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A high-accuracy blackbody for CLARREO

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ABSTRACT

The NASA climate science mission Climate Absolute Radiance and Refractivity Observatory (CLARREO), which is to measure Earth's emitted spectral radiance from orbit for 5 years, has an absolute accuracy requirement of 0.1 K (3σ) at 220 K over most of the thermal infrared. To meet this requirement, CLARREO needs highly accurate on-board blackbodies which remain accurate over the life of the mission. Space Dynamics Laboratory is developing a prototype blackbody that demonstrates the ability to meet the needs of CLARREO. This prototype is based on a blackbody design currently in use, which is relatively simple to build, was developed for use on the ground or on-orbit, and is readily scalable for aperture size and required performance. We expect the CLARREO prototype to have emissivity of ~0.9999 from 1.5 to 50 μm, temperature uncertainties of ~25 mK (3σ), and radiance uncertainties of ~10 mK due to temperature gradients. The high emissivity and low thermal gradient uncertainties are achieved through cavity design, while the SI-traceable temperature uncertainty is attained through the use of phase change materials (mercury, gallium, and water) in the blackbody. Blackbody temperature sensor calibration is maintained over time by comparing sensor readings to the known melt temperatures of these materials, which are observed by heating through their melt points. Since blackbody emissivity can potentially change over time due to changes in surface emissivity (especially for an on-orbit blackbody) an on-board means of detecting emissivity change is desired. The prototype blackbody will include an emissivity monitor based on a quantum cascade laser to demonstrate the concept.

Keywords: Blackbody, emissivity, radiance uncertainty, temperature uncertainty, phase change materials, SI-traceable, emissivity monitor, CLARREO

1. INTRODUCTION

The future NASA Climate Absolute Radiance and Refractivity Observatory (CLARREO)[1,2] is a mission to measure the Earth's average outgoing spectral radiance with unprecedented accuracy for 5 years in order to provide a climate record. The mission plan is to have two or more satellites in polar orbits continuously collecting infrared and visible spectra as well as GPS occultation data. While CLARREO may detect change over its 5 year lifetime, absolute accuracy is required to be able to compare the obtained climate record unambiguously with similarly accurate future data to show change over a longer time. For the infrared spectrum, the accuracy specification is ~0.1 K (3σ) at 220 K over most of the 200 to 2000 cm⁻¹ (5 to 50 μm) range. Somewhat surprisingly, high precision in an individual CLARREO spectrum is not required since it is long term (seasonal to annual) and large scale (large longitudinal bands to global) averages that are of interest; variation due to weather make smaller scale averages of limited use as climate records. Total CLARREO systematic errors must be at or below the accuracy specification, and meeting this specification will require on-board blackbodies capable of providing high absolute accuracy over the life of the mission.

Space Dynamics Lab (SDL) of Utah State University is currently building a prototype blackbody to demonstrate the ability to build blackbodies that can support the CLARREO requirements as part of the NASA Langley IIP program Calibrated Observations of Radiance Spectra from the Atmosphere in the far Infrared (CORSAIR). This blackbody is based on a design developed at SDL for the Far-Infrared Spectroscopy of the Troposphere (FIRST)[3,4] program, which developed an instrument similar to the CLARREO infrared instrument. The FIRST instrument, built by SDL (for an Instrument Incubator Program lead by NASA Langley), is a Fourier Transform Interferometer designed to measure atmospheric radiance from the ground or a high-altitude balloon. FIRST had an accuracy goal of 0.2 K (1σ) at 230 K from 170 to 1000 cm⁻¹ and 0.5 K at 230 K from 100 to 170 cm⁻¹, and to attempt to meet this accuracy goal required the construction of accurate blackbodies. Three separate blackbodies were built, one at a constant temperature that is attached to the instrument, a ground unit that simulates a view of cold space, and a variable temperature ground

calibration unit, the Long Wave Infrared Calibration Sources (LWIRCS). LWIRCS has since been used as a calibration source for a variety of other programs.

The blackbody design presented here is simple to build and readily scalable to other programs with different aperture or performance requirements. The following sections discuss the CORSAIR blackbody, beginning with a discussion of the requirements, followed by the sources of uncertainty in a blackbody, and finally by the blackbody design and how it is designed to meet requirements over the life of the mission.

2. BLACKBODY REQUIREMENTS
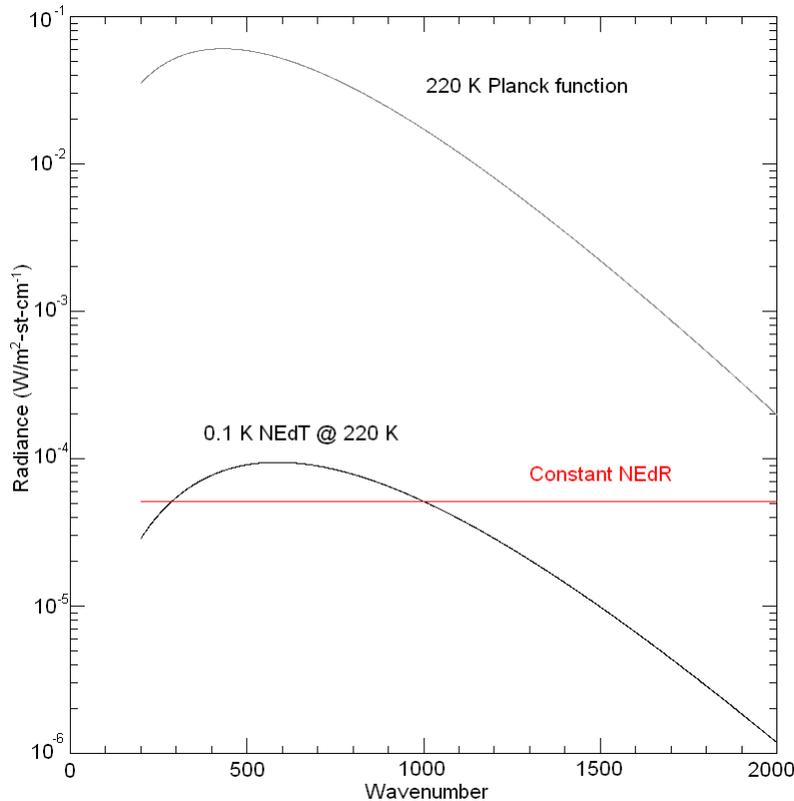
Figure 1: The CLARREO absolute accuracy requirement SDL is using in designing the prototype blackbody, which is constant in radiance, compared to the approximate constant brightness temperature requirement and a 220 K Planck function.

2.1 CLARREO On-board Blackbodies

The exact requirements for the on-board CLARREO blackbodies are not precisely defined because the CLARREO requirements are still subject to revision, especially at the ends of the spectral range. Based on input from NASA Langley, which is managing the CLARREO mission, SDL is working toward a constant radiance uncertainty specification of 5.1×10^{-5} W/m^2-sr-cm^{-1} (3σ) for CLARREO. Figure 1 shows the relationship between the constant radiance and constant brightness temperature uncertainty specifications. Clearly, to meet the CLARREO mission requirements, the radiance accuracy of the blackbodies will need to be better than the mission requirements because of other significant error sources in the CLARREO instrument, such as detector non-linearity. The requirement flow-down to the blackbodies depends on undefined instrument specifics such as the number of blackbodies to use for the calibration scheme and instrument operating temperatures. The number of blackbodies (e.g. a high and low temperature blackbody vs. a warm blackbody and a space view) will affect how errors in blackbody radiance translate into errors in radiance measured by the instrument. In addition, the temperature of the operating environment for the blackbodies greatly affects the uncertainty due to non-zero reflectivity. An estimate of the flowed-down blackbody requirements based on best estimate of instrument properties has been made and these were used in developing the prototype.

2.2 CORSAIR Blackbody Requirements

The prototype blackbody under development is not intended to be just a development model for the flight blackbodies but also to be a useful ground blackbody. As a result it is designed to operate under different conditions than future flight units. Table 1 lists the operating parameters of the blackbody. To meet the range of operating environments requires a vacuum shell and additional shield which makes the prototype considerably larger than a flight blackbody intended for a relatively stable environment.

Table 1: CORSAIR blackbody operating specifications.

Blackbody temperature range	100 to 350 K
Well-controlled temperature range	200 to 350 K
Operating Environment	Ambient (unit includes vacuum chamber) or inside a larger vacuum chamber
Coolant	Liquid Nitrogen
Environment temperature	77 K to ambient
Aperture	1.5 inches
Beam divergence accommodated	6° full angle

3. SOURCES OF BLACKBODY UNCERTAINTY

Sources of blackbody radiance uncertainties can be divided into three categories:
- Temperature Sensor Performance
- Blackbody Temperature Gradients
- Non-zero Blackbody Reflectivity

Temperature sensor uncertainties propagate directly into an uncertainty in blackbody brightness temperature constant over the entire spectral range, as do uncertainties in temperature gradients in the blackbody. The uncertainty due to non-zero blackbody reflectivity depends on the radiance entering in the blackbody and the blackbody temperature and is generally not constant in either brightness temperature or radiance. There are two separate sources of uncertainty from non-zero blackbody reflectivity: uncertainty in the radiance entering the blackbody and uncertainty in the reflectivity value. The difference in radiance between an ideal blackbody and one with a non-zero reflectivity, R, is given by

$$\Delta L = L - P(T_{BB}) = (1-R)P(T_{BB}) + RP(T_{env}) - P(T_{BB}) = R[P(T_{env}) - P(T_{BB})] \qquad (1)$$

where P is the Planck function, T_{BB} is the blackbody temperature (assumed to be uniform here) and T_{env} is the environmental temperature. This equation is a simplification because it assumes the environment is at a constant temperature; this is not necessarily the case but is useful to show the error propagation here. The uncertainty in blackbody radiance due to unknown environmental radiance is thus

$$\Delta L = R[P(T_{env} \pm \Delta T) - P(T_{env})] \qquad (2)$$

where ΔT is the possible variation in environment temperature, while the uncertainty due to uncertainty in the reflectivity, ΔR, is

$$\Delta L = \Delta R[P(T_{env}) - P(T_{BB})]. \qquad (3)$$

The resulting blackbody radiance uncertainties are dependent on the operating environment. For CLARREO, we estimate the most difficult case to be a 300 K blackbody with surrounding at 260 K and up to ±9 K (3σ) variation. (More complicated environments with multiple temperatures have been considered but this is the dominant source of uncertainty in the environmental radiance.) Figure 2 shows the resulting uncertainties assuming a blackbody reflectance of 0.0001 and an uncertainty in reflectance of 0.00015 (3σ) for the expected CLARREO environment. For a given environmental temperature variation, the uncertainty in blackbody radiance due to unknown environmental radiance will fall rapidly if the environment temperature is reduced, while the uncertainty due to limited reflectivity knowledge slowly rises as environment temperature is reduced. In both cases the blackbody radiance uncertainty scales directly with R or ΔR. The peak radiance uncertainty in the figure due to uncertainty in reflectivity is a factor of 5.5 below the requirement. Estimation of other CLARREO instrument uncertainties shows this is about what required of the blackbody for the CLARREO to meet its requirements. Therefore, the blackbody emissivity should be known to about 0.00015 (3σ) to meet CLARREO needs.
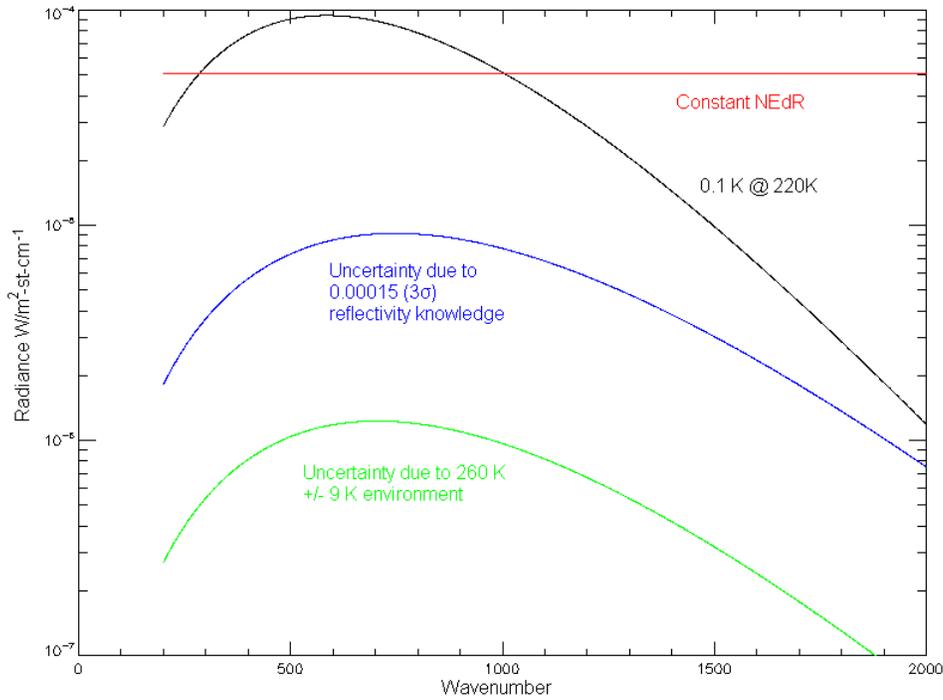
Figure 2: The uncertainty in blackbody radiance due to uncertainty in the environment temperature and uncertainty in the blackbody reflectance for the expected CLARREO environment. The CLARREO uncertainty specifications are shown for comparison.
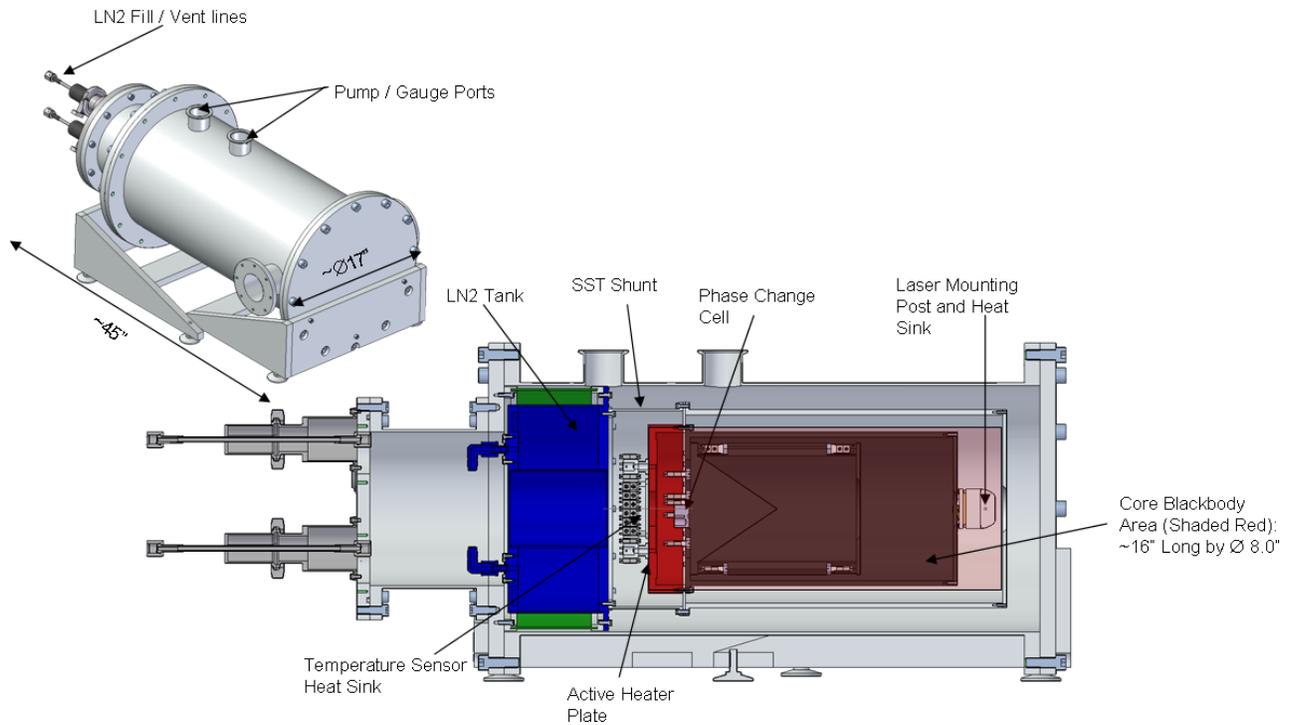

Figure 3: The CORSAIR blackbody mechanical design.

4. BLACKBODY DESIGN

4.1 Design Overveiw

The CORSAIR blackbody design is shown in Figure 3. The outer layer is a vacuum skin with both the end cap and the cylinder detachable from the remainder of the components. A liquid nitrogen tank at the back end provides cooling to the inner components of the blackbody through a stainless steel cylinder that provides a thermal resistance that allows the blackbody to cool in a reasonable amount of time while keeping heating requirements and tank hold time reasonable. This shunt connects to an outer shield and the inner components of the blackbody. The shield has its own heaters that will be used to keep it at approximately the same temperature as the blackbody cavity. This is required because of the variety of environments and temperatures the prototype blackbody will handle. For a blackbody in a less variable environment, only the core components inside of this shield are required with a shunt to hold them to the external structure.

A close-up of the core components, which consist of a blackbody cavity attached to a heater plate, is shown in Figure 4. The cavity consists of a cone inside two nested cylinders and is a specular trap design with the surfaces painted with Aeroglaze Z302 paint. For near-normal incidence, Z302 has a specular reflectance of 5-6% from 200 to 2000 cm^{-1} with little diffuse reflectance. This cavity design ensures that any ray exiting the blackbody into the specified 6° full angle cone can be traced backward through more than 5 specular reflections before it enters the blackbody aperture. For an instrument looking into the blackbody, the surface viewed is entirely on the cone and the surface reflected in the cone is the cylinder adjacent to the cone. The next two reflected surfaces are the cone again and then the adjacent cylinder. Thus, virtually all the observed light is from these surfaces.
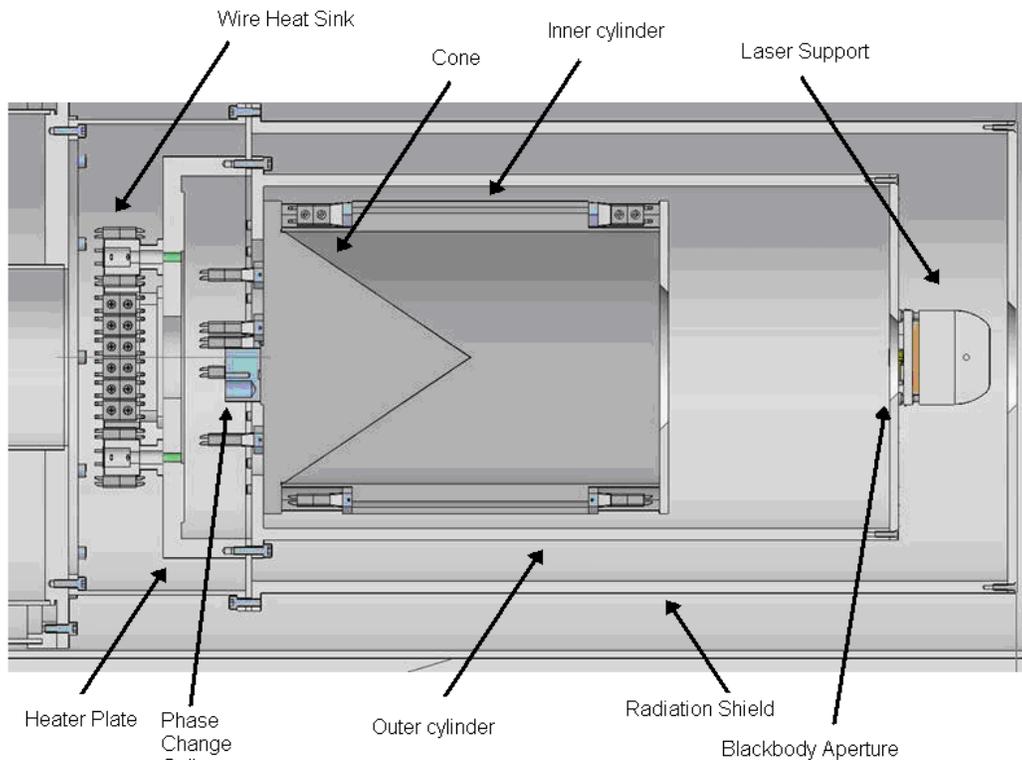
Figure 4: A close up of the core components of the CORSAIR blackbody. The structures shown at either end of the inner cylinder and at the back of the cone are temperature sensors. The laser support is behind the aperture hole in this view and does not block the hole.

The cavity is designed to reduce temperature gradients on the critical surfaces where the observed radiation is emitted. Blackbody cavities using a cone and cylinder are common, but generally the cone is inverted from the design shown in Figure 2. A forward-pointed cone is used for the CORSAIR blackbody because it effectively minimizes gradients across

the viewed surface. Two cylinders are used to reduce temperature gradients on the inner cylinder caused by radiation from the surroundings or entering through the aperture hole.   The cone and cylinders are made of aluminum as is the bulk of the blackbody structure. Other materials can provide better conductivity but are not required here.

The heater used to maintain blackbody temperature is attached to the heater plate to avoid introducing gradients from heater non-uniformities into critical portions of the blackbody. Also attached to the heater plate are heat-sink posts for wires to temperature sensors located throughout the blackbody. Wires going to temperature sensors attach here where they are thermally well connected to the heater plate, which runs at about the same temperature as the blackbody cavity. Without this heat sinking, conduction through the wires to temperature sensors would significantly affect the measured temperature.

The following sections describe in further detail how the low blackbody reflectivity is achieved, how blackbody temperature gradients are controlled, and how the temperature sensors are traceable to SI-standards.

4.2 Blackbody Reflectivity

Over the 200 to 2000 cm^{-1} range several dark surface coatings exist and many have been used in space applications. These typically have reflectivities of 2-10%[5]. Some of these coating are smooth surfaces such as Z302 for which the reflectance is almost entirely specular. The darkest are rough coatings where the rough surface helps trap some of the light, thereby reducing the reflectance but in the process making the reflectance mainly diffuse. For example, Martin Black, an extremely rough coating, has reflectance of ~1% over most of this range with a peak near 5 μm to ~5%.

To reduce blackbody reflectivity below that of a surface coating reflectance requires a cavity. If the surface coating is specular, the cavity must be designed so that when looking into the blackbody, there are enough reflections on the blackbody surfaces that only a sufficiently small portion of the light observed comes from outside the blackbody. For a diffuse coating reflectance, the view factor to the entrance hole from the surface observed when looking into the blackbody must be made small enough to keep reflectance at the desired level. This view factor depends on the size of the entrance hole and distance from hole to surface, so for a given aperture size, the reducing blackbody reflectance is possible only by increasing blackbody length.   In reality, surface coating have a specular and diffuse reflectance component so both must be considered.

We chose to use a specular blackbody design because the diffuse component of Z302 reflectance is lower than that of available diffuse coatings. A Z302-painted cavity large enough to reduce the effect of the diffuse Z302 reflectance to a desired level is large enough to allow reducing the effect of specular paint reflectance to insignificance. Using an available diffuse coating would require a larger blackbody to achieve the same blackbody reflectance. In addition, the specular reflectivity of all surfaces generally increases with incidence angle and wavelength, which is of particular concern at the long wavelengths where coating reflectance data is usually unavailable and difficult to obtain. Finally, Z302 is straightforward to apply while the best diffuse coatings such as Martin Black are difficult to apply and result in a fragile surface. Possibly improved rough surface coatings, such as carbon nanotubes, are currently in the research phase.

Figure 5 shows the total reflectance of Z302 at several incidence angles. The oscillations seen at the longer wavelengths are due to interference between the light reflected at the paint surface and light passing through the paint and reflecting off the substrate underneath. Their amplitude falls with increasing paint thickness. These oscillations are superimposed on a relatively flat baseline reflectivity, which follows the equations for reflectivity at a surface as a function of index of refraction.   Figure 6 shows the best available data on the diffuse component of the Z302 reflectivity. This data set only goes out to 15 microns and shows the diffuse reflectance is ~0.1% except for a peak to 0.5% near 5 μm.   Additional measurements that we believe give a valid upper limit show the diffuse component is at most 0.9% to 1.5% at all relevant incidence angles from 10 to 40 microns. As far as we know, no high-quality diffuse reflectance data is available beyond 15 μm.
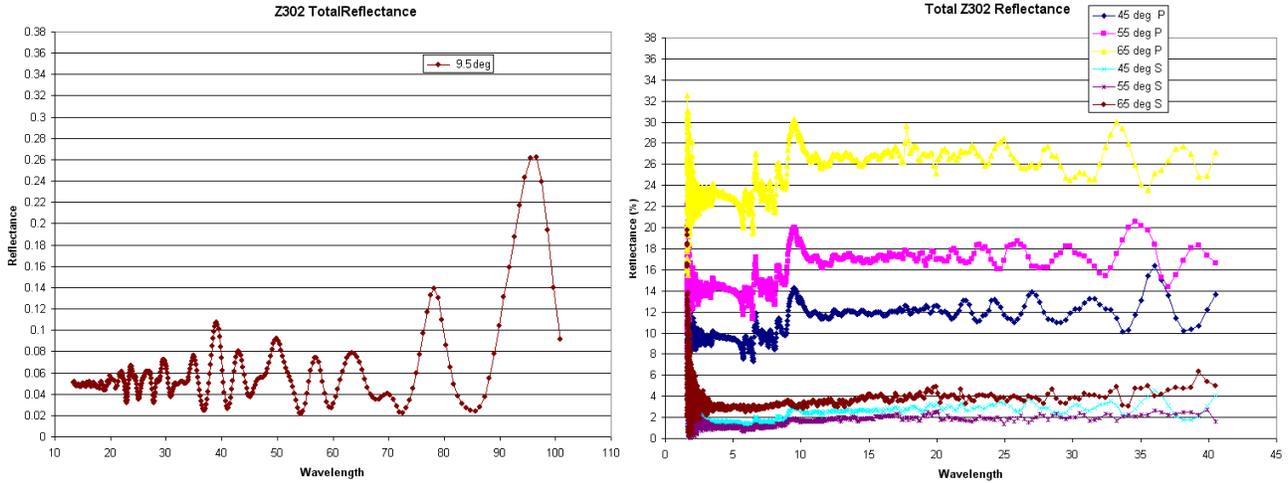
Figure 5: Z302 total reflectance (specular and diffuse) as a function of wavelength. The plot on the left is at 8° incidence angle with polarizations averaged for 14 to 100 µm in wavelength, while the plot on the right shows both polarizations at 45°, 55° and 65° angles from 2 to 40 µm.
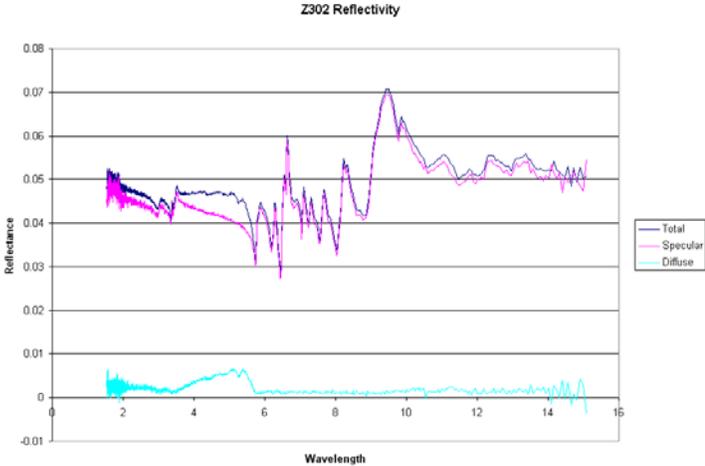
Figure 6: Z302 total, specular and diffuse reflectance at 8° incidence angle from 1.7 to 15 µm.

The blackbody reflectivity due to the specular paint reflectance is straightforward to calculate from a raytrace showing where the light exiting the blackbody originates. Table 2 shows the fraction of light originating from various surfaces in the blackbody. These data show that an insignificant portion of the light originates beyond the 5th surface. Since all rays that can exit the blackbody within a 6° full angle cone can be traced back through more than 5 reflections (many more in most cases), the blackbody reflectance due to specular paint reflectance is clearly at an insignificant level. Software to calculate blackbody reflectance exists but currently available versions can not correctly perform this calculation because they do not accept reflectivity as a function of angle.

Table 2: The blackbody specular reflection surfaces and the sources of light exiting the blackbody for the case of normal incidence to the blackbody aperture. The surfaces are the surface viewed, surface reflected in that, etc. The incidence angle at each surface and the worst case reflectivity for S and P polarized light is listed for each surface. The fraction beyond this surface is the fraction of the light that is emitted from surfaces beyond this one assuming the given surface reflectivity and that all reflectance is specular.

Surface	Where	Angle of incidence	Reflectivity		Fraction from beyond this surface		
			P	S	P	S	Average
1	Cone	56°	2%	20%	0.020000	0.200000	0.110000
2	Cylinder near cone	22°	8%	11%	0.001600	0.022000	0.011800
3	Cone	12°	8%	8%	0.000128	0.001760	0.000944
4	Cylinder near cone	46°	4%	14%	0.000005	0.000246	0.000126
5	Cylinder	46°	4%	14%	0.000000	0.000034	0.000017

The blackbody reflectance due to diffuse paint reflectance is straightforward if the diffuse component is assumed to be isotropic. It is then the product of the diffuse reflectance times the view factor to the entrance hole from the surface viewed inside the blackbody. Blackbody reflectance software can effectively perform this calculation. However, this model is an oversimplification; to properly perform the calculation requires paint BRDF data at at least the angles of interest. This is not available for Z302 from 5 to 50 microns.

As previously discussed, the blackbody requires low uncertainty in the reflectivity. In general, blackbody reflectance is equal to surface reflectance divided by a factor that depends on the cavity (the cavity enhancement factor; note that this factor is usually different for specular and diffuse components). Uncertainty in blackbody reflectance thus depends on uncertainty in surface reflectance divided by the cavity enhancement. As stated, precise Z302 reflectivity is not available. (Paint reflectance can vary with application and thickness too, though this can be mostly controlled with sufficient paint thickness and by using witness samples.) Reducing the uncertainty in blackbody reflectivity down in the absence of accurate paint reflectivity requires high cavity enhancement. This essentially reduces the cavity reflectivity down to the point where paint reflectance variations can not have much effect.

Because of the limited paint reflectance information available especially at the long wavelengths, in developing the blackbody design we assumed the diffuse reflectance is isotropic and about 1% with a maximum of 2%. The cavity reflectance as thus designed under these assumptions is ~0.00005, with a maximum of 0.0001. Performance may be better, and given improved paint data, we expect a smaller cavity will meet the CLARREO requirements.

The tip of the cone, which will have a small dome, could significantly affect the blackbody reflectivity through a specular reflection of the hole by this surface. Estimates of the size of the dome show this will not be a significant factor and this size will be measured once the cone is built and painted.

4.3 Emissivity Monitor

Since CLARREO requires a 5 year mission, any on orbit blackbody must maintain performance over the life of the mission. While past experience does not show significant degradation for Z302[6], it is necessary to monitor the blackbody emissivity on orbit. Various types of emissivity monitors are possible in principle, but to be useful, the monitor output must be clearly and directly related to the blackbody emissivity, since a monitor that does not directly measure emissivity can potentially miss a change. The monitor should thus make a direct reflectance measurement by shining a known source onto the blackbody surface and observing the change in radiance. Furthermore, since the geometry of emissivity measurement matters, the monitor should mimic as well as possible light entering the blackbody at all angles through the entrance hole and viewing the blackbody at the angle used by the instrument. The simplest method for accomplishing the latter is to use the instrument viewing the blackbody as the monitor detector because this clearly observes the relevant angles and also avoids a separate detector. Mimicking the entrance angles is more difficult because the view to the instrument must not be blocked, so the light from the monitor must either enter the hole from angles that do not block the view or enter through a separate hole near the entrance.

Two basic types of monitor sources are possible. The first is a thermal source that can be heated a known amount while the blackbody is observed. The simplest implementation of this is a collar outside the aperture of the blackbody, referred to as a heated halo. Variations of this are currently used to measure blackbody emissivity; however it is not likely to be

effective for CLARREO, especially at the long wavelength end. In brief, the source must not be too hot or it will affect the blackbody, and in the time required to heat the source, collect enough data, and allow it to cool, other changes in instrument response are likely to swamp the monitor signal. CLARREO sensitivity is currently expected to be fairly low, but if the instrument sensitivity is greater than anticipated, the viability of the heated halo improves.

The second source option is a laser. For an on-orbit application at these wavelengths the laser of choice is a Quantum Cascade Laser (QCL)[7]. These are solid state lasers, less than 1 cm^3 in size, and commercially available in wavelengths ranging from 4 to 10 μm with power outputs on the order of 100 mW. QCLs maintain an output stable to <1% over years given a consistent current. Detailed calculations show that the signal from such a laser-based monitor should be observable in a short time with a CLARREO instrument. The obvious drawback to a laser source is that monitoring is possible at only one wavelength per laser, so multiple lasers would be required to cover the spectral band. Furthermore, QCLs past 10 μm currently have significantly reduced power and increasing cooling requirements with wavelength. From 10 to 20 μm, improvements may raise the power sufficiently to be of use as a CLARREO monitor, while past 20 μm significant improvements are not likely before CLARREO is to be built.

For the CORSAIR blackbody, we are including a single QCL at 9.5 μm to verify its utility as an emissivity monitor. The QCL shines into the blackbody through a hole in located in near the blackbody aperture, as shown in Figure 7. This location was chosen because it better mimics light entering through the aperture hole at all angles (the QCL beam is 50°×90° FWHM) than a laser located outside the hole out of the light path to the instrument, which necessarily enters at a more limited set of angles. The relationship between the monitor signal and the blackbody reflectance has been calculated using the measured beam pattern of the laser that will be placed in the CORSAIR blackbody. This design also avoids imaging optics, especially fiber optics, which tend to be fragile in this wavelength range and would at the least require testing for space qualification.


Laser Aperture
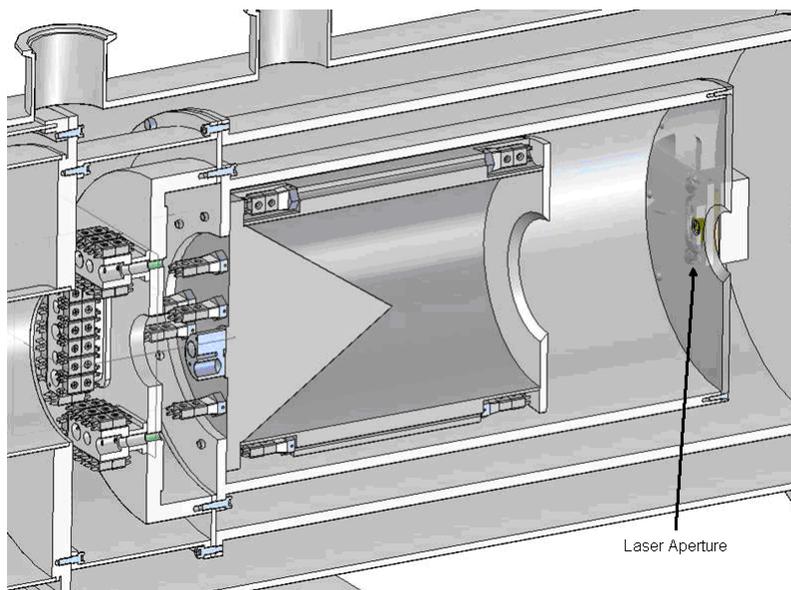
Figure 7: The blackbody mechanical design showing the location of the QCL.

4.4 Blackbody Temperature Gradients

Gradients across the blackbody surface clearly affect the blackbody radiance, with the effect dependent on where the gradients occur. Nearly all of the light exiting the blackbody comes from the cone, so gradients there have a nearly directly effect on the radiance. The effect of gradients on the section of cylinder reflected by the cone will be reduced by a factor of ~9 (see table 2). Since the next 2 reflections are of the cone and inner cylinder again, gradients on surfaces beyond these have little effect.

Uncertainty in the gradients leads to uncertainty in the blackbody radiance. If the gradients are known, then in principle they add no uncertainty as the blackbody radiance can be corrected. Gradients can be modeled using thermal finite element models, and the modeled gradients can be used to correct the blackbody temperature. Since models are imperfect, some uncertainty will remain at a level that is unknown though almost certainly smaller than the modeled gradient. It is thus best not to attempt to correct for a large gradient with a model.
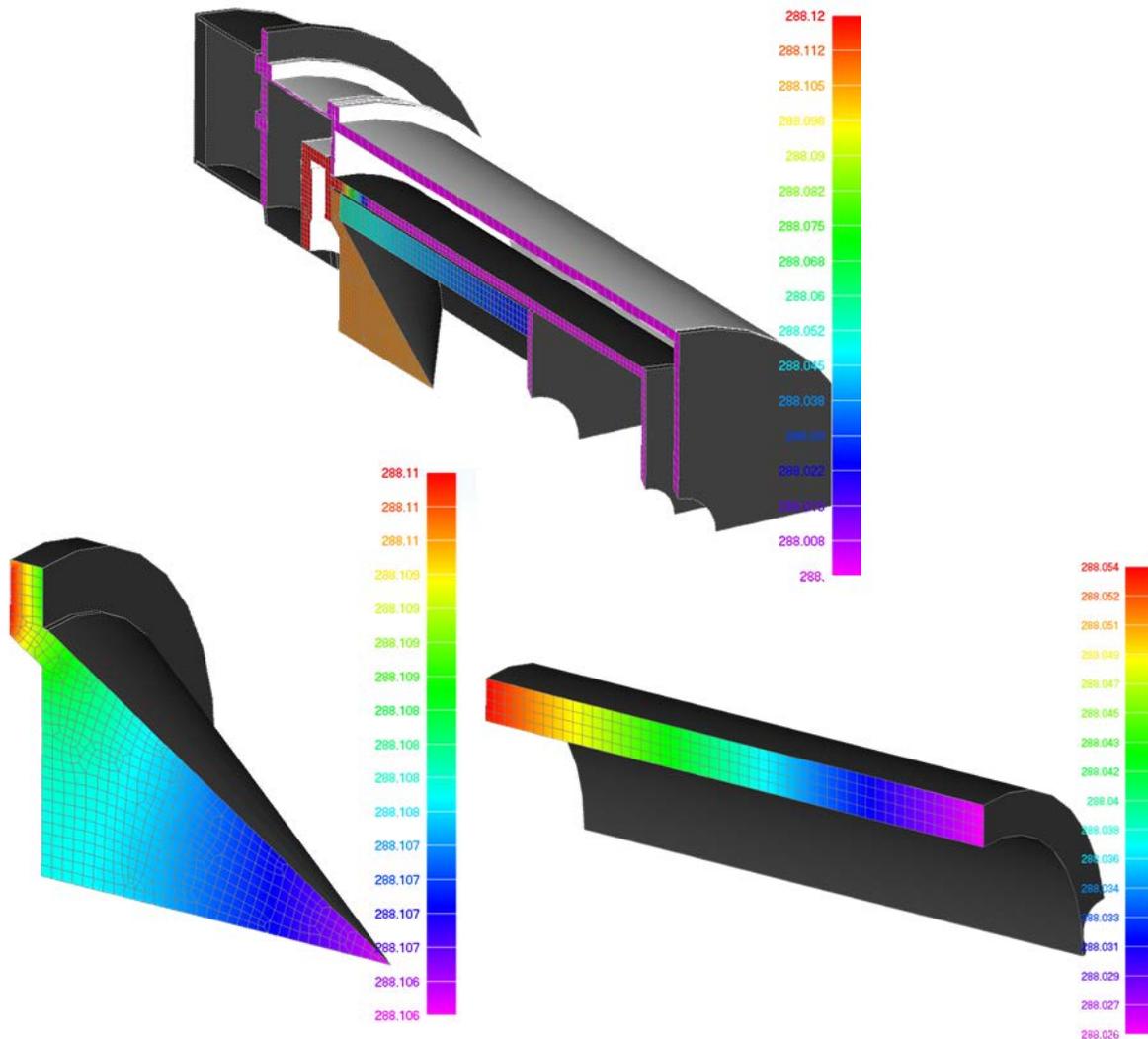

Figure 8: Modeled blackbody gradients for a 300 K blackbody (heater set point temperature) with 77 K surroundings and the outer shield heater set point at 275 K. The top figure shows the overall blackbody, with a close-up on the cone and cylinder shown below.

Potential sources of gradients are temperature difference between blackbody and environment, heater non-uniformities, and conduction through wires. These gradients are managed by the blackbody design. Figure 8 shows the modeled gradients in the aluminum for the blackbody with a heater set point of 300 K, a 77 K external environment, and a full tank of liquid nitrogen. This is a conservative model in that the heater on the outer shield (third cylinder out) is controlled to 275 K (it could be kept much closer to 300 K), the contact between cylinder and cone is assumed to be two bolted aluminum parts (contact can be improved to reduce thermal resistance), and the aperture plate at the end of the inner cylinder is assumed to be painted (the outer surface will be left unpainted to reduce gradients on the inner

cylinder). The model shows the cone surface and location of the temperature sensors are isothermal to 3mK, and the adjacent cylinder is within 80 mK of the cone. Gradients through the paint are not shown in this model but additional modeling shows these are ~6 mK under similar conditions.

Gradients from heater non-uniformities are controlled by placing the heaters on the heater plate and away from the critical surfaces. Non-uniformities in heating smooth out before the heat flows to the cavity. Likewise, all wires are heat-sunk at the heater plate to prevent flow into the cavity. Modeling shows that gradients in the cone due to a non-uniform heater at the heater plate or due to conduction along the wires are insignificant. One additional source of gradient in the CORSAIR blackbody is changing liquid nitrogen level in the tank. Modeling shows that a 35% full tank will add a gradient to the cone surface but this is no more than 5 mK. Based on these results, and assuming minimal ability to model gradients we expect blackbody radiance uncertainties due to gradients to be below ~10 mK (3σ), especially under CLARREO like-conditions.
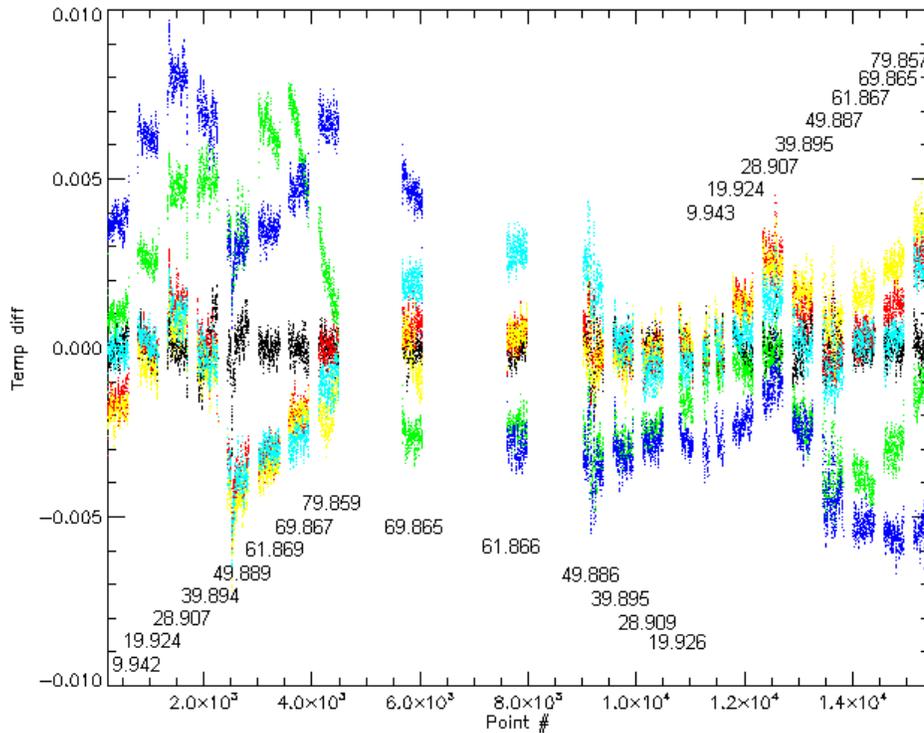
Figure 9: Temperature sensor drift over time when cycled in a thermal bath. The bath is cycled through a range of temperatures and held at several temperatures along the range. The average temperature on these plateaus as measured by a very stable calibrated PRT is specified in °C above or below each plateau. The plot shows the difference in °C between readings from a temperature sensor on the plateaus and calibrated PRT average on that plateau. Different colors represent different sensors with the black representing the calibrated PRT itself. The sensors under test were calibrated using this data and the calibrated PRT reading, so this represents the best possible calibration for these sensors. Drift in the sensor readings is quite clear; no sensor consistently returns the same reading at the same bath temperature.

4.5 Temperature Sensors Performance
The CORSAIR blackbody temperature will be measured using platinum resistance thermometers (PRTs) and thermistors. Both are available in the small sizes required, can be calibrated to ~10 mK accuracy, can be read to mK accuracy with commercially available hardware, and are commonly in use with blackbodies. However, PRTs and thermistors show non-ideal behavior such as hysteresis, susceptibility to change due to mechanical or thermal shock, and drift over time when their temperature is cycled at a level that is significant to CLARREO. Figure 9 shows example data for PRT temperature cycled in a thermal bath. The sensors shown in the figure are not extreme cases; poor performers

can drift by up to 0.5 K under similar conditions while others are consistently stable to the 1 mK level. The amount of drift can vary from unit to unit of one particular model.

Clearly, sensors need to be screened prior to use and stable sensors chosen. However this is not sufficient for a space blackbody that must handle launch vibrations and remain accurate to the levels required CLARREO for 5 years. On-board temperature sensor calibration can be provided by the use of phase change materials. The CORSAIR blackbody will include a phase change cell for temperature recalibration attached to the blackbody cone as shown in Figure 4. This phase change cell contains pure Hg, H_2O and Ga in separate compartments, and the cell can be thermally isolated and temperature controlled independently from the blackbody (to within ~30 °C of the blackbody temperature) by its thermoelectric cooler and heater. The cell is used by taking it to the material melt points and calibrating a temperature sensor in the cell at these melt points. When the cell temperature control is turned off, the cell temperature sensor quickly comes to equilibrium with the blackbody and its temperature sensors and the calibration can be transferred. Since the melt points are unchanging and SI traceable, the cell allows SI traceable calibration of the blackbody temperature.

The melt point can be found by taking the cell through the melt temperature of the material resulting in a melt curve where the temperature rise slows as the material melts. Because of the limited amount of material in these cells, the melt curve, while repeatable to the few mK level, never completely flattens, resulting in some ambiguity over when the absolute melt temperature is reached. The prototype blackbody will employ a cell design that avoids this ambiguity by monitoring the expansion of the material and using feedback from the expansion monitor to hold the material in equilibrium where both solid and liquid are present, clearly identifying the absolute temperature. We have estimated the uncertainty in the ability to calibrate the cell temperature sensor, transfer of calibration to the blackbody, the uncertainty in the PRT resistance vs. temperature curve fits, and drift in sensors and electronics between cell uses, and expect a total uncertainty due to temperature sensor performance of ~25 mK (3σ) under CLARREO like conditions.

5. CONCLUSIONS

Based on modeling and design, a blackbody can be built that meets the strict absolute accuracy required for the CLARREO mission. The design is straightforward to build and can be readily scaled in size for different aperture and accuracy requirements. Assumptions used in designing the cavity were generally conservative, and given additional data (e.g. for paint diffuse reflectance) is likely that a smaller cavity of this design will meet the same specifications.

The anticipated performance described here is based on modeling and it is possible that errors in the models or unanticipated factors will reduce performance below what is expected. This is of significant concern at the high performance levels required. Testing is necessary to prove that performance meets expectations. We are currently considering methods to verify the predicted high performance of the CORSAIR blackbody.

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