G-band Reflectivity Results of a Conical Blackbody for Radiometer Calibration

Derek A. Houtz[1], Dazhen Gu[1]

[1]National Institute of Standards and Technology, Boulder, CO.

***Abstract* — Two hollow conical cavities have been developed and built for the National Institute of Standards and Technology (NIST) for use as radiometer calibration sources, or blackbodies. We seek high emissivity, thus low reflectivity, to approximate an ideal blackbody. We present new results on the reflectivity of the smaller conical blackbody in G-band between 130 GHz and 230 GHz. We found monostatic reflectivity, or return loss, no larger than -45 dB at critical remote sensing bands near 165 GHz, 183 GHz, and 229 GHz. We found that use of a thin closed-cell polyethylene insulation layer has a significant impact on reflectivity performance. We compared the reflectivity of the conical blackbody with the reflectivity of a pyramidal absorber array of the type typically used as on-board radiometer calibration sources. The insulated conical blackbody showed an average of 15 dB lower reflectivity than the pyramidal array over the measured band.**

***Index Terms* — Free-space reflectivity, materials characterization, millimeter-wave radiometry, radiometer calibration.**

I. Introduction

Microwave and millimeter-wave radiometers measure passively-emitted Planck and spectral radiation, and have principal applications in weather forecasting and environmental remote sensing. Operational weather satellites use radiometers to collect data on tropospheric temperature, sea-surface temperature, cloud moisture and precipitation, sea ice, ocean salinity and soil moisture, to name a few. Because of the lack of long-term stability of active components in microwave radiometers, continuous calibration is a necessity. Satellite-borne, aircraft-borne, and ground based or in-situ sensors commonly have some form of internal calibration source. Whether this be via an internal blackbody or a noise diode, gain and offset drifts in the radiometer's detection hardware must be quantified and accounted for.

Use of unreliable or non-traceable internal and pre-launch blackbody calibration sources across radiometer platforms has created a lack of consistency and has led to offset biases between instruments [1]. At the National Institute of Standards and Technology (NIST), we are developing reliable and accurate microwave brightness temperature sources to act as a traceability standard for microwave radiometers.

We have designed two conical blackbodies to interface with the Advanced Technology Microwave Sounder (ATMS) [2] instrument's pre-launch calibration hardware. The ATMS is an integral part of the Joint Polar Satellite System (JPSS). The ATMS is currently flying on the Suomi-NPP satellite, a copy will fly aboard the JPSS-1 satellite in late 2017, and there are plans for ATMS copies aboard JPSS-2 and JPSS-3.

The two most important characteristics of a radiometer calibration source, or blackbody, are high emissivity and uniform temperature. According to Kirchoff's law of reciprocity, high emissivity can be demonstrated by showing low reflectivity and thus high absorptivity. In this paper, we measure reflectivity in G-band (130 GHz to 230 GHz) to demonstrate the blackbody performance of the small NIST conical blackbody. We also measure a microwave absorber-coated pyramidal array, the type of blackbody typically used as onboard calibration sources for airborne and spaceborne radiometers.

The two conical blackbodies have radii of 6.8 cm and 10.8 cm respectively and have been designed to operate at frequencies between 18 GHz and 230 GHz. The larger of the two devices was characterized and discussed in [3] but, until now, no measurements have been made on the smaller target or above 110 GHz. Both the small and large targets have the same nominal absorber-layering structure consisting of 3 layers of carbonyl-iron-powder (CIP) impregnated epoxy. In the direction from the copper base structure to the air, the layering structure consists of: 1.3 mm pure epoxy, 2.2 mm 50% CIP by volume, 1.7 mm 5% CIP by volume, and a 3 mm layer of HD-80 closed-cell polyethylene foam. The structure has a cone half-angle of 10°. The pyramidal array we measured has a pyramid height-to-base aspect ratio of 3 to 1, with a base length of 1 cm and a 1 mm coating of microwave absorber.

The organization structure of this paper is as follows: in Section II, we discuss the reflectivity measurement technique and setup, and present the raw measurement data. Section III presents the processed results of the reflectivity measurements in G-band. Section IV discusses the results and draws conclusions.

II. Reflectivity Measurement

Measuring the true emissivity of a body requires knowledge of the full bi-directional scattering function, sometimes referred to as the bi-directional reflectance distribution function (BRDF), as discussed in [3]. This is an extremely difficult measurement to make experimentally, and the monostatic reflectance has often been considered sufficient to approximate emissivity at normal incidence. We have also provided simulations to justify this approximation at low reflectance magnitudes [3]. We measure the monostatic reflectance of the blackbody following the technique developed in [4].

We use a network analyzer with a WR-05 (140 GHz to 220 GHz) frequency-extender head. In this investigation, we expanded the operation down to 130 GHz and up to 230 GHz without introducing spurious modes. Measurements are made at 0.1 GHz steps across the 100 GHz frequency range. The entire measurement was conducted within a small anechoic chamber to attenuate background noise and eliminate reflections from the surrounding laboratory environment. The waveguide flange of the extender head was calibrated with the Short-Offset-Load (SOL) 1-port calibration technique. After calibration of the network analyzer, a pyramidal standard-gain horn was attached to the waveguide flange. The pyramidal horn was aligned to a flat and polished aluminum plate affixed to a linear translation stage. The linear translation stage has one-dimensional repeatability of less than 2 µm, or λ/650 at 230 GHz.

The aluminum plate is stepped across about 5.2 mm, in the direction of propagation, at a step size of 0.0408 mm (λ/32 at 230 GHz) for 128 steps. The IF bandwidth of the network analyzer is set to 10 Hz for maximum sensitivity, though this results in slow measurements, allowing time for the network analyzer to drift. We measure the complex S_{11} one-port scattering parameter at each step, and the standing wave pattern of the aluminum plate is traced out in space. The aluminum plate effectively acts as a short and a multiple offset short as described in the free-space calibration technique of [4]. Next, the conical blackbody is aligned and measured with the same horn and we obtain S_{11} at the same distance steps. The conical blackbody is measured both with and without the HD-80 closed-cell polyethylene layer that was included in the original design to act as an insulator and thermal radiation block. This stepping procedure is then repeated for the pyramidal array. A photograph of the measurement setup with the conical blackbody is shown in Figure 1. Figure 2 shows the setup with the pyramidal array.

Figure 3 shows the measured standing wave pattern for the aluminum plate at 165.5 GHz and 183.3 GHz, two important remote sensing frequencies, one being a window channel and the other a water vapor absorption band. Figure 4 and Figure 5

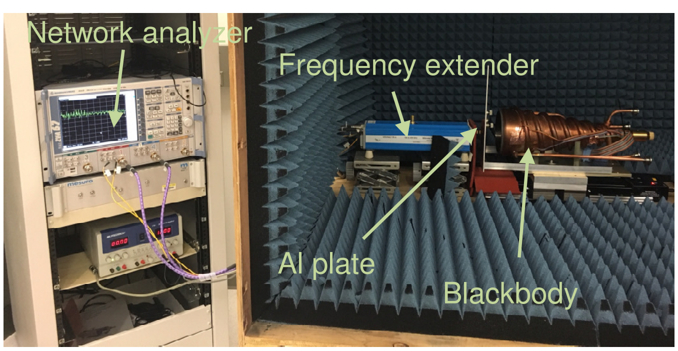

Fig. 1. Photograph of the measurement setup, where components are labeled.

show the results for the insulated and non-insulated blackbody at the same two frequencies respectively. Due to the relatively high magnitude reflections from the plate, we see a multiple reflection interference pattern at 183.3 GHz. This likely causes a slight overestimation of the blackbody reflectivity because the plate is effectively used as a normalizing scalar in the two-tier calibration. At 183.3 GHz without the polyethylene insulation, the blackbody standing wave is not observed. The standing wave, in theory, should have the same wavelength as seen in the polyethylene insulated case, corresponding to half the excitation wavelength (~0.82 mm in this case). Instead, we see a lower frequency signal likely caused by near-field effects and network analyzer drift.

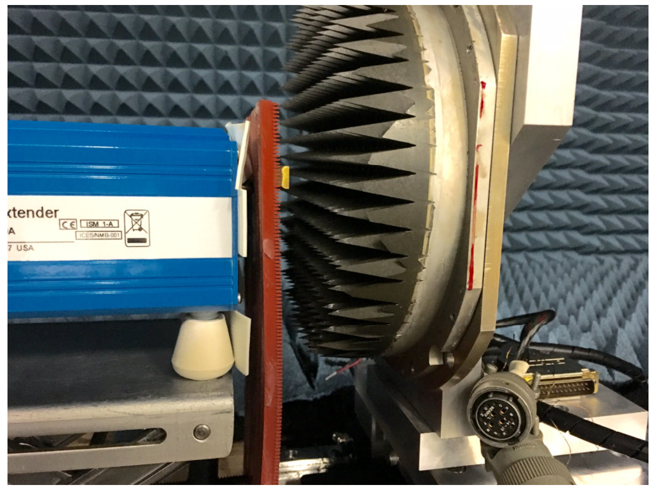

Fig. 2. Photograph of the measurement setup for the pyramidal array.

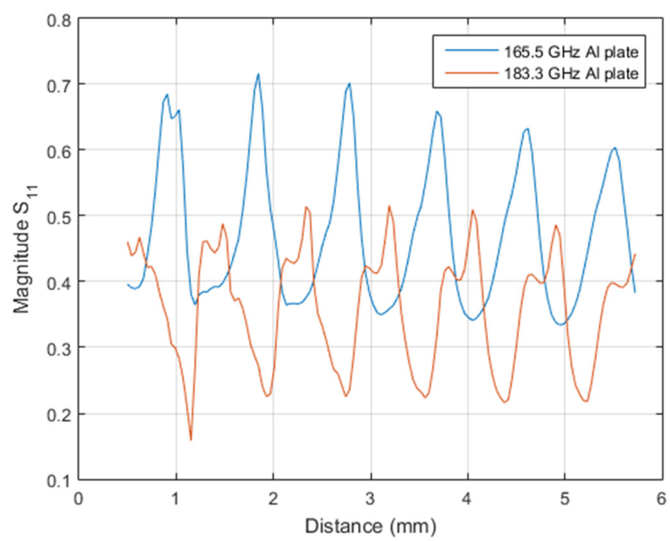

Fig. 3. Plot of S_{11} reflections from aluminum plate versus distance at 165.5 GHz and 183.3 GHz.

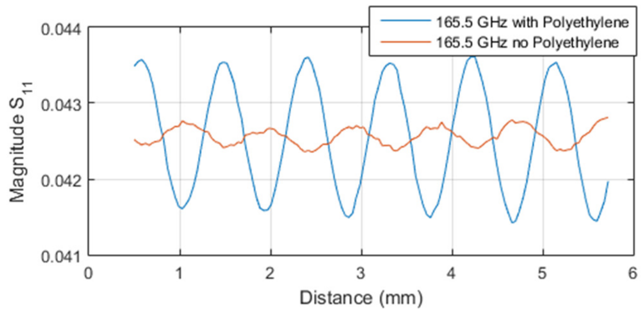

Fig. 4. Plot of S_{11} of the conical blackbody versus distance for the polyethylene insulated and non-insulated cases at 165.5 GHz.

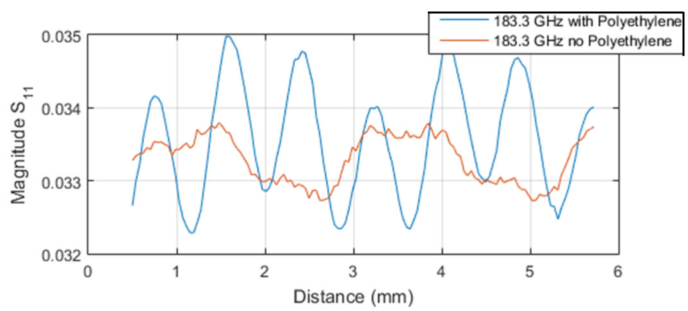

Fig. 5. Plot of S_{11} of the conical blackbody versus distance for the polyethylene insulated and non-insulated cases at 183.3 GHz.

III. Results and Discussion

The data are processed according to the linear fitting procedure outlined in [3] and [4]. This procedure can be thought of as a calibration of single-mode plane-wave scattering matrix in free space. The flat plate acts as a short, or ideal reflector, and is effectively used to normalize the magnitude of the standing wave between the source and the blackbody. We also measured the stationary target in the chamber over the same time span and under similar measurement conditions as the distance-stepped target, and processed these data as a nominal noise-floor estimate. Figure 6 shows the processed reflectivity data and uncertainty for the conical blackbody, pyramidal array, and the noise floor estimate.

In Figure 6 we see much poorer performance, or higher reflectivity, for the insulated blackbody compared to the non-insulated case. This contrasts with our design model which suggested equivalent or slightly better performance from the insulated blackbody. The design model, discussed in [3], assumed non-dispersive dielectric properties of the polyethylene foam, which could have resulted in the design model underestimating the reflectivity for the frequency range considered here. The layer of polyethylene is also not perfectly formed near the apex of the cone and does not form a precise point at the cone apex. There may be some specular reflecting

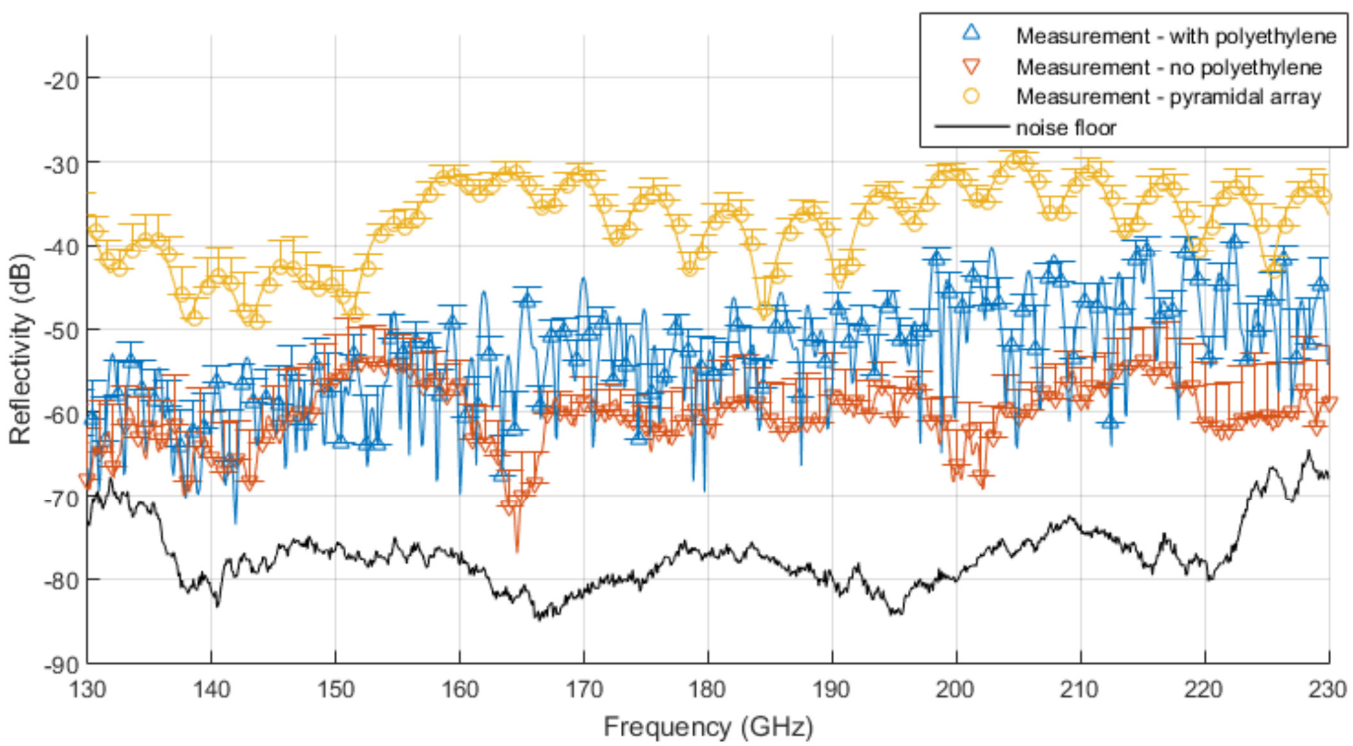

Fig. 6. Monostatic reflectivity results in G-band. The blue line shows the measured result with the polyethylene insulation. The red line shows the measured result with no polyethylene insulation. The yellow line shows the measured result for the pyramidal array blackbody. The black line shows the estimated measurement noise floor from the stationary measurement. The plotted errorbars have a magnitude of one standard error in the positive direction, the lower errorbars have been omitted as they mostly reach to 0 which is undefined in a log scale. Data lines are plotted at 0.1 GHz steps but for clarity errorbars and symbols are shown at 1 GHz intervals.

surface at the seam of the polyethylene sheet causing a relatively strong return signal not predicted in the idealized design model. Though the insulated target has poorer performance than the non-insulated case, the reflectivity magnitudes are all still well within the requirements for accurate radiometer calibration.

In Figure 6, we see that the reflectivity of the pyramidal array is considerably higher than for either of the conical blackbody configurations. This particular pyramidal array was designed to provide high-emissivity in channels at 150 GHz and around 183 GHz where we see dips in the reflectivity below -40 dB. Table 1 provides a summary of the results plotted in Figure 6.

Table 1. Summary of reflectivity results

	With polyethylene	No polyethylene	Pyramidal array
Maximum Reflectivity	-38.9 dB	-53.8 dB	-29.9 dB
Frequency of maximum	218.7 GHz	215 GHz	204.6 GHz
Mean G-band Reflectivity (130 GHz – 230 GHz)	-53.5 dB	-60.4 dB	-37.5 dB

The polyethylene layer reduces physical temperature gradients on the absorber surface by reducing radiative heat transfer. Uniform physical temperature is the other most crucial requirement for a high-performance blackbody along with high emissivity. The use of a thin closed-cell polyethylene foam insulation layer directly on the surface of the absorber was a novel approach to reducing surface temperature gradients, and we have demonstrated low reflectivity achievable with this approach.

We have also demonstrated the marginal and highly frequency-dependent performance of a traditional pyramidal array blackbody. This supports our claim that differences between the on-board calibration sources of various radiometer instruments can vary the resulting brightness temperature calibrations significantly. Introducing traceability back to a consistent standard would increase the long-term consistency and accuracy of radiometric remote sensing data.

IV. Conclusion

We have demonstrated low monostatic reflectivity in G-band for the smaller of the two NIST conical blackbodies. This band contains a number of critical remote sensing channels near 165 GHz, 183 GHz, and 229 GHz. Low monostatic reflectivity is critical to achieving high emissivity and allows us to relate physical temperature to microwave brightness temperature. In order to use the NIST conical blackbodies as a traceable standard for microwave brightness temperature, we must demonstrate performance and uncertainty equal to or better than that of remote-sensing instruments we intend to transfer this standard to. We have demonstrated the high emissivity achievable from the conical geometry and directly compared it to a traditional pyramidal array-type calibration source. The conical geometry also minimizes physical temperature gradients as compared to pyramidal array geometry. Previously, we had shown reflectivity results from 18 GHz to 110 GHz and, in this paper, we have more than doubled this frequency range by demonstrating its low-reflectivity performance between 130 GHz and 230 GHz. We intend to measure within the gap from 110 GHz to 130 GHz in the near future as this range contains a set of important channels in the oxygen absorption band near 118 GHz.

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