Cryogenic Fourier Transform Infrared Spectrometer from 4 to 20 Micrometers

Simon G. Kaplan, Solomon I. Woods, Timothy M. Jung, and Adriaan C. Carter
National Institute of Standards and Technology, Gaithersburg, MD 20899

ABSTRACT

We describe the design and performance of a cryogenic Fourier transform spectrometer (Cryo-FTS) operating at a temperature of approximately 15 K. The instrument is based on a porch-swing scanning mirror design with active alignment stabilization using a fiber-optic coupled diode laser and voice-coil actuator mechanism. It has a KBr beamsplitter and has been integrated into an infrared radiometer containing a calibrated Si:As blocked impurity band (BIB) detector. Due to its low operating temperature, the spectrometer exhibits very small thermal background signal and low drift. Data from tests of basic spectrometer function, such as modulation efficiency, scan jitter, spectral range, and spectral resolution are presented. We also present results from measurements of faint point-like sources in a low background environment, including background, signal offset and gain, and spectral noise equivalent power, and discuss the possible use of the instrument for spectral characterization of ground-based infrared astronomy calibration sources. The Cryo-FTS is presently limited to wavelengths below 25 micrometers but can be in principle extended to longer wavelengths with changes in beamsplitter and detector.

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

1. INTRODUCTION

Since 2001, the Low-Background Infared (LBIR) facility at the National Institute of Standards and Technology (NIST) has provided radiometric calibrations of the collimated output beam irradiance from ground test chambers used in the development and testing of infrared (IR) sensors for missile defense applications. These calibrations have been performed using the Ballistic Missile Defense Transfer Radiometer (BXR), a cryogenic radiometer with a 7 cm entrance pupil [1]. The BXR is calibrated against an absolute cryogenic radiometer (ACR) at NIST and uses a Si:As blocked-impurity band (BIB) detector and a set of 10 bandpass filters from 2 μm to 14 μm wavelength to provide coarse spectral coverage over the wavelength range of interest to the missile-defense community. The uncertainty (k=1) in these calibrations is typically ± 3 % over a range of approximately 10^{-14} W/cm^2 to 10^{-9} W/cm^2.

However, spectrally complex or tunable sources cannot be adequately characterized or calibrated with a discrete filter radiometer such as the BXR. NIST has thus developed a new portable cryogenic radiometer, the Missile Defense Transfer Radiometer (MDXR), which includes several enhancements relative to the BXR, and specifically a cryogenic Fourier-transform spectrometer (Cryo-FTS) designed to provide continuous spectral coverage from 4 μm to 20 μm with < 1 cm^{-1} resolution. The Cryo-FTS/BIB detector combination is capable of measuring spectral fluxes in the long-wave infrared of the order of ~ 14 fW in a 4 cm^{-1} spectral interval with 1 minute of averaging, thus potentially making it of interest in calibration of astronomical instruments as well. In particular, the Cryo-FTS could be used for ground-based absolute spectral calibrations of the following components in the calibration chain of infrared astronomical missions: low power calibration sources used in the design and testing of mission instruments, infrared detectors, and test chambers where the combined throughput of numerous optics must be determined.

The Cryo-FTS was constructed to NIST specifications under contract to Telops, Inc. [2]. Its design, construction, and preliminary ambient temperature performance have been reported previously [3], along with the results of initial performance testing at 15 K [4]. In this paper, we describe the results of initial radiometric testing and calibration of the Cryo-FTS mounted in the MDXR.

2. DESIGN OF THE CRYO-FTS

The Cryo-FTS [5] is shown in Figure 1 as mounted in the MDXR. All of the mechanical and IR optical components, including the BIB detector and preamplifier, are contained in the vacuum cryogenic space of the radiometer chamber. The metrology beam originates from a single-mode 783 nm distributed feedback (DFB) diode laser that is fed into the vacuum chamber using a single-mode optical fiber. The collimated metrology beam is passed through the Michelson

Modern Technologies in Space- and Ground-based Telescopes and Instrumentation, edited by Eli Atad-Ettedgui, Dietrich Lemke, Proc. of SPIE Vol. 7739, 77394D · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.857441

interferometer, parallel to the IR beam, and is collected by an array of multimode fibers designed to measure the optical path difference in the interferometer as well as wavefront tilt. The metrology exits the vacuum space through a fiber optic feedthrough to photodiode detectors in the ambient control electronics box. The beamsplitter and compensator are made from KBr substrates, with a coating on the beamsplitter to optimize modulation efficiency from 4 µm to 20 µm wavelength. The moving mirror mechanism is a porch-swing design with steel flexures that provides a maximum optical path difference of 1.4 cm.

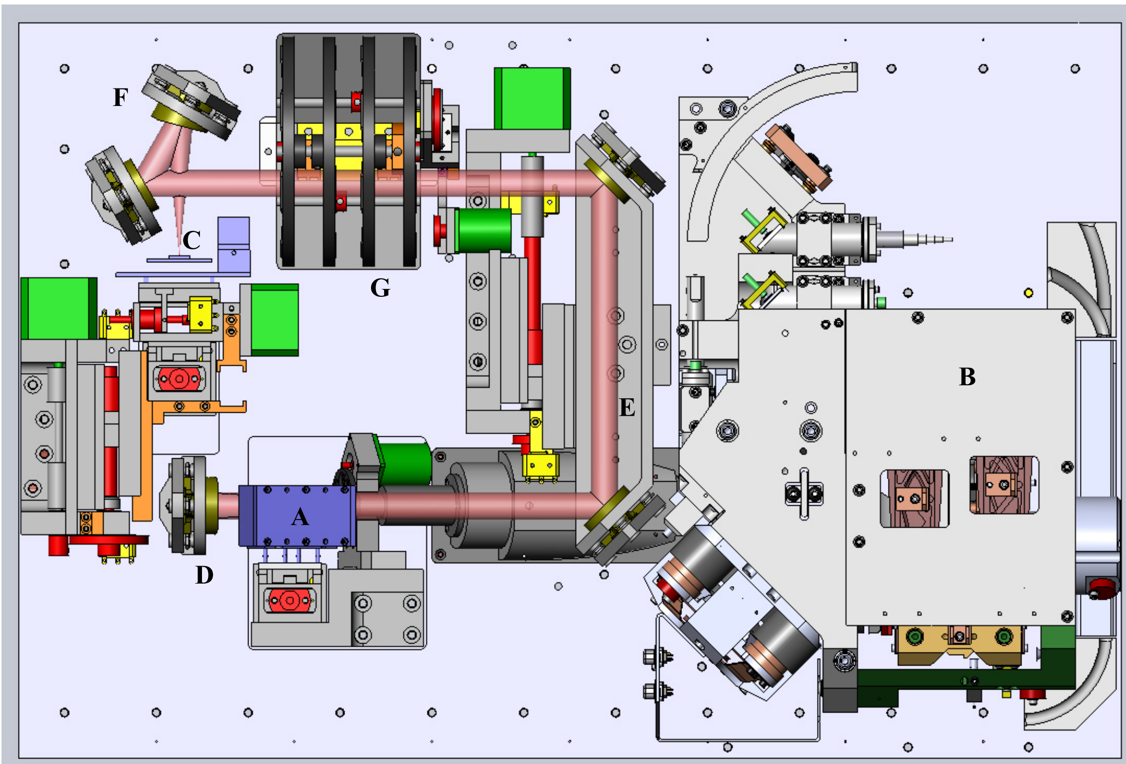

Figure 1. Schematic of the detector side of the MDXR showing the beam path to the ACR (A), Cryo-FTS (B) and BIB detector (C). The beam is directed by the secondary paraboloid (D), periscope (E) and tertiary paraboloid (F). The periscope is moved vertically to allow the incident beam to enter the Cryo-FTS and then exit through the set of filter wheels (G) onto the detector.

Wavefront alignment is maintained using a two-axis voice-coil actuator on a fold mirror placed on the moving mirror side of the beamsplitter. The IR beam, metrology beam, and white light beam for determination of zero optical path difference (ZPD) are displaced horizontally across the beamsplitter. Provision is made in the control software for an offset in the optimum wavefront alignment mirror tilt between the metrology and infrared beams.

The Cryo-FTS clear aperture for the input IR beam is 2.0 cm. Figure 2 shows a photographic view of the layout shown in Figure 1. The MDXR accepts a highly collimated 7.0 cm diameter input beam, which is reduced to a 2.0 cm beam with 3.5 times increased divergence. After passing through the Cryo-FTS, the output beam travels through a set of filter wheels which contain spectral bandpass and neutral density filters, as well as two orthogonal fixed polarizers and a rotatable polarizer, before being focused onto a Si:As BIB detector using an off-axis paraboloidal mirror. The detector is temperature-stabilized at 10 K and mounted on a motorized *x-y-z* stage for alignment.

The MDXR also contains an onboard blackbody source with a 1 mm diameter aperture and 7 cm diameter collimating telescope (on the opposite side of the optics plate shown in Figure 2) which can be rotated into place in front of the defining aperture to allow the Cryo-FTS to alternately view the external beam or a stable internal reference source which can be calibrated with an onboard ACR.

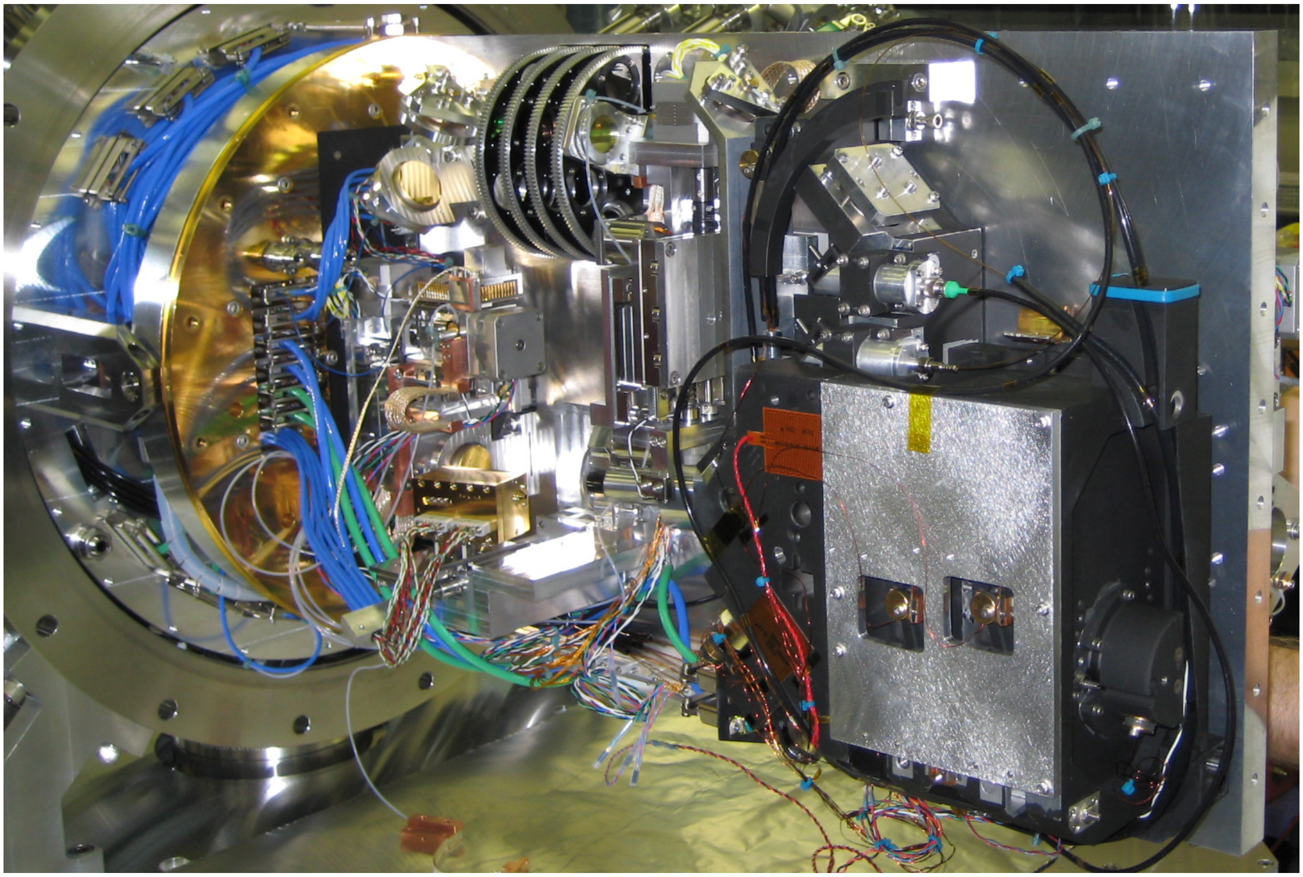

Figure 2. The Cryo-FTS (lower right) as mounted in the MDXR chamber. The output beam from the Cryo-FTS passes through the filter wheel assembly in the top center of the picture before striking a fold mirror and being focused down to the detector stage by the off-axis paraboloidal mirror in the upper left.

The basic function of the Cryo-FTS was tested in a cryogenic test chamber with a 1.7 cm defining aperture using an external 3.39 mm HeNe laser source to determine the modulation efficiency and limiting spectral resolution. The modulation efficiency was found to be between 78 % and 90 % of ideal [6] , and the limiting resolution is 0.85 cm^{-1}. The results of these tests have been reported previously [4, 7]. Also, an external 500 K blackbody source was used to determine the stability of the spectral response over a broad wavelength range. Scan to scan jitter was found to be approximately 0.5 %, and drift over a period of hours was found to be approximately 1 %. Comparisons of blackbody spectra taken at temperatures of 500 K and 600 K indicated linearity of system response to within approximately 1 %.

3. RADIOMETRIC CALIBRATION OF THE CRYO-FTS

The goal of the Cryo-FTS in the MDXR is to acquire calibrated irradiance spectra of user sources with a relative expanded radiometric uncertainty of 1 % . The stability of the scanning mechanism appears to be able to meet this requirement at moderate spectral resolutions. However, we must also consider the contribution of systematic uncertainty components such as nonlinearity, inter-reflections, stray light, and FTS phase error. The Cryo-FTS was mounted in the MDXR vacuum chamber, as shown in Figure 2, and optically aligned to within 0.5 mrad using retroreflection from an optically flat reference surface adjacent to the IR beam entrance port of the spectrometer. The Cryo-FTS was used to view either the internal MDXR blackbody source, with its 1 mm diameter aperture, or the output of the NIST 10 cm collimator source, with variable apertures from 50 μm to 2 mm diameter.

Figure 3 shows a set of spectra acquired with the Cryo-FTS viewing the 10 cm collimated source with a blackbody temperature of 600 K. A 2 mm thick AgCl filter is placed in the beam path inside the collimated source in order to block long wavelength radiation beyond the limit of the Si BIB detector (30 μm). Comparisons can then be made to the spectrally integrated power measured by the MDXR ACR. Ratios for the three largest signals in Figure 3 show agreement to within 3 % with the power ratios measured by the ACR. For the smallest (50 μm) aperture, the signal drops below the noise floor for wavelengths longer than 15 μm. The spectra taken with the 10 cm collimator shutter closed show detector and amplifier noise but no evidence for background signal from the 15 K environment.

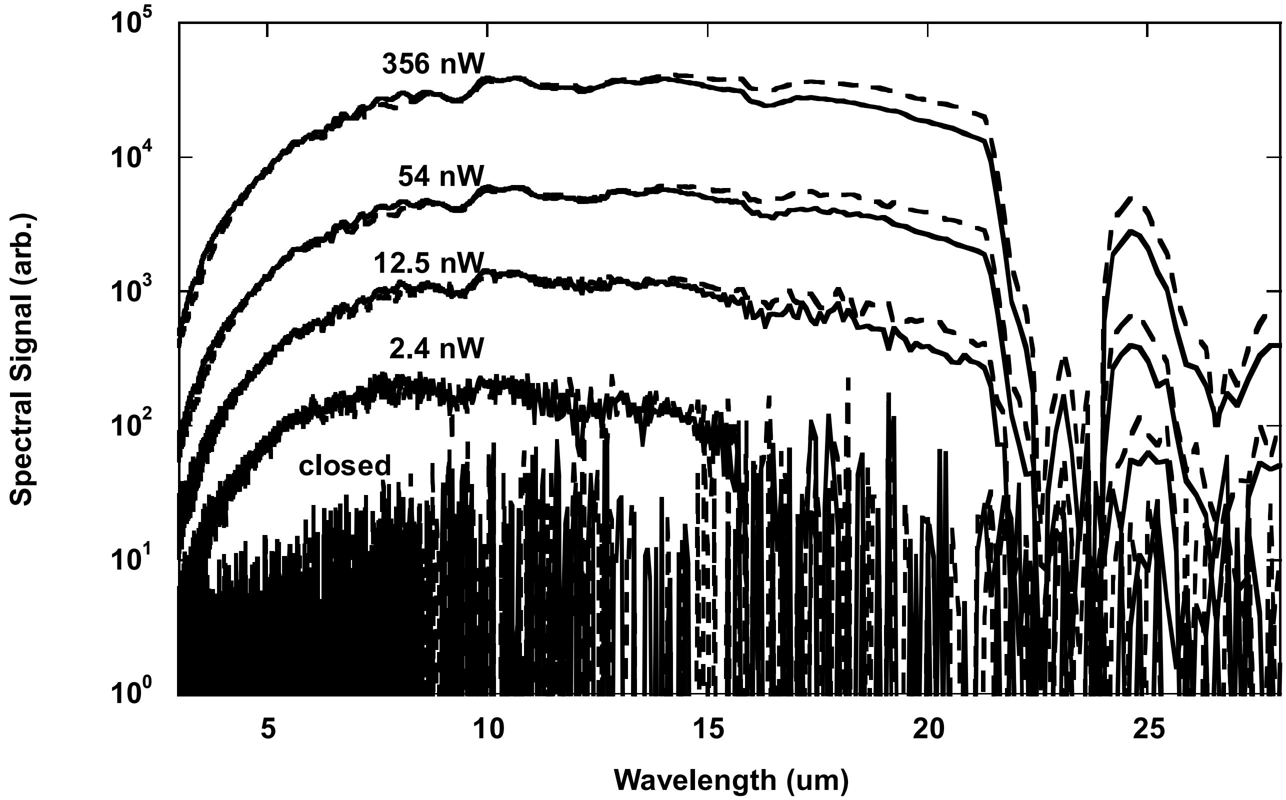

Figure 3. Cryo-FTS spectra of the 10 cm collimator output with a blackbody temperature setpoint of 600 K. Dashed curves, horizontal polarization; solid curves, vertical polarization. Spectra were taken with aperture stops of 0.5 mm, 0.2 mm, 0.1 mm, and 0.05 mm. They are labeled by the expected spectrally integrated power incident on the MDXR defining aperture, as measured by the ACR. Also shown are spectra with the 10 cm collimator shutter closed.

A standard method for calibrating the spectral radiance response of an FTS radiometer is based on using alternate views of the scene of interest and blackbody sources at two different temperatures [8]. In our case, with the background signal viewed by the Cryo-FTS being indistinguishable from zero (within the noise), we can take one of the two blackbody temperatures as effectively zero, and use the internal MDXR blackbody source at a fixed temperature to derive a radiometric scale for the Cryo-FTS. Figure 4 shows the Cryo-FTS spectral signal acquired with 1 min of averaging while viewing the internal MDXR blackbody source at a temperature of 400 K.

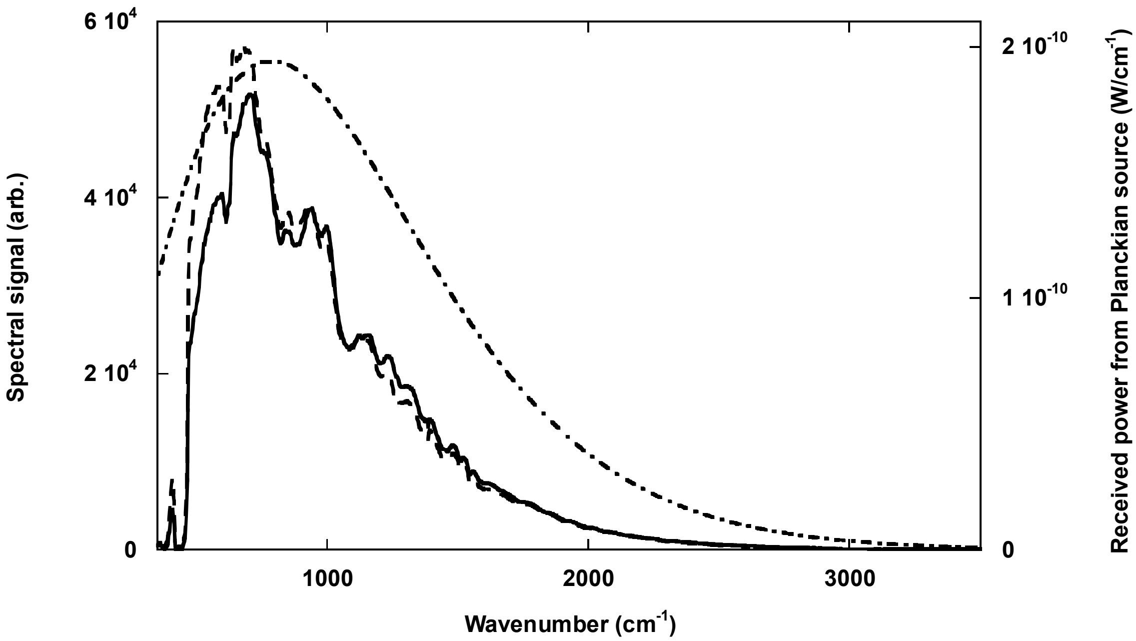

Figure 4. Spectral signal measured by the Cryo-FTS viewing the internal MDXR blackbody source at 400 K. Dashed and solid curves show the response for horizontally and vertically polarized light, respectively. Also shown (dash-dotted curve) is the expected received power per unit wave number for an ideal Planckian source at 400 K.

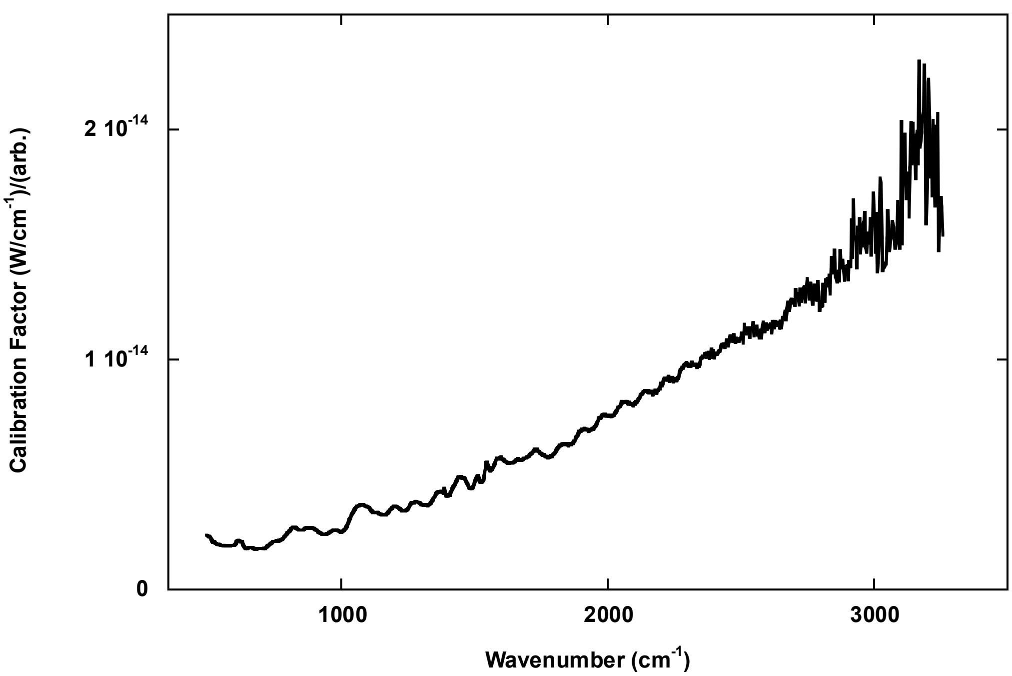

Figure 5. Spectral responsivity calibration curve for the Cryo-FTS derived from internal MDXR blackbody source at 400 K.

The calculated expected received spectral power is derived from the product of Planck's radiance equation with the geometrical throughput of the MDXR 7 cm collimator, 1.738×10^{-10} m^2, and the reflectance throughput of the two collimator mirrors, estimated as 0.99^2. A spectral responsivity curve is derived for the Cryo-FTS by dividing the calculated received spectrum by the sum of the measured spectra for horizontal and vertical polarization, This curve is shown in Figure 5.

The nearly linear wavenumber dependence above 1000 cm^{-1} is expected from the responsivity of the Si:BIB photodetector. In order to test the Cryo-FTS calibration, we examine spectra acquired from the 10 cm collimator output with a blackbody temperature of 600 K, four different apertures, and a set of bandpass filters, for which the spectrally integrated received power at the MDXR input aperture has also been determined by measurements with the ACR placed in the beampath before the Cryo-FTS. Spectra for the 0.5 mm aperture are shown in Figure 6.

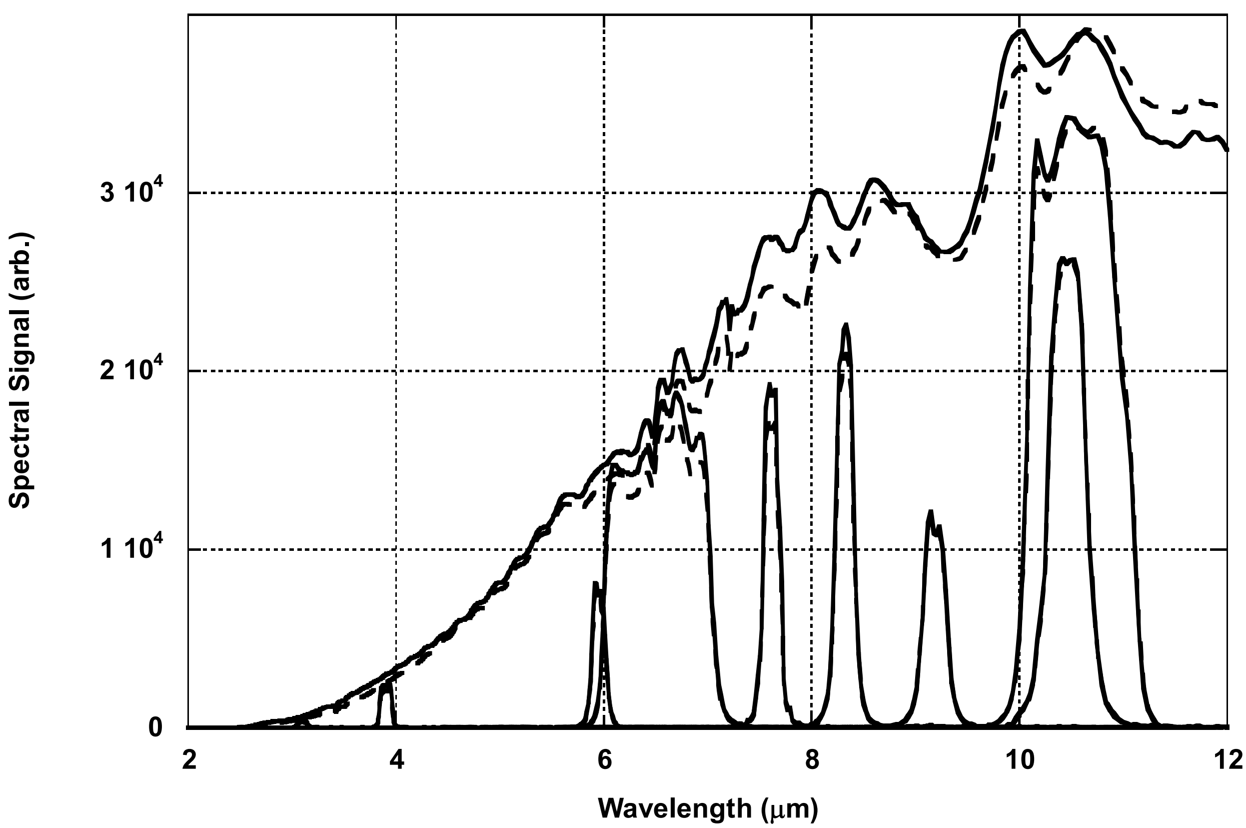

Figure 6. Spectra acquired with the Cryo-FTS from the 10 cm collimator with a blackbody temperature of 600 K, 0.5 mm aperture, and a set of nine bandpass filters with center wavelengths between 3.2 μm and 10.6 μm.. Also shown is the spectrum with only the AgCl long-wave blocking filter in place. In each case, the dashed curve is for horizontal polarization and the solid curve for vertical polarization.

For each 10 cm collimator aperture, the pairs of polarized spectra for the 8 longer wavelength filter bandpasses were summed, multiplied by the calibration curve shown in Figure 5, and then integrated over wavenumber from 500 cm^{-1} to 3000 cm^{-1}. The results of these calculations are shown below in Table 1(c), along with the measured powers from the ACR viewing the 10 cm collimator outputs for the same configurations in Table 1(a). The standard deviations for the ACR measurements are shown in Table 1(b); the estimated standard uncertainties in the integrated Cryo-FTS spectral powers listed in Table 1(c) are +/- 0.5 %. The ratioed powers shown in Table 1(d) show good agreement within the standard uncertainties for a filter center wavelength of 4.0 μm, but increasing deviation toward longer wavelengths, with the Cryo-FTS apparently measuring relative excesses of up to ~6 %. This systematic behavior is in qualitative agreement with preliminary diffraction correction calculations for the 7 cm collimator in the MDXR. The excess flux is expected at longer wavelengths because of diffraction from baffles placed in the beam path to restrict the field of view to the internal blackbody aperture.

More extensive tests over a range of internal MDXR and 10 cm collimator blackbody temperatures are being conducted. In addition, the ACR can be used to view the internal MDXR blackbody source to derive its effective radiance temperature. Preliminary measurements of spectral ratios of the internal blackbody output flux between 280 K and 400 K indicate that the measured cavity temperature corresponds to the radiance temperature within 1.5 K. It is expected that these data along with modeling of the blackbody cavity and cavity reflectance measurements at several infrared laser wavelengths can be used to establish the MDXR blackbody as a reliable reference source to within an uncertainty of one percent in spectral irradiance.

Table 1. Power measurements of 10 cm collimator output for apertures 1 through 4 (2 mm, 1 mm, 0.5 mm, and 0.2 mm diameter, respectively), 8 bandpass filters denoted by center wavelength in μm, and a blackbody temperature setpoint of 600 K. Frames (a) and (b) list the power measurements and respective standard deviations made by the ACR, (c) the integrated calibrated Cryo-FTS spectra, and (d) the ratio of the Cryo-FTS to ACR results.

(a) ACR Power (nW)

Filter	Apt 1	Apt 2	Apt 3	Apt 4
4.0	67.921	17.060	4.246	---
6.075	58.006	14.464	3.625	---
7.81	66.220	16.553	4.121	---
8.35	70.962	17.746	4.382	---
9.4	40.651	10.384	2.545	---
10.6	73.249	19.747	---	---
10.5	222.572	55.508	13.644	2.055
6.5	600.206	150.116	37.384	5.915

(b) ACR Std Deviation (nw)

Filter	Apt 1	Apt 2	Apt 3	Apt 4
4.0	0.016	0.008	0.003	---
6.075	0.016	0.007	0.003	---
7.81	0.012	0.007	0.004	---
8.35	0.017	0.008	0.004	---
9.4	0.007	0.005	0.004	---
10.6	0.012	0.007	---	---
10.5	0.048	0.010	0.005	0.004
6.5	0.256	0.040	0.007	0.004

(c) CFTS Power (nW)

Filter	Apt 1	Apt 2	Apt 3	Apt 4
4.0	67.800	17.000	4.264	0.702
6.075	60.030	14.980	3.728	0.601
7.81	69.130	17.200	4.311	0.677
8.35	74.200	18.440	4.619	0.706
9.4	42.530	10.810	2.690	0.417
10.6	77.790	20.810	5.108	0.809
10.5	234.920	58.370	14.380	2.210
6.5	621.500	155.090	38.590	6.147

(d) CFTS/ACR

Filter	Apt 1	Apt 2	Apt 3	Apt 4
4.0	0.998	0.997	1.004	---
6.075	1.035	1.036	1.028	---
7.81	1.044	1.039	1.046	---
8.35	1.046	1.039	1.054	---
9.4	1.046	1.041	1.057	---
10.6	1.062	1.054	---	---
10.5	1.055	1.052	1.054	1.075
6.5	1.035	1.033	1.032	1.039

4. CONCLUSIONS

We have demonstrated the operation of a cryogenic Fourier-transform spectrometer in a 15 K vacuum environment, intended for measuring spectral irradiance from low-power collimated output beams from low-background infrared calibration chambers. Initial testing of stability, linearity, and sensitivity of the Cryo-FTS indicate that it will be capable of making calibrated spectral irradiance measurements to within 1 % uncertainty, with a noise floor of approximately 4 fW/cm^{-1} in the long-wave infrared spectrum between 4 μm and 20 μm wavelength.

7. REFERENCES

1. Adriaan C. Carter, Raju U. Datla, and Timothy M. Jung, "Calibration of low-background temperature IR test chambers used to calibrate space sensors," Metrologia **46**, S213-S218 (2009).

2. The mention of certain commercial products or trade names in this manuscript is for informational purposes only and not meant to imply an endorsement by NIST or that the materials or products identified are necessarily the best suited for the task.

3. Philippe Lagueux, Martin Chamberland, Frédérick Marcotte, André Villemaire, Marc Duval, Jérôme Genest, and Adriaan Carter, "Performance of a cryogenic Michelson interferometer," Proc. of SPIE **6692**, 669209-1 to 669209-11 (2007).

4. Solomon I. Woods, Simon G. Kaplan, Timothy M. Jung, Adriaan C. Carter, and Raju U. Datla, "Cryogenic Fourier transform spectrometer for infrared spectral calibrations from 4 μm to 20 μm," Proc. of SPIE **7660**, 76602I (2010).

5. *Cryogenic Fourier Transform Spectrometer User's Guide*, Telops, Inc. Quebec, Canada, Revision C, p. 1 (2009).

6. Peter Griffiths and James A. DeHaseth, *Fourier Transform Infrared Spectrometry*, 2nd edition, Wiley Interscience, Chapter 1 (2007).

7. Louis Belhumeur and André Villemaire, *Cryo-FT acceptance test report*, Telops, Inc. Quebec, Canada, Revision E, sections 3 and 4 (2009).

8. Henry E. Revercomb *et al* "Radiometric calibration of IR Fourier transform spectrometers: solution to problem with the high-resolution interferometer sounder," Appl. Opt. **27** 3210-3218 (1998).