Infrared Transfer Radiometer for Broadband and Spectral Calibration of Space Chambers

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ABSTRACT

The Low-Background Infrared (LBIR) facility at NIST has recently completed construction of an infrared transfer radiometer with an integrated cryogenic Fourier transform spectrometer (Cryo-FTS). This mobile system can be deployed to customer sites for broadband and spectral calibrations of space chambers and low-background hardware-in-the-loop (HWIL) testbeds. The Missile Defense Transfer Radiometer (MDXR) has many of the capabilities of a complete IR calibration facility and will replace our existing filter-based transfer radiometer (BXR) as the NIST standard detector deployed to Missile Defense Agency (MDA) facilities. The MDXR features numerous improvements over the BXR, including: a cryogenic Fourier transform spectrometer, an on-board absolute cryogenic radiometer (ACR), an internal blackbody reference, and an integrated collimator. The Cryo-FTS can be used to measure high resolution spectra from 4 µm to 20 µm, using a Si:As blocked-impurity-band (BIB) detector. The on-board ACR can be used for self-calibration of the MDXR BIB as well as for absolute measurements of customer infrared sources. A set of filter wheels and a rotating polarizer within the MDXR allow for filter-based and polarization-sensitive measurements. The optical design of the MDXR makes both radiance and irradiance measurements possible and enables calibration of both divergent and collimated sources. Details of the various MDXR components will be presented as well as initial testing data on their performance.

Keywords: infrared, radiometry, calibration, cryogenic, transfer radiometer, Fourier-transform spectrometer

1. INTRODUCTION

The Low Background Infrared (LBIR) facility at the National Institute of Standards and Technology operates reference detectors that are used to maintain the national standard for low power infrared radiation in the range from nanowatts to milliwatts. LBIR shares this standard with the user community through two primary methods: calibration of customer sources at our facility against our primary standards and by calibration of infrared testbeds at customer sites against our secondary standard transfer radiometers. The primary standard reference detector used is an absolute cryogenic radiometer (ACR), an electrical substitution device which provides a direct physical connection between the optical Watt and the electrical Watt [1-3]. The transfer radiometers contain our secondary standard detectors, which are Si:As blocked-impurity-band detectors which have been calibrated against the ACR standards. These detectors display significant responsivity from 2 µm to 30 µm and noise floor near the femtowatt level.

Since 2001, LBIR has conducted radiometric calibrations of infrared space chambers at customer sites using the Ballistic-Missile-Defense Transfer Radiometer (BXR), our legacy transfer radiometer [4,5]. The BXR is a filter-based radiometer that can calibrate instruments in particular spectral bands from 2 µm to 14 µm and can also perform polarization-dependent measurements. The BXR has exhibited excellent stability over time but has limitations in its spectral capability and, in addition, must be measured before every deployment at our facility to verify its calibration. In 2003, LBIR began development of a new transfer radiometer with expanded radiometric capability, the ability to internally assess its own calibration, and for use as a backup in case the BXR failed or required repair.

LBIR finished construction of its new transfer radiometer, the Missile Defense Transfer Radiometer (MDXR), at the end of 2009 and has completed initial performance tests. The MDXR incorporates a cryogenic Fourier-transform spectrometer (Cryo-FTS), providing full spectral capability over the range from 4 µm to 20 µm [6]. Like the BXR, the MDXR also contains a set of filter wheels, allowing measurements in particular spectral bands. The Cryo-FTS allows the MDXR to characterize spectrally complex or tunable sources which are not smoothly varying in wavelength and to provide high resolution spectral data on the outputs of customer chambers. The MDXR also incorporates an on-board ACR and an on-board blackbody with integrated collimator, allowing for self-calibration. The MDXR will still need to

Capability	**BXR**	**MDXR**
spectral capability	filter-based	Cryo-FTS and filters
stability assessment	limited	ACR and blackbody
polarization capability	rotatable linear polarizer	rotatable and fixed linear polarizers
calibration modes	irradiance, polarimeter	irradiance, radiance, polarimeter, FTS, absolute power
detector base temperature	9 K	2 K

Table 1. Comparison of capabilities of the new NIST transfer radiometer (MDXR) with those of the legacy transfer radiometer (BXR).

be calibrated and inter-compared from time to time with instruments at NIST, but unlike the BXR will be able to assess its own stability over the period of numerous deployments.

In addition to its expanded spectral capability and self-assessment ability, the MDXR will provide several functional advancements beyond the BXR. The MDXR will allow for radiance calibrations, as well as irradiance calibrations similar to those provided by the BXR. The MDXR contains well-defined small area apertures that can be overfilled by the beam under test, so a well-defined solid angle of the source can be sampled in radiance mode. The MDXR internal ACR can make absolute power measurements at the outputs of customer chambers. The BXR has the capability to stabilize its reference detectors at temperatures down to about 9 K, but the MDXR can reach detector temperatures near 2 K using its pumped liquid helium cryostat, allowing optimal operation of its ACR.

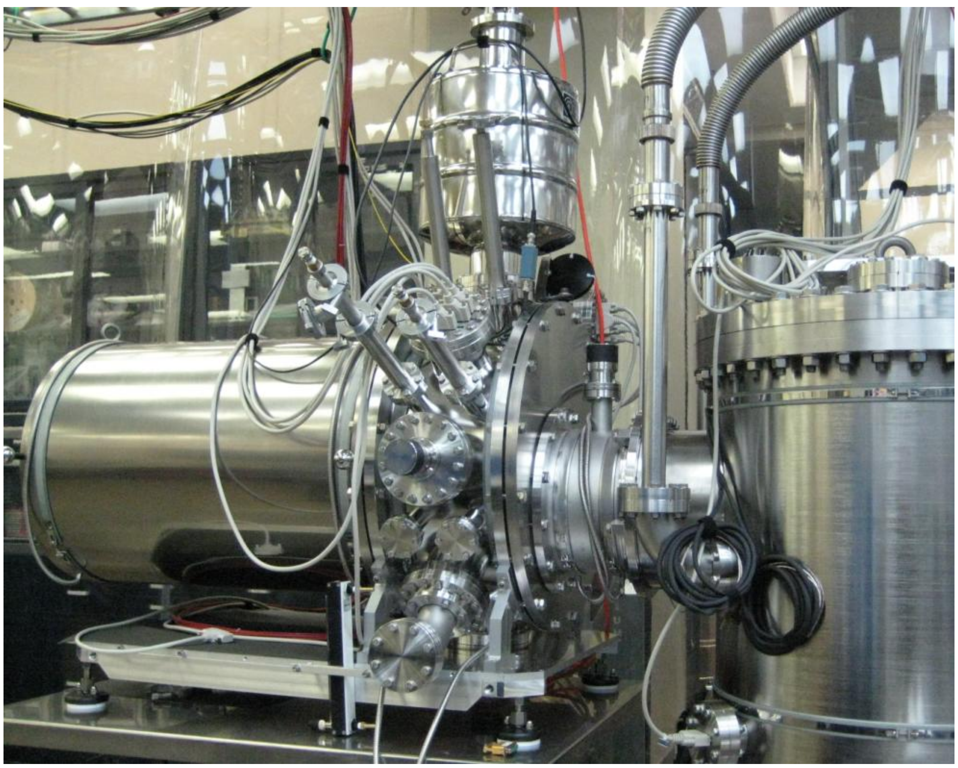
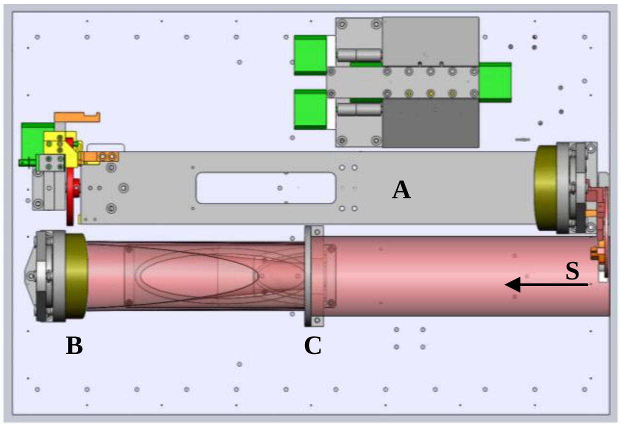


Figure 1. MDXR during calibration with the 10 Centimeter Collimator (10 CC) calibrating source at NIST.

2. DESIGN OF THE MDXR

2.1 Functional Design

The challenge of the MDXR design was to develop a mobile radiometer small enough to be transported to customer sites which could include as complete a calibration suite as possible. Most of the radiometer optics and instruments are attached to an aluminum optics plate with dimensions 610 mm x 406 mm x 25.4 mm (24” x 16” x 1”). The optics plate can tilt in two orthogonal directions relative to the incoming beam and is cooled by flowing liquid helium and surrounded by a liquid nitrogen cooled shroud. The radiometer has a titanium vacuum chamber, a collar with numerous ports for introducing electrical and fiber optic signals from the outside, and is mated to other chambers by a flange with a 250 mm inner diameter. The entire radiometer has a maximum diameter of 610 mm (24”) and total length 1219 mm (48”). A photo of the MDXR attached to one of our calibrating instruments is shown in Figure 1.



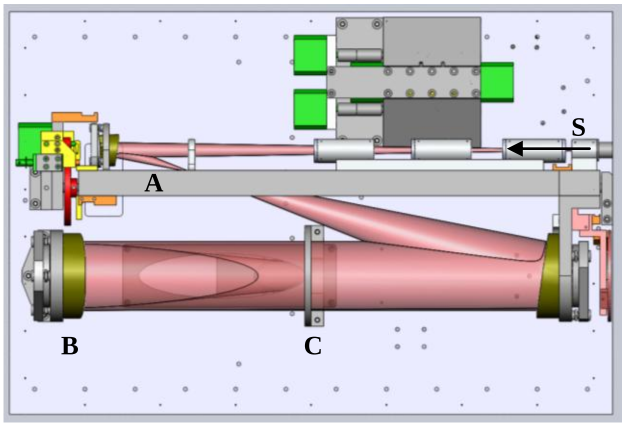


Figure 2. Schematic of the beam entry side of the MDXR showing the beam path (in pink) in two different operational configurations: from an external collimated source (left image) and from the internal blackbody (right image). In the case of the internal blackbody, the collimator plate (A) is rotated into place, and the beam is collimated before reaching the entrance pupil (C) and primary paraboloid (B). The blackbody source is located outside the frame in the images, but the source beam enters each image at the location marked by an arrow and (S).

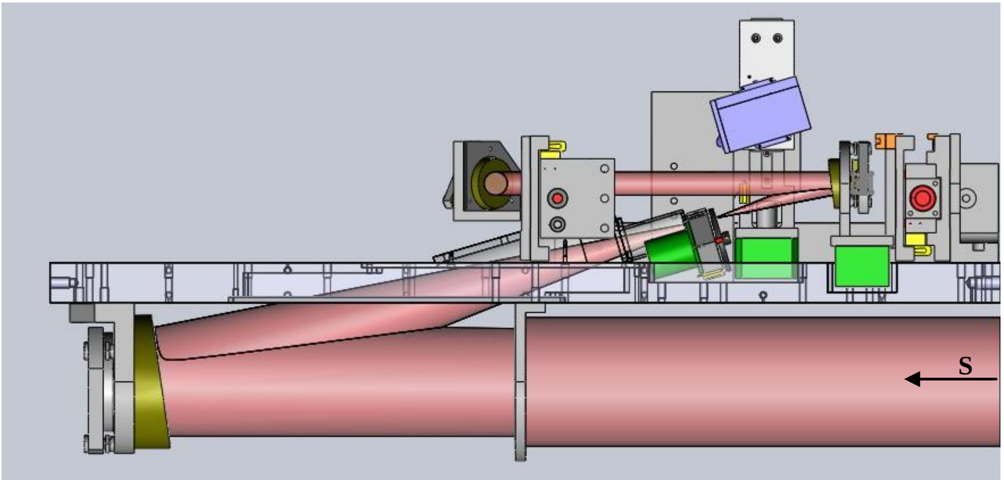


Figure 3. Top view schematic of the MDXR showing the beam path (in pink) from an external collimated source reflecting off the primary paraboloid and traversing the optics plate to reach the detector side of the optics plate.

The optical components of the MDXR populate both sides of the vertically-oriented optics plate in order to minimize the size requirements of the radiometer. Two operational configurations of the beam entry side of the MDXR are shown in

Figure 2. The collimator, comprised of an ellipsoid mirror and a confocal paraboloid mirror, can rotate into and out of the incoming beam path. The collimator is rotated into place for use with the internal blackbody and rotated out of the beam path for calibration of external sources. In all cases, the beam passes through a 7 cm entrance aperture and is focused by the primary paraboloid mirror through a hole in the optics plate to the detector side of the plate, as shown in Figure 3. A view of the detector side of the MDXR optics plate is shown in Figure 4, displaying the beam paths to the Cryo-FTS, ACR and BIB detectors. After passing through a baffle snout from the beam entry side, the beam passes through a field stop wheel with multiple apertures for radiance and irradiance measurements. The ACR can be moved into the beam just beyond the field stop wheel, limiting the uncertainty of the ACR measurements from optical

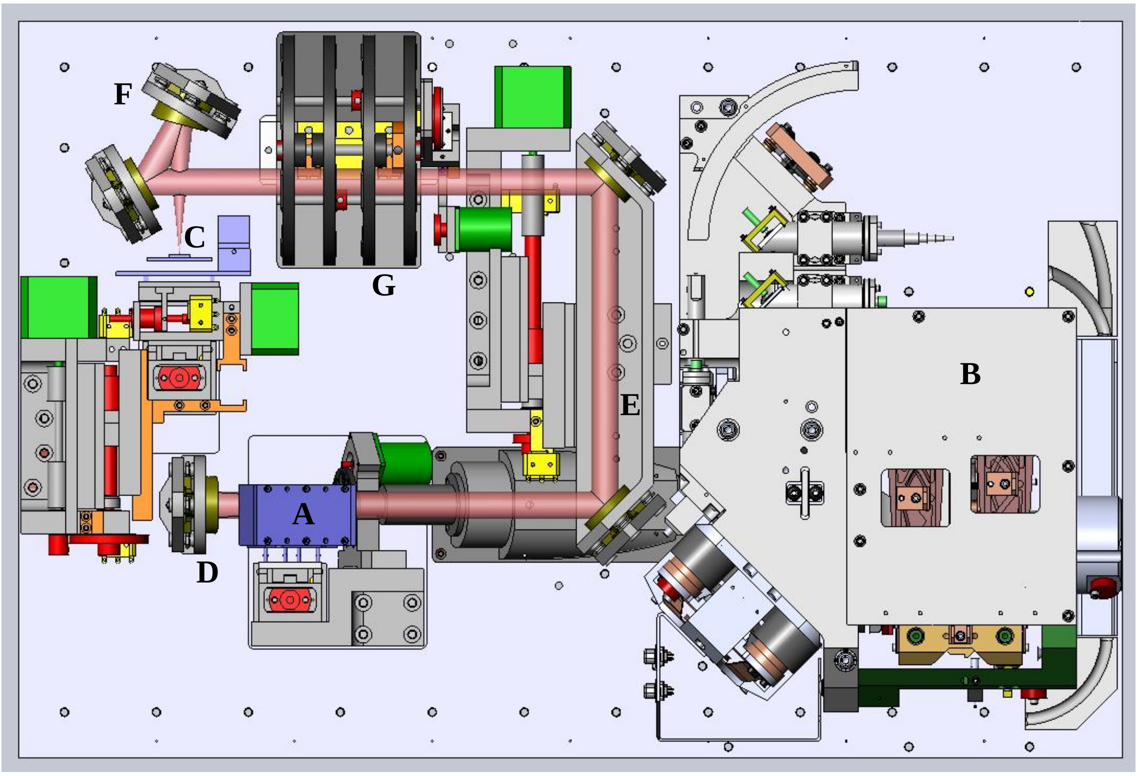


Figure 4. Schematic of the detector side of the MDXR showing the ACR (A), Cryo-FTS (B) and BIB detector (C). The beam is directed by the secondary paraboloid (D), periscope (E) and tertiary paraboloid (F). A set of four filter wheels (G) controls the power and spectral range of the signal which reaches the BIB detector. The beam path shown is for the direct BIB detector configuration (without Cryo-FTS) and in this image the beam can be followed from the secondary paraboloid (D) to the BIB detector (C).

components to the uncertainty of the measured reflectance of the primary paraboloid and the uncertainty of the modeled diffraction correction.

For Cryo-FTS and BIB measurements, the ACR can be moved all the way out of the beam using a single axis motorized stage, allowing the beam to proceed to the secondary paraboloid. The secondary paraboloid produces a nominal 1.5 cm diameter collimated beam. The periscope can be moved up to allow the beam to pass through the Cryo-FTS or down to allow it to proceed directly to the BIB detectors, circumventing the Cryo-FTS. In either case, the beam traverses four filter wheels before being focused by the tertiary paraboloid onto the BIB detectors. The filter wheels contain long-pass filters, short-pass filters, band-pass filters, neutral density filters, fixed polarizers and a spectral reference for the Cryo-FTS. The rotating polarizer is attached to a moveable arm positioned before the filter wheels so it can be rotated into and out of the beam path. The BIB detectors are mounted on a 3-axis stage, allowing for centering and focus of the beam as well as measurements where the spatial profile of the beam can be mapped (using a 100 µm diameter detector).

Cryogenic operation of the MDXR and its detectors is achieved with liquid nitrogen and liquid helium cooling. As shown in Figure 5, a liquid nitrogen (LN_2) cooled, double-walled shroud surrounds a gold-plated shield enclosing the

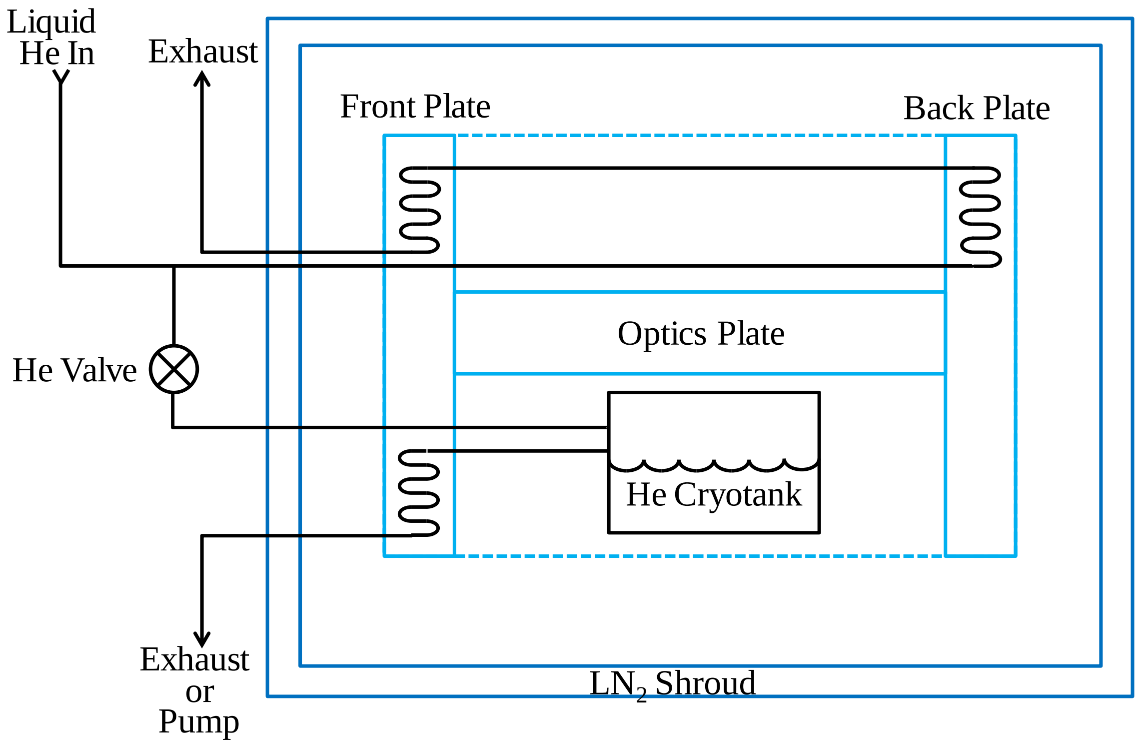


Figure 5. Schematic of the cooling system for the MDXR. Cryogenic control is achieved with a liquid nitrogen cooled shroud, a flowthrough circuit for liquid helium and a liquid helium cryotank.

MDXR optics plate. The shroud is connected to an LN_2 reservoir which is maintained in a filled state throughout a calibration run. A liquid helium flowthrough circuit sunk to the optics plate through its endplates allows cooling of all instruments and optics on the optics plate to temperatures below 20 K. In addition, a liquid helium cryotank within the MDXR can be filled and used to cool the detectors to liquid helium temperatures. The 3 liter liquid helium cryotank can be filled by the same helium dewar used for flowthrough cooling of the optics plate through the operation of a helium valve. The helium reservoir can be pumped at its exhaust to allow the ACR to be operated at temperatures down to 2 K. The cryotank and detectors are thermally isolated from the optics plate in order to achieve one to two day liquid helium hold-times.

2.1 MDXR Detectors and Sources

The Cryo-FTS is a fully functional Fourier-transform spectrometer that can operate within the MDXR cryogenic environment. At its operating temperature near 20 K, the Cryo-FTS exhibits negligible thermal background signal and drift compared to conventional Fourier-transform spectrometers, making it an ideal tool for low power calibrations. Fiber optic connections from an external metrology source and controller are used to launch metrology signals to the Cryo-FTS and enable functional tests. The Cryo-FTS employs a KBr beamsplitter and provides data over the wavelength range of 4 µm to 20 µm. In acceptance testing the Cryo-FTS demonstrated resolution less than 1 cm^{-1}, scan-to-scan reproducibility less than 1 % and modulation efficiency near 40 %.

The MDXR makes use of Si:As BIB detectors with sizes from 100 µm diameter to 3.2 mm square. The largest detector is used with the Cryo-FTS and for most applications, and the smaller detectors can be used for spatial mapping of the beam and for low-power, high-sensitivity measurements. These BIB detectors have spectral sensitivity from 2 µm to 30 µm, detectivity near 10^{14} cm·$Hz^{1/2}$/W at 12 K, response times less than 10 µs and spatial uniformity better than 1 % over 1 mm [7,8]. The BIB signal is amplified by a cryogenic amplifier mounted near the detector board to minimize noise. The detector is kept near 10 K, but the cryoamp, thermally isolated from the detector on a G-10 tower, is kept at temperatures above 130 K.

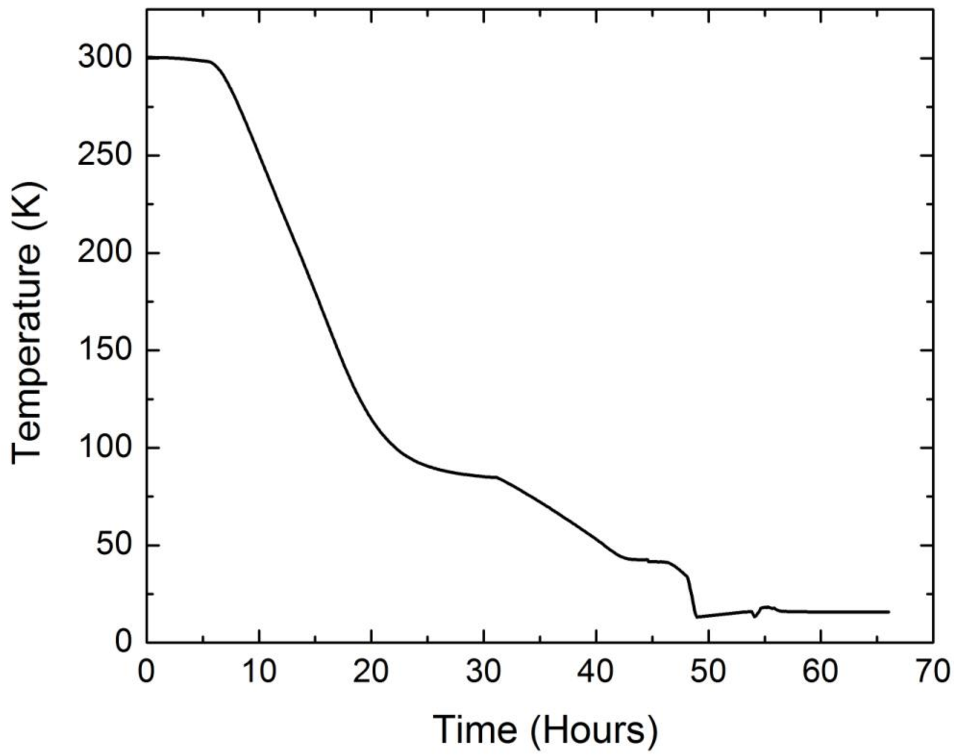


Figure 6. Cooldown trajectory of the MDXR optics plate. It takes approximately 50 hours to cool from room temperature to the base temperature of 15 K to 20 K. The data shown has been clipped at two locations where we dwelled at fixed temperatures before initiating further cooling.

The MDXR ACR is compact and utilizes a weak thermal link to maximize its power sensitivity. The receiver is composed of an electroformed Cu cone, and it is painted with infrared-absorbing black paint on its inside to maximize absorptivity. There is an opening at its entrance, offset with respect to the cone axis, and photons reflect specularly a minimum of 12 times before exiting the receiver. The thermal link between receiver and heat sink is made from thin-wall stainless steel tubing and in acceptance testing the time constant of the ACR was approximately 70 s with peak-to-peak noise of about 100 pW at 2.8 K.

Designed to operate between 200 K and 400 K, the internal blackbody of the MDXR can assess stability of the radiometer and potentially act as a calibration source once it is fully characterized. The blackbody is composed of a core approximately 32 mm in diameter and 40 mm long which contains a conical cavity painted with IR absorbing paint and is heated by a single 25 W compact cartridge heater. The blackbody optical output passes through a 0.5 mm aperture and is collimated by the integrated collimator of the MDXR before reaching the detectors or Cryo-FTS. In addition to the blackbody, the MDXR also contains an infrared LED and a broadband-IR filament source for cryoamp and Cryo-FTS functional tests and characterization.

3. INITIAL TESTING RESULTS

To date there have been 5 successful cooldowns of the MDXR, with the last two runs featuring its complete set of working instruments. The cooldown of the MDXR to its base temperature requires about 50 hours, as shown in Figure 6. It takes approximately 24 hours to cool the MDXR optics plate, optics and instruments below 100 K using liquid nitrogen and another 24 hours to reach the base temperature near 20 K using liquid helium. By increasing the flow rate of helium through the cooling circuit, the temperature of the MDXR chamber parts have been cooled as low as 12 K. Base temperature for the BIB detector is less than 5 K and the ACR has reached temperatures below 2 K. Hold time for the helium cryostat is 48 hours without pumping and 18 hours when pumped down to a base temperature near 2 K. All

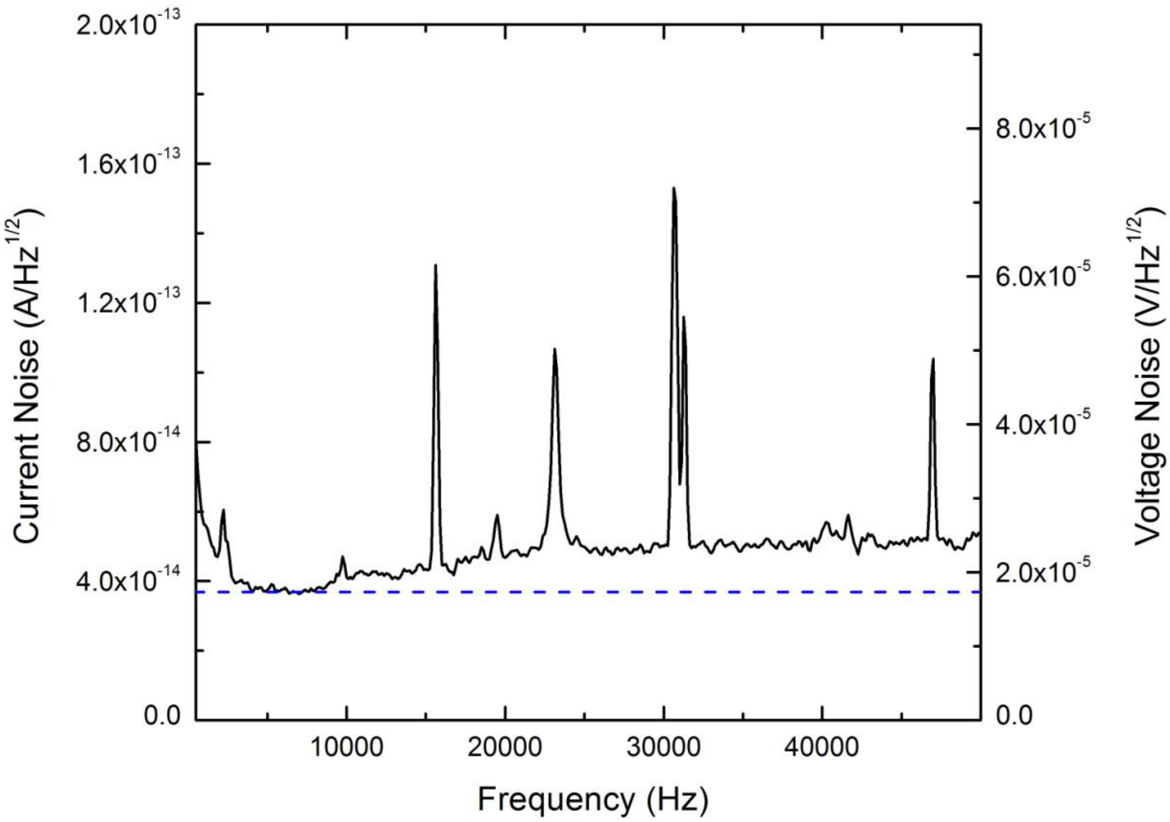


Figure 7. Noise data (solid black line) from the BIB cryoamplifier assembly with the BIB detector operated at 10 K. The detector noise performance is near the theoretical Johnson- and shot-noise floor (dashed blue line).

MDXR components are operational and work as intended, except for the rotatable linear polarizer which still requires mechanical adjustment of its mount.

BIB detector and cryoamplifier tests have demonstrated low noise as well as sufficient bandwidth for FTS measurements. Dark current of the 3.2 mm x 3.2 mm BIB detector measured at a temperature of 10 K within the MDXR is approximately 4.25 nA. The frequency dependent noise of the detector-cryoamplifier combination is shown in Figure 7, exhibiting levels near the theoretical Johnson- and shot-noise level for the BIB detector for frequencies below 50 kHz. Frequency-dependent response measurements exhibit a 3 dB falloff point near 20 kHz. Tests of response to square wave optical inputs exhibit little ringing, which means the Cryo-FTS can operate without detector frequency response artifacts.

ACR noise levels and reproducibility measured for the miniature radiometer within the MDXR were similar to those of the larger ACRs operated as low power primary standards at our NIST facility. Peak-to-peak noise of around 200 pW was seen near low receiver power levels on the order of 10 nW. Reproducibility of average power level was approximately 11 pW (k=1). The ACR in the MDXR was used to view the output of a blackbody source from our 10 Centimeter Collimator (10CC) calibrating instrument, which has been previously measured by other ACRs and secondary standards at our facility. Comparing with previous ACR measurements of this blackbody, the MDXR ACR data was 2 % to 3 % lower in its initial tests. We have measured output signal from both the MDXR BIB and ACR for various MDXR optical configurations and 10CC blackbody temperatures and have begun recording the reproducibility of the measured signals from run to run in order to quantify their relative uncertainty.

Tests of the Cryo-FTS show that it operates reliably at temperatures near 20 K within the MDXR. Background measurements of the MDXR by the Cryo-FTS with all sources shuttered indicate that thermal offsets are below the noise floor of our BIB detector and cryoamplifier. Estimates of noise level have been made from repeatability measurements of the Cryo-FTS viewing the internal blackbody. It is estimated that the Cryo-FTS noise floor is approximately 14 fW in a 4 cm^{-1} interval about 600 cm^{-1}. The Cryo-FTS has been used to collect data on the blackbody, LED and thermal IR sources of the MDXR as well as various filters. The left image of Figure 8 displays data from a high resolution 1 cm^{-1} scan, showing that the Cryo-FTS can distinguish etalon interference fringes of the MDXR BIB detector which have a periodicity of approximately 4 cm^{-1}. The spectral signature of a 10 µm to 11 µm band-pass filter in the MDXR was captured by the Cryo-FTS and is shown in right image of Figure 8.

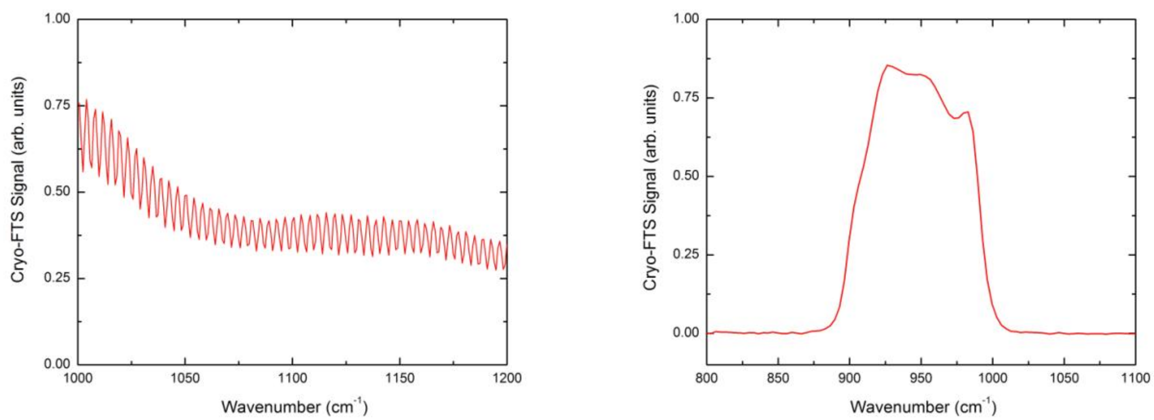


Figure 8. Data showing some capabilities of the Cryo-FTS operating within the MDXR. The Cryo-FTS, operated with a scan resolution of 1 cm^{-1} can distinguish the intrinsic 4 cm^{-1} Fabry-Perot interference fringes of the MDXR BIB detector (left image). The Cryo-FTS has been used to help characterize the properties of the 10 µm to 11 µm band-pass filter in one of the MDXR filter wheels (right image).

4. CONCLUSIONS

NIST's new transfer radiometer with full spectral capability from 4 µm to 20 µm is ready for deployment to customer facilities for broadband and spectral calibration of infrared test chambers and hardware-in-the-loop testbeds. Initial measurements show that all major instruments and assemblies of the MDXR are fully operational and performing well. Reproducibility tests are underway to quantify uncertainty associated with the BIB detector, ACR, Cryo-FTS and blackbody for all possible MDXR optical configurations. The MDXR will be fully calibrated against legacy ACRs at our facility once it has been determined the MDXR is in its final hardware configuration. The BXR, our legacy transfer radiometer, will be kept operational but it is expected that the MDXR will soon be the primary NIST instrument for infrared test chamber calibrations.

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