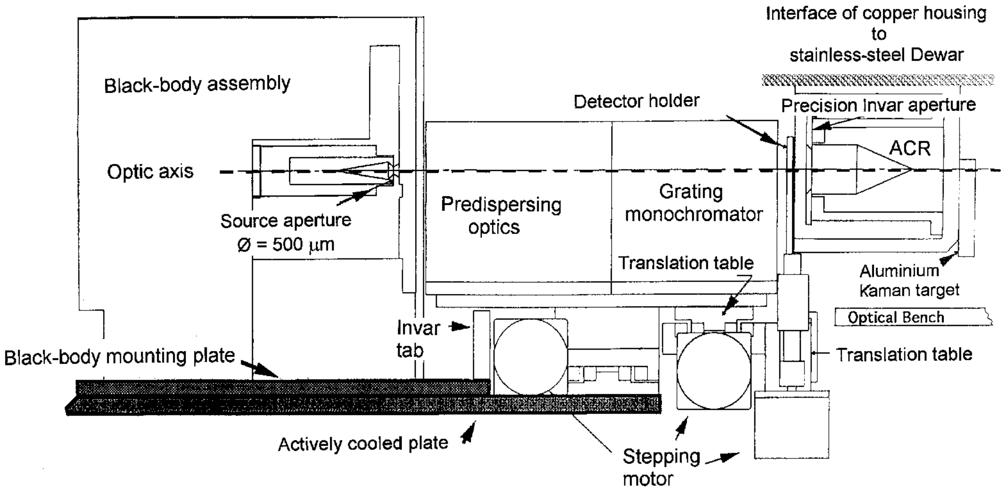

Figure 5. Schematic drawing of the experimental arrangement in the spectral calibration chamber.

background environment. They cover the spectral range 2 µm to 30 µm, which matches the designed range of the spectral instrument. These detectors, once fully developed as transfer standards, will be available for distribution to the infrared-user community.

A black body with a temperature range 50 K to 450 K has been developed for use in the SCC as an infrared source for detector calibration and materials characterization. The black-body assembly includes an aperture wheel with six apertures and a blank position, an eight-element filter wheel, and a chopper wheel. Figure 5 is a schematic drawing of the experimental arrangement in the SCC. The vacuum vessel and the 20 K shroud enclosing the apparatus is not shown. The spectral instrument is mounted on a translation stage which travels perpendicularly to the optical axis. This was done so that the instrument could be translated out of the optical path to allow for the measurement of the broadband radiant flux from the source directly by the ACR without opening the chamber. A detector holder mounted on a two-axis translation stage is also installed so that detectors can be moved on to the optical axis for direct comparison with the power measured by the ACR.

5. Summary

The LBIR facility has been active in the broadband calibration of infrared sources since 1990. The facility is currently undergoing considerable expansion with the completion of a second cryogenic chamber and spectral instrument. This facility represents a considerable enhancement to the infrared user community in traceability to primary national standards.

References

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