The Fermilab Large Cold Blackbody Test Stand for CMB R&D

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Abstract

The Fermilab Large Cold Blackbody Test Stand can be used to expose a microwave receiver and horn assembly to a large blackbody at cryogenic temperatures (as low as 20 K). The temperature of the blackbody can be varied while keeping the receiver temperature constant, facilitating Y-factor measurements of the receiver noise temperature and gain. The test stand has recently been used for studying a QUIET-I receiver module. The test stand will be used to measure both QUIET-I and prototype QUIET-II modules.

1. Introduction

The Q/U Imaging Experiment (QUIET) was designed to measure polarization anisotropy in the Cosmic Microwave Background, especially to target the imprint of inflationary gravitational waves. Between October 2008 and December 2010, two independent receiver arrays were deployed sequentially on a 1.4-m side-fed Dragonian telescope operating on the Chajnantor plateau in the Atacama Desert in Chile. The warm optics fed a cryostat that housed an array of coherent receivers cooled to 20 K. In each receiver, the signal was amplified by InP-based HEMT MMICs, phase-modulated at two distinct rates, diode-detected, and then sent to warm electronics for processing. The 19-element Q-band array had an average center frequency of 43.1 ± 0.4, average bandwidth of 7.6 ± 0.5 GHz, and a sensitivity of 69 μKs^{1/2}, as presented in the QUIET paper on Q-band results [1]. The W-band array was comprised of 90 receivers with a center frequency of 95 GHz. Analysis of the W-band data is nearing completion. Instrument sensitivity to angular scales l ~ 25–950 is expected from a combination of the two arrays. The instrument is described in Refs. 2 and 3.

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To better-understand the noise performance of the observations as well as to test new receiver design, the Fermilab Large Cold Blackbody Test Stand was developed. The test stand was designed to facilitate testing (at cryogenic temperatures) of the entire receiver chain: horn, septum polarizer, and radiometer. The large area of the blackbody presents a uniform radiation field to the horn, mimicking the sky. This provides a realistic test of the system, as it would respond on the telescope. The design, construction, and measured properties of the blackbody are described in Section 2. The design of the cryostat and thermal control are covered in Section 3. Test stand electronics and recent measurements of the QUIET receiver temperature are described in Section 4. Concluding remarks including plans for future applications of the test stand are described in Section 5.

2. Blackbody design, construction and properties

2.1. Blackbody design

The blackbody is designed as a single array of pyramids (Fig. 1), unlike many (and our prototype) that are an assembly of many individual pyramids wedged together. We used a 10-degree half angle and 0.75” spacing. The pyramid aspect ratio was loosely based on the Arcade-II design [4,5], while the ARCADE calibrator design was based on that used for COBE/FIRAS [6]. The advantage of the solid design is elimination of cracks between pyramids that inhibit thermal flow and provide a path for light leaks.

Fig. 1. Blackbody (left) and view of the blackbody’s solid aluminum core (right).

2.2. Blackbody construction

The base was machined out of a solid piece of high thermal conductivity aluminum (Alloy 1100-F). The pyramid shapes were milled into the aluminum (Fig. 1) using a custom-made mill cutter. They are sized 3 mm smaller than the desired finished size. Reference mounting holes are used to locate the base to the milling machine. After milling the base shape, dams were installed and Eccosorb CR-112 was poured to fill over the tops of the pyramid tips (Fig. 2). The Eccosorb was mixed in relatively small batches, degassed, and poured slowly into the mold. Great care was taken to ensure no air was trapped in the epoxy. Next, the assembly was put into an oven and cured for 12 hrs at 165 degrees F.

After the epoxy cure, the base was returned to the milling machine. The same cuts were made, but leaving 3 mm of cured epoxy on the pyramids. We used Eccosorb CR-112, made by Emerson-Cumming with <1% Cabosil. Eccosorb is a mixture of black epoxy and iron powder. Care was taken to obtain a
uniform mixture. The iron is an important ingredient. It contributes significant imaginary terms to mu and epsilon and so forms the absorptive part of the index of refraction. Cabosil is a thickening agent. It prevents the iron from settling to the bottom while the blackbody is curing.

2.3. Blackbody properties

Reflectance measurements placed an upper limit of -45 dB return loss for a prototype blackbody as shown in Table 1. The blackbody was illuminated at a 7-degree angle by a 90 GHz Gunn diode and the reflected power was measured with a switched diode detector, also at a 7-degree angle (Fig. 3). The prototype was comprised of individual pyramids (not the improved, solid design) so had ‘cracks’ between each pyramid. It is expected that the solid blackbody’s performance is even better.

Table 1. Measured properties of the blackbody.

<table>
<thead>
<tr>
<th>Device Under Test</th>
<th>90 GHz Reflected Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper Plate</td>
<td>1 mV</td>
</tr>
<tr>
<td>Flat sheet of Eccosorb CR-112</td>
<td>0.3 mV (~5 dB)</td>
</tr>
<tr>
<td>Blackbody Eccosorb CR-112</td>
<td>0.01 ± 0.01 µV (~-45 dB)</td>
</tr>
<tr>
<td>AR-coated window in front of blackbody</td>
<td>~ 3 µV</td>
</tr>
</tbody>
</table>

Fig. 3. The blackbody was illuminated at a 7-degree angle by a 90 GHz Gunn diode (upper left) and the reflected power was measured with a switched diode detector, also at a 7-degree angle (upper right).

3 Cryogenic system

3.1. Cryostat

The cryogenic system is comprised of a CP8000 He compressor, a Cryomech AL63 cryocooler, and an Adixen Drytel 1025 turbo vacuum pump (Fig. 4). The vacuum system is pumped down to the range of 10⁻³ Torr. Then the cryocooler is turned on. It takes ~10 hrs to cool down to 20 K with the stainless steel disk (see Fig. 6b). When the blackbody gets to about 80 K to 70 K, the vacuum starts to cryo-pump into the range of 10⁻⁷ Torr.
3.2. Cooling the blackbody

It was shown (Fig. 5) that the tip of the blackbody tracks the temperature at the aluminum base, so there is no need to install temperature sensors on the blackbody during operation; the control loop can operate on the input from a sensor on the aluminum base.

3.3. Thermal control

There are two thermal control loops: one for the receiver and one for the blackbody. In both cases, DT-470 silicon diode temperature sensors provide input to a Lakeshore controller, which regulates the temperature via Lakeshore cartridge heaters. Temperature monitoring is achieved by interfacing the Lakeshore 336 and Lakeshore 325 temperature controllers through RS232 and USB PC ports. LabView software allows us to read six silicon diode temperature sensors at a desired sample interval, creating data files that are easily imported into Excel and other applications for analysis.

There are two thermal designs that differ in the thermal coupling of the cold head to the blackbody. These are shown schematically in Fig. 6. One uses an aluminum disc for coupling. This provides fast thermal changes of the blackbody but limits the blackbody temperatures to 18 K – 48 K, while keeping...
the module temperature at a constant 26 K. The other uses a stainless steel disk for coupling. The thermal changes are very slow but have the advantage of a wider range of operating temperatures: up to 60 K or higher. It is useful to be able to test at blackbody temperatures near that of LN (77 K) to compare to measurements made at other labs that only have access to LN cooling.

4. Measurements

The Fermilab large cold blackbody test stand facilitates testing the QUIET receiver as used on the telescope, with the receiver connected to the septum polarizer and horn as shown in Fig. 7.

4.1 Electronics

A custom PC board made at Fermilab, based on a 32 bit ARM microcontroller, provides voltage biasing and bias current monitoring of the receiver’s active components via 14-bit DAC/ADCs, 12-bit digitization of the output, and digital demodulation and averaging of the amplitude-modulated output signals. The PC board is connected to the receiver module via an interface board (seen at the top of the image in Fig. 7) and is controlled via LabView. It employs low noise (2 nV/Hz^{1/2}) amplifiers resulting in ~10 nV/Hz^{1/2} referred to input. The board is operated at a 300 kHz cutoff frequency. A copy of the amplified analog output is sent to a KEK-designed ADC [7], which has onboard demodulation electronics.

Fig. 7 View of test stand’s open cryostat with horn, septum polarizer, receiver module, and electronics interface board exposed to the blackbody. The blackbody area is large so that it encompasses the entire horn beam pattern.
4.2. Y-factor measurement of QUIET receiver module

An example of a Y-factor measurement of a QUIET-I module is shown in Fig. 8. The receiver module temperature was held constant at 26 K while the blackbody temperature was varied in discrete 5 K steps from 20 K to 30 K. In this configuration, where the aluminum disk conducts heat between the blackbody and cold head, it took approximately 10 minutes for the temperature changes to settle.

![Y-factor measurement graph]

Fig. 8. Y-factor measurement of a QUIET-I module with the Fermilab cold blackbody.

5. Summary and future plans

We described construction of a monolithic blackbody that can be cooled to 20 K. The entire system is in the same cryostat, so there is no intervening vacuum window as there is in a fielded experiment. Temperature changes of 5 K require approximately 10 minutes of settling time. The blackbody has a large area, so that the response of the combination of horn and receiver to unpolarized signals can be cleanly studied. We will be using this device to evaluate prototype receiver modules for QUIET-II.

6. Acknowledgements

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References