CARBON NANOTUBE FLAT PLATE BLACKBODY CALIBRATOR

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ABSTRACT

Evolving remote sensing missions present a growing need for satellite sensors with significantly enhanced measurement accuracies beyond current capabilities. For example, the on-board calibration needed for very precise (e.g., <1% radiance uncertainty), spectrally resolved IR radiances typically requires high-emissivity, ε (≥0.999) calibration blackbodies (BBs). The challenge is that conventional BBs have coating emissivities that are usually limited to ≈0.98. Additionally, they generally have complex geometries that create fabrication and coating non-uniformities which leads to radiance, emissivity, and temperature calibration uncertainties. Moreover, conventional BBs are typically large size, weight, and power (SWaP), which is not optimal for on-board calibration and can be very expensive.

At Ball, our approach to enhance remote sensing missions beyond current capabilities is to leverage the unique optical properties of Carbon Nanotubes (CNTs) to develop advanced coatings that overcome the limitations of conventional BB coatings. We have developed "Flat-Plate, Extreme-ε (0.999), BB Calibrator" based on a Vertically Aligned CNT (VACNT) coating. Key BB elements, such as the extreme-ε VACNT, have been verified for Ball by NIST to be ≈0.999. Extreme-ε provides a significantly reduced BB radiance uncertainty by minimizing the radiance error due to the radiation reflected from the BB's background environment. Additionally, the flat-plate simplifies instrument design, is optimal for on-board calibration due to its low SWaP, and it eliminates the fabrication and coating difficulties associated with the complex geometry of conventional BBs. This paper summarizes the results of our design, characterization and plan for implementing the technology on a small satellite platform with a micro-bolometer sensor.

CNT PROPERTIES

Our various Internal Research and Development (IRAD) and Contract Research and Development (CRAD) efforts have collected a wide range of reflectance and environmental data on the VACNT surfaces. This data informs our decision to use the surface in a blackbody and provides high confidence that it will survive the space environment.

VACNT Structure

The VACNT surface is comprised of multi-walled cylinders of sp2 bonded carbon. These VACNTs are on the order of 10-30 nm in diameter and for our surfaces from 100 to 300 µm in length. The grown VACNT surface has a density greater than 10^{10} CNTs/cm^2. Figure 1 shows a schematic view of a single walled CNT and a side view of a VACNT surface. A key aspect of our IRAD effort has been selection of the optimum substrate on which to grow the VACNTs and consistent growth over a range of sizes and thicknesses of the substrate.

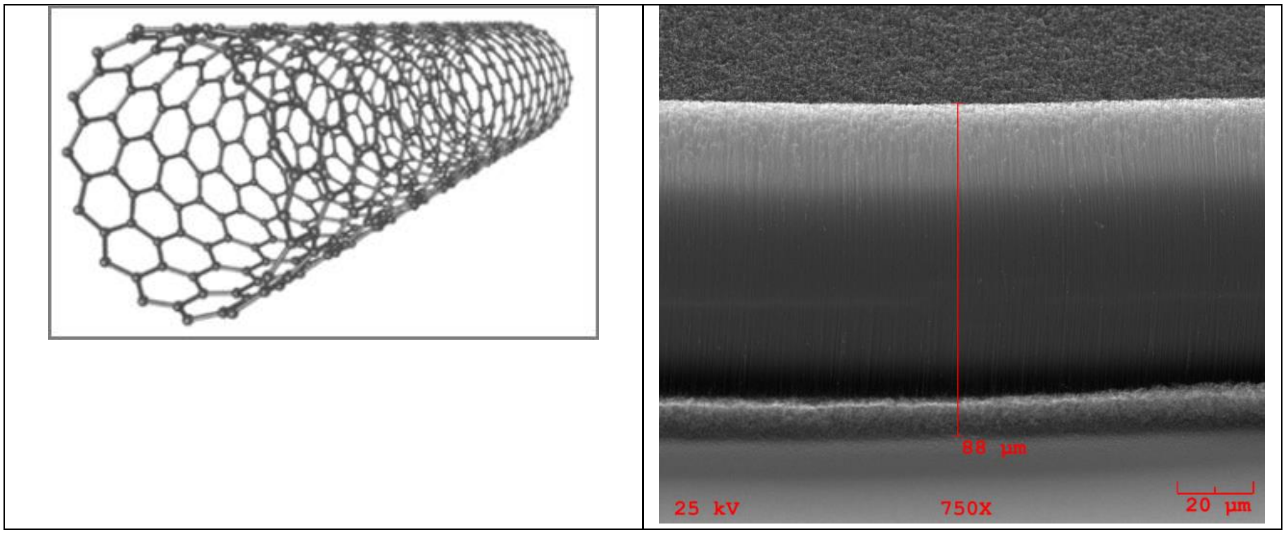

Figure 1. Schematic View of a single CNT and SEM image of a VACNT surface

VACNT Surface Reflectance and BRDF

The reflectance of the VACNT surface is extremely low at all wavelengths we have measured. NIST measured the spectral emissivity of two coupons in 2012. This data in Figure 2 show very high emissivity from the mid-wavelength infrared (MWIR) through the long-wave infrared (LWIR). Figure 3 shows the bi-directional reflectance distribution function (BRDF) of a typical sample measured at 3.39 µm. The BRDF is very flat up to a 30° angle of incidence (AOI). At a 60° AOI, the specular reflectance increases but is still very low. Also shown on the plot is the typical field angles (±10°) where a blackbody is observed. At these view angles and even out to a 60° AOI the BRDF is very low. This low BRDF over a wide range of illumination angles will be highly effective in limiting stray light from other sources that are adjacent to the blackbody.

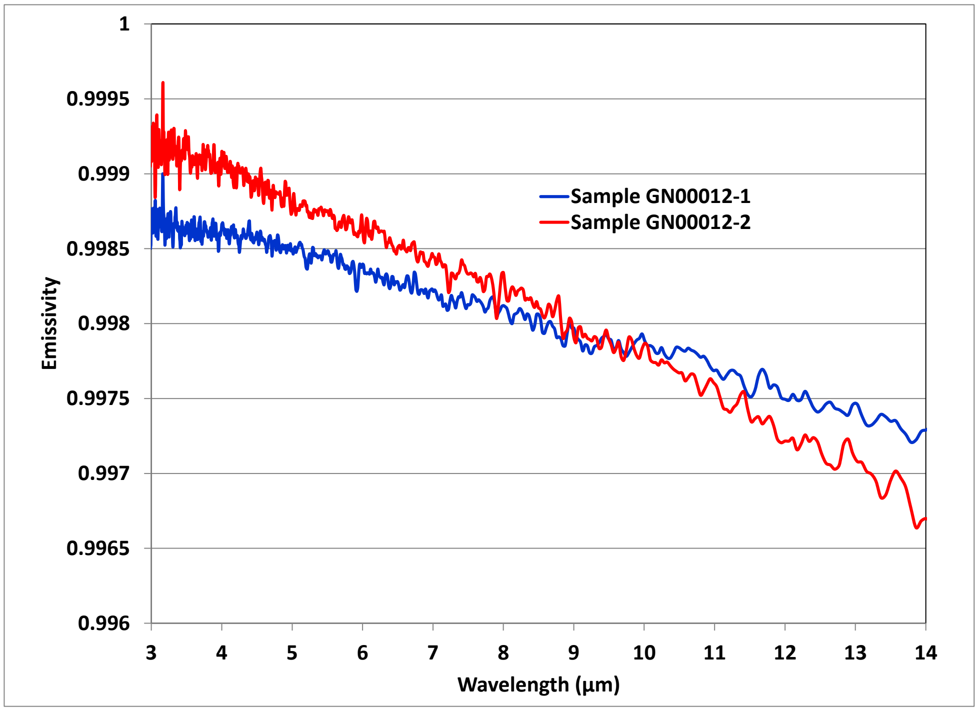

Figure 2. Spectral Emissivity as Measured by NIST

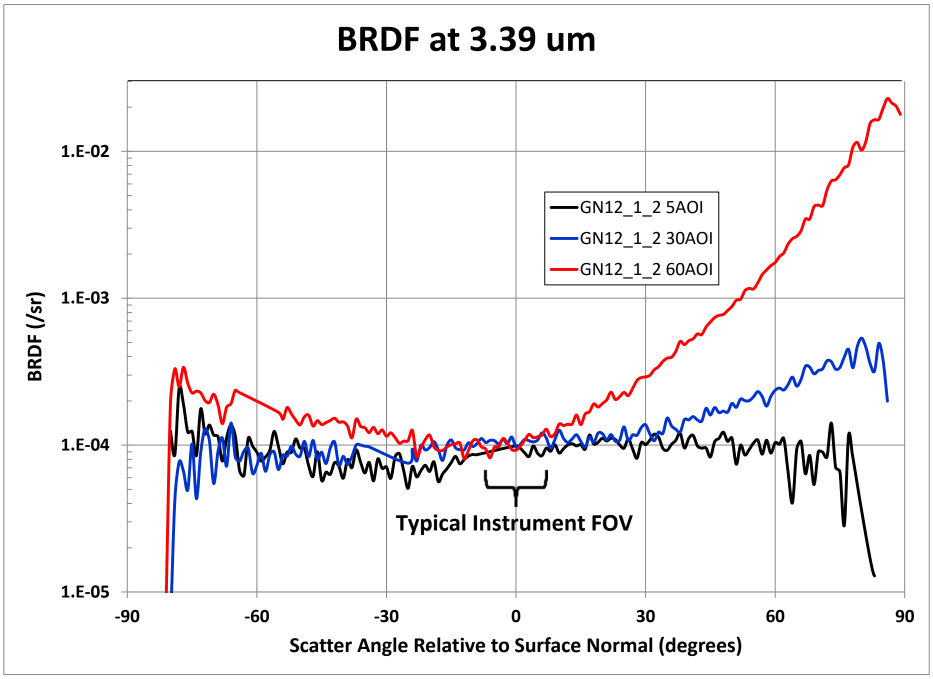

Figure 3. BRDF measured at 3.39 µm

NIST documented a technique to reduce the reflectance of CNT samples[1]. This process was repeated on Ball samples and the reduction was significant. The data below shows the change in reflectance over the 250-2500 nm range. The data in the SWIR range is noisy, but the processing reduced the reflectance by approximately a factor of 3x. We plan to employ this post-processing on the blackbodies we build and test this year.

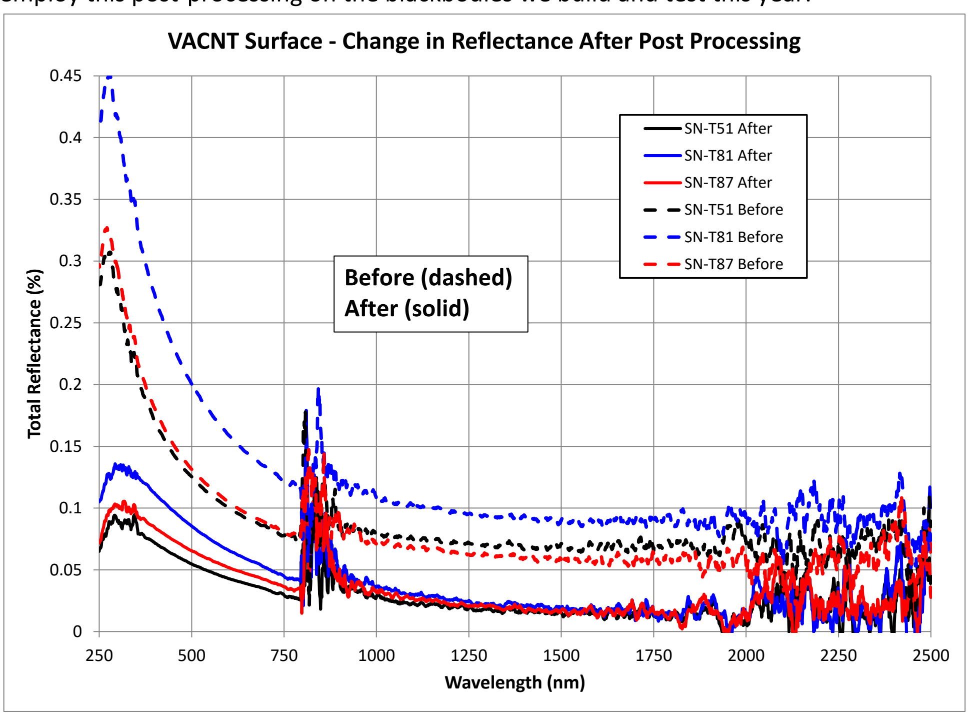

Figure 4. Change in Visible to NIR Reflectance after Post-Processing

Environmental Testing

We have tested the survivability of the VACNT surface through temperature cycling, vibration, radiation exposure and atomic oxygen (AO) exposure. The only testing that revealed some negative effects was the atomic oxygen exposure. Figure 5 compares the BRDF measured before and after eight temperature cycles from -30 to +50C. Later testing has exposed the VACNT surface to temperatures up to 450K with no evidence of any change. Since the VACNT growth is at temperature well above 450K, this is not a surprising result.

Vibration testing of VACNT coupons was performed in 2 axes parallel and perpendicular to the CNT surface at 14.1 Grms (GEVS) and 43.8 Grms. Results from all CNT vibration tests showed contamination levels below CL300. For these results all particulates found were counted even though the majority were not CNTs. This same result was seen on VACNT surfaces provided by multiple suppliers.

Figure 6 shows the total reflectance of VACNT coupon before and after exposure to radiation. The exposure was equivalent to 5 years in a 700 km sun-synchronous orbit with a 2x radiation design margin. There is no evidence of any change in reflectance. Figure 7 shows the change in reflectance due to AO exposure. The first round of exposure simulating multi-year exposure in low-Earth orbit in the Ram direction completely removed the coating. For the data in the figure the AO exposure was 3E21 atoms/cm2 at 0.03eV. The AO exposure slightly reduced the total reflectance.

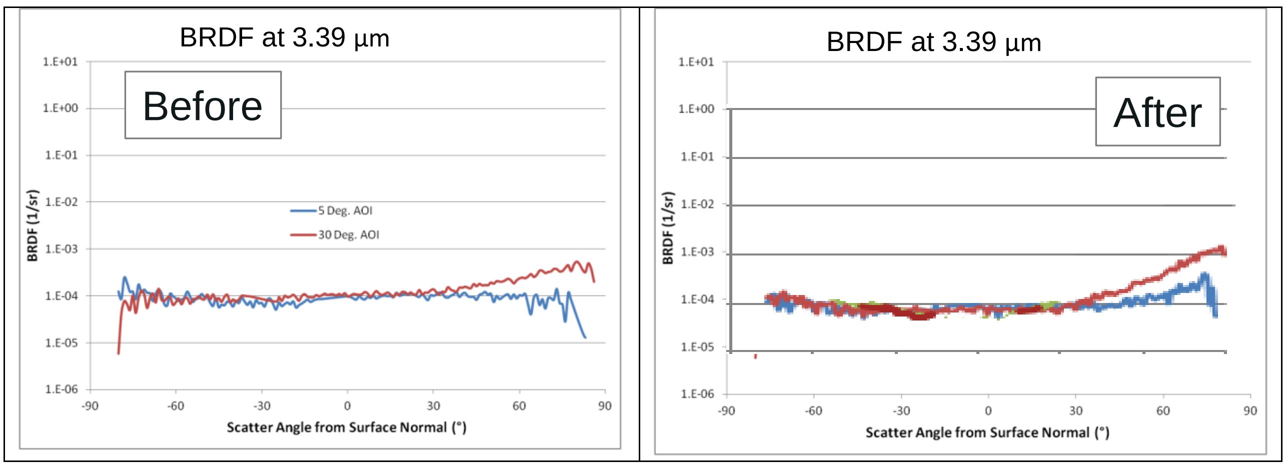

Figure 5. Comparison of VACNT Surface BRDF Before and After Thermal Cycling

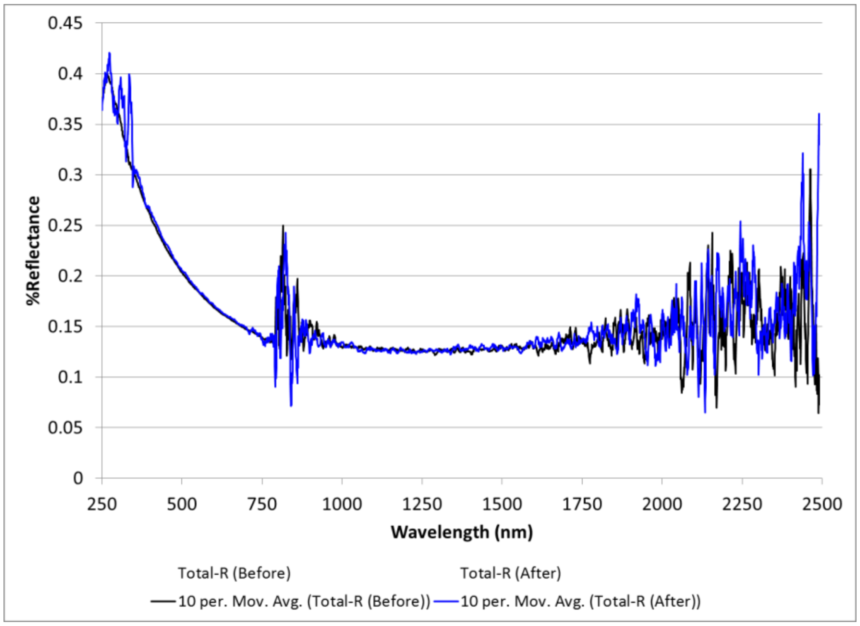

Figure 6. Total Reflectance Before and After Radiation Exposure

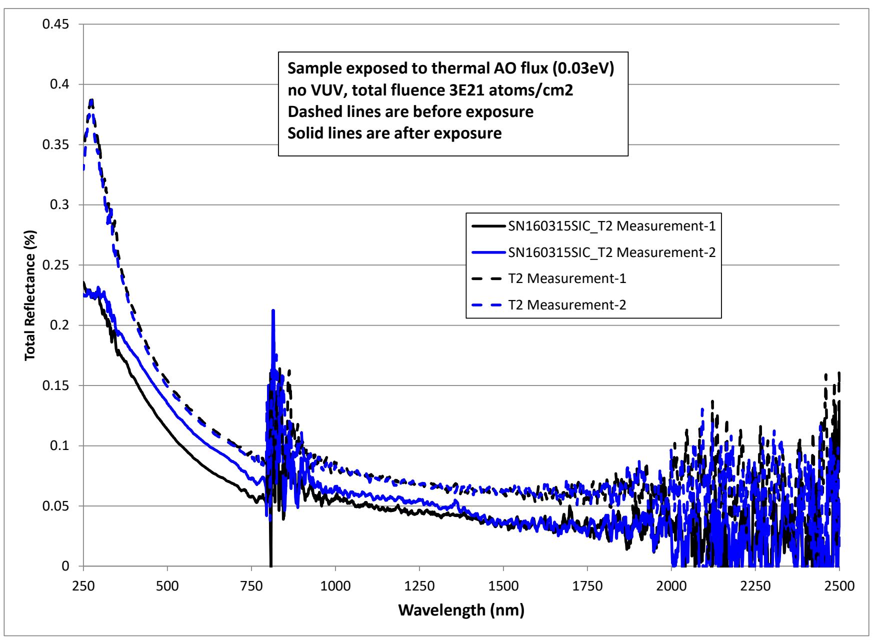

Figure 7. Change in Reflectance after AO Exposure

CNT BLACKBODY DEVELOPMENT

Ball's first flight of a system employing VACNT blackbodies is the Compact Infrared Radiometer in Space (CIRiS) expected to launch in 2018. "The CIRiS calibration approach uses a scene select (fold) mirror to direct three calibration views to the focal plane array and to transfer the resulting calibrated response to earth images. The views to deep space and two blackbody sources, including one at a selectable temperature, provide multiple options for calibration optimization."[2] Both blackbodies utilize the VACNT technology developed on Ball's various IRAD efforts. One blackbody is thermally connected to the spacecraft structure while the other can be controlled up to 20K above ambient. The scene select mirror is in the path and at the same angle for both imaging and calibration so its transmission and polarization effects are eliminated. Figure 8 shows two views of the CIRiS optical system and spacecraft.

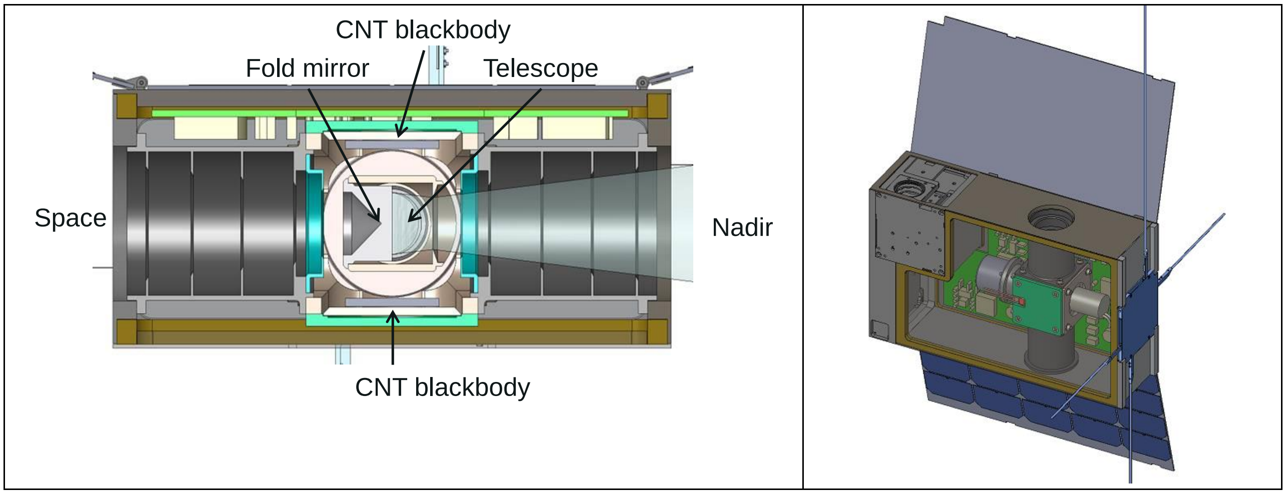

Figure 8. Views of CiRIS Design with CNT Blackbodies

Ball has been provided funding the last several years from a government customer to further develop VACNT technology for use in future space missions. This funding enabled much of the environmental testing documented above and also blackbody and system level testing of the technology. In 2016 we assembled and tested a tiled blackbody calibrator consisting of four 3”x3” VACNT coated coupons bonded into a 6”x6” blackbody. The setup of the blackbody inside a vacuum chamber is shown in **Figure 9**. Results of this testing are shown in **Figure 10**. The uniformity was not as good as we had hoped, but the test results still provided highly valuable lessons learned for assembling large blackbodies from smaller coupons.

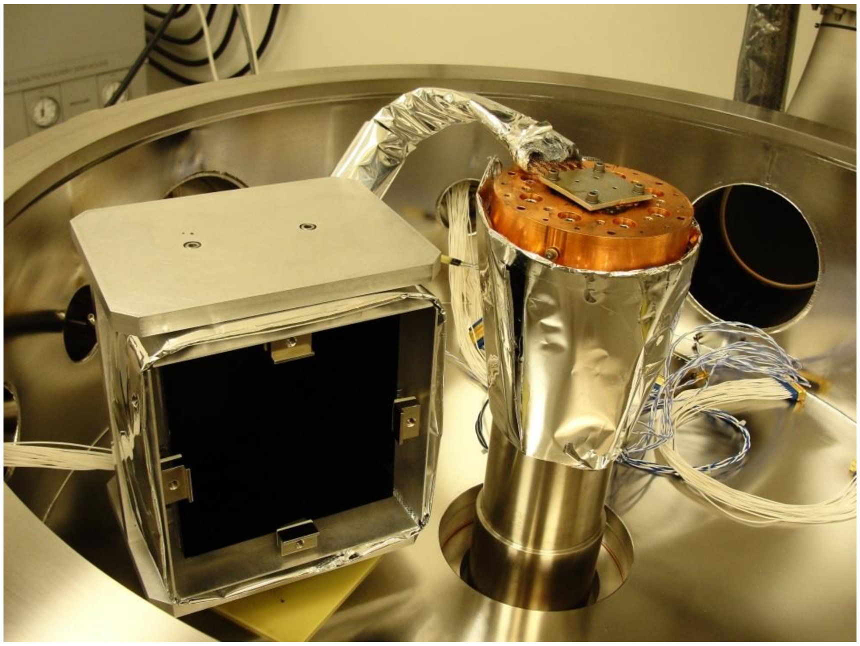

Figure 9. CRAD Blackbody in Vacuum Chamber

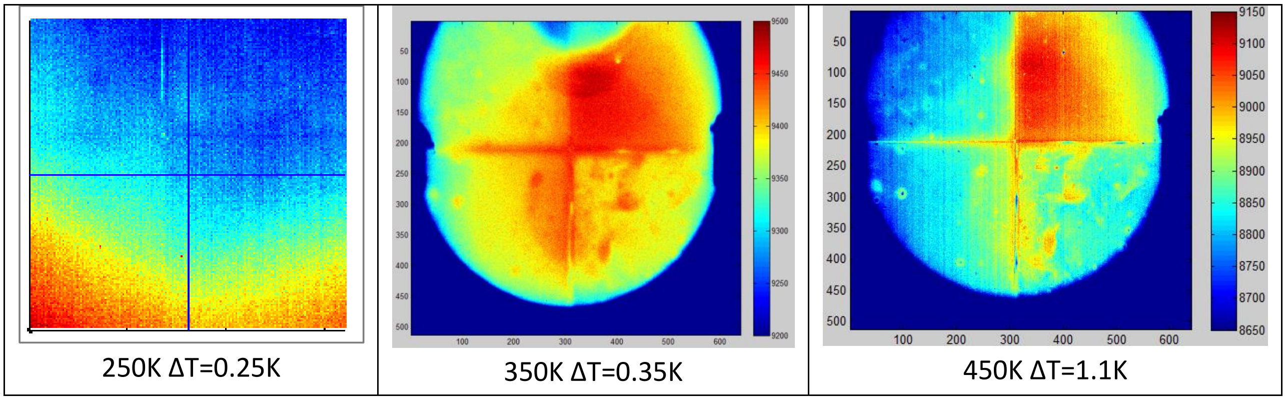

Figure 10. Test Results from 2016 CRAD Test of Tiled VACNT Blackbody

In 2017, our CRAD effort is focused on building and testing a flight-like blackbody. We will build and test two VACNT blackbodies and image them with a state-of-the-art digital infrared focal plane. At each temperature setpoint we will also image a GSE blackbody that provides a highly uniform reference calibration. This test design is shown in Figure 11. Figure 12 shows raytraces to the two VACNT blackbodies. Testing will compare the radiance and uniformity of the two CNT blackbodies to the reference blackbody from 250 to 450K. Testing will also demonstrate the temperature rate of change that we expect to be significantly faster than conventional blackbodies.

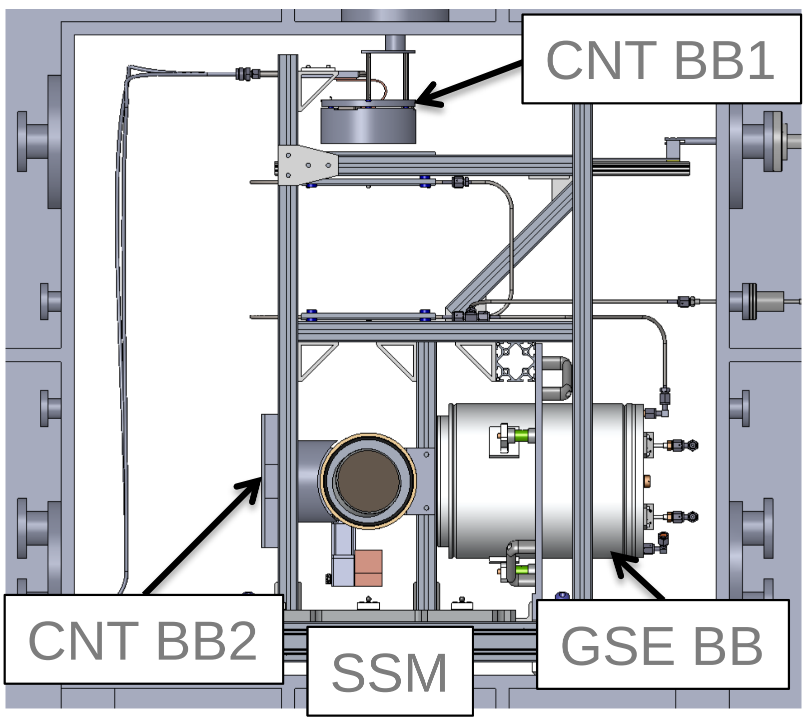

Figure 11. Test Design of 2017 VACNT Blackbody Test System

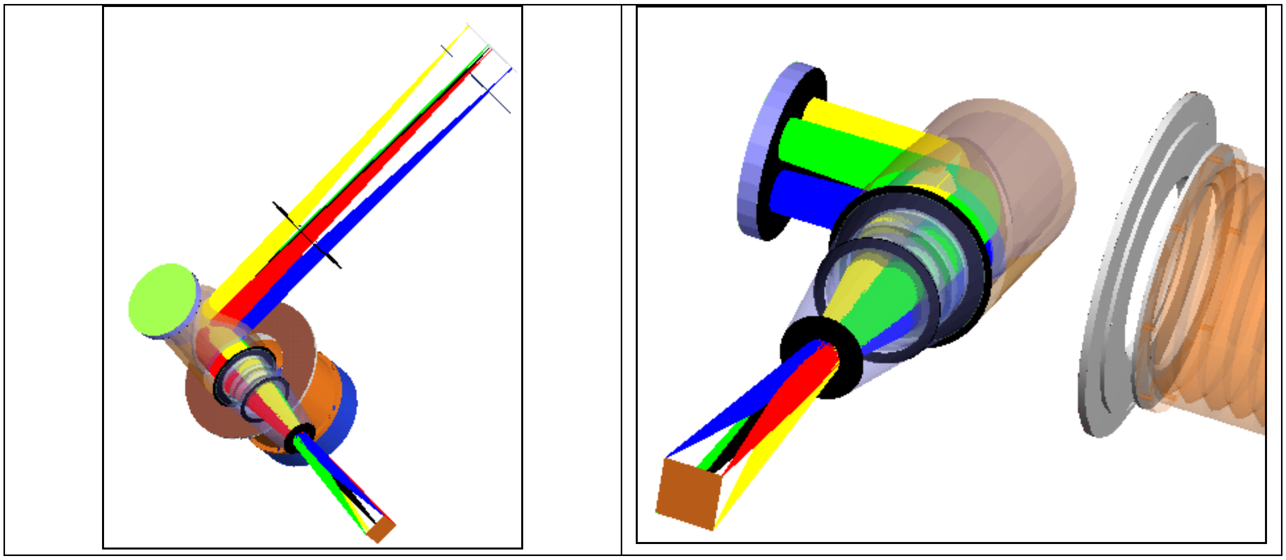

Figure 12. Raytrace Paths to Two VACNT Blackbodies

SUMMARY

Through Ball investment, a NASA program and CRAD funded efforts from a government customer we have made significant strides toward building flight blackbodies incorporating VACNT surfaces. These blackbodies show excellent potential to be used in future NASA and DoD missions requiring exquisite infrared calibration. Key attributes are the high emissivity, survival in challenging environments including thermal, vibration, radiation, and atomic oxygen. This technology will be further demonstrated in a flight-like test this year and the CIRiS launch in 2018.

[1] Tomlin, N. A, et. al, "Decrease in reflectance of vertically-aligned carbon nanotubes after oxygen plasma treatment", Carbon Journal, 2014, pp. 329-332.

[2] Osterman, D. P., et. al., "CIRiS: Compact Infrared Radiometer in Space", SPIE 9978, September 2016