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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.

Keywords: QUIET; cosmic microwave background; polarization; microwave receivers

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. The QUIET experiment is described in these proceedings [1]. Between 2008 and 2010, two independent receiver arrays were deployed sequentially on a 1.4-m dual-mirror crossed-Mizuguchi-Dragone telescope. The warm optics feed a receiver that houses an array of coherent polarimeters cooled to 20 K. The warm telescope optics are coupled to each array of correlation polarimeters via an array of platelet corrugated feedhorns which feed septum polarizers (for the polarization sensitive channels) or hybrid-Tees (in the case of the differential temperature monitors). In each polarimeter module, the signal is amplified by InP-based HEMT MMICs, phase-modulated at two distinct rates, diode-detected, and then sent to warm electronics for processing.

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To better-understand the noise performance of the observations as well as to test new receiver designs, the Fermilab Large Cold Blackbody Test Stand was developed. The test stand was designed to facilitate testing (at cryogenic temperatures) 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 of array of pyramids (Fig. 1), unlike many (and our prototype) that are an assembly of many individual pyramids wedged together. The pyramid aspect ratio was loosely based on the Arcade-II design [2]. We used a 10-degree half angle and 0.75” spacing. The advantage of the solid design is elimination of cracks between pyramids that inhibit thermal flow and provide a path for light leaks.

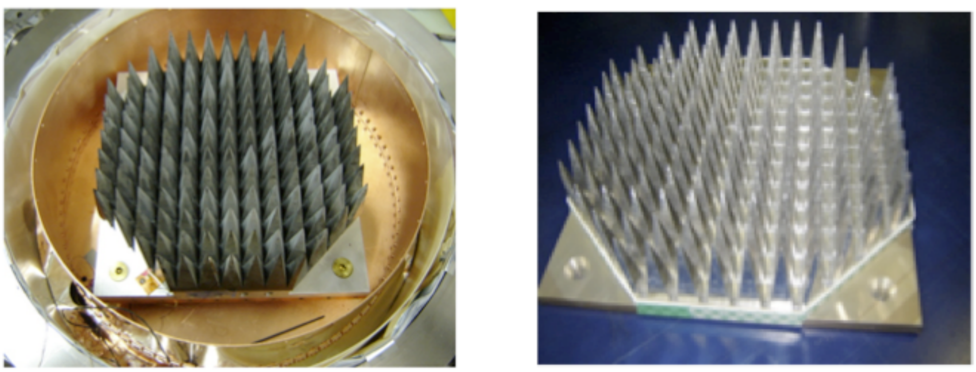

Fig. 1. Blackbody (left) and view of the blackbody’s solid aluminum core (right).

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 using a custom-made mill cutter (Fig. 1). 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 gives the complex coefficient 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.

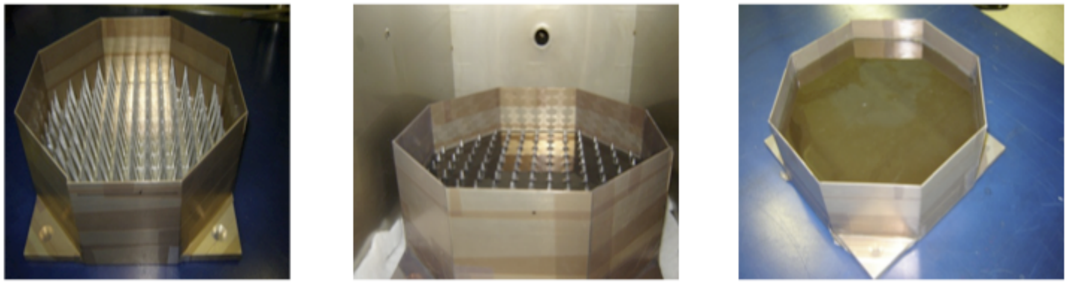

Fig. 2 Views of the pyramids with the dams installed. Shown are three stages of covering the pyramids with Eccosorb CR-112.

2.3. Blackbody properties

Reflectance measurements (Fig. 3) placed an upper limit of -45 dB return loss for a prototype blackbody as shown in Table 1. 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.

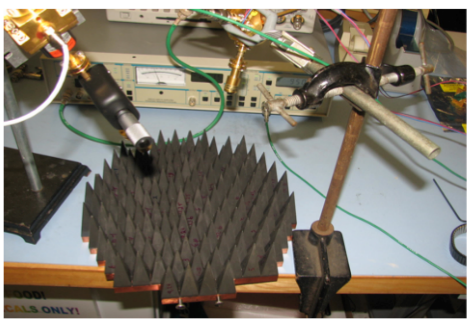

Fig. 3. Reflectance measurement setup of the prototype blackbody at 90 GHz using Gunn diode oscillator (top left) and switched diode detector (top right).

Table 1. Measured properties of the blackbody.

Device Under Test	90 GHz Reflected Power
Copper Plate	1 mV
Flat sheet of Eccosorb	0.3 mV (~-5 dB)
Blackbody	0.01 ± 0.01 μV (< -45 dB)
AR-coated window	
Front of blackbody	~ 3 μV

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. 4a). 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.

Fig. 4 (a) Dewar, vacuum pump, cryocooler, and compressor (b) Copper heat intercept shield (c) Closing the dewar

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.

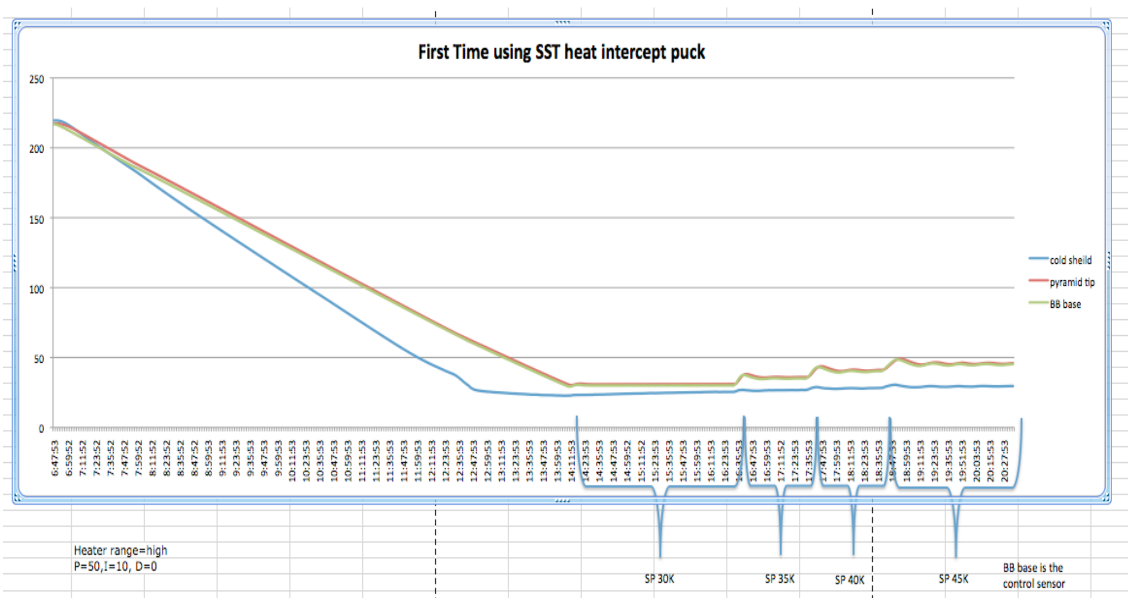

Fig. 5. Typical cool-down cycle of the black body. The temperature of the black body's aluminum base was set sequentially to 30K, 35K, 40K, and 45K. The pyramid tip temperature lags behind aluminum base temperature by

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.

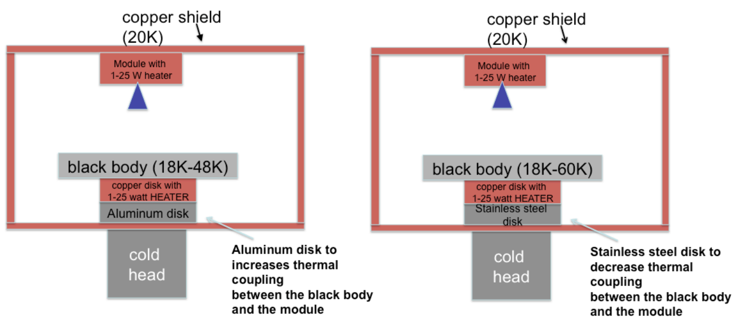

Fig. 6. Schematic of the two thermal designs with different thermal couplings of the cold head to the blackbody

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.

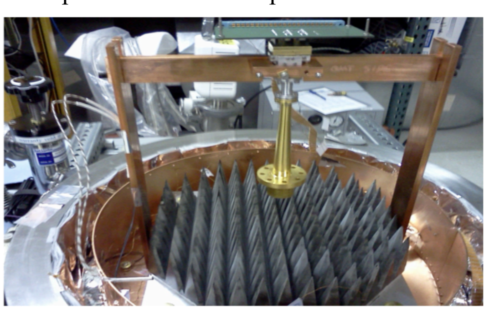

Fig. 7 View of test stand's open cryostat with horn, septum polarizer, receiver module, and electronics interface board exposed to the blackbody. The blackbody area is large so that it encompasses the entire horn beam pattern.

A copy of the amplified analog output is sent to a KEK-designed ADC, which has onboard demodulation electronics. The KEK electronics are described in these proceedings [3].

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.

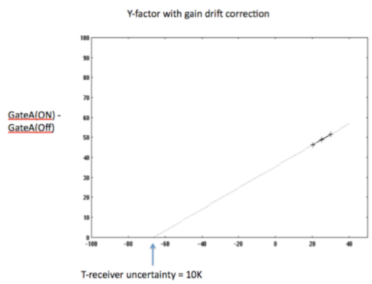

Fig. 8. Y-factor measurement of a QUIET-I module with the Fermilab cold blackbody.

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 modules for QUIET-II.

6. Acknowledgements

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