# Design of an Optimization System for South Pole Telescope Third-Generation Detectors

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## Executive Summary

The cosmic microwave background that pervades the universe is an ancient signature of universal structure, and the information it contains tells us about the earliest forms of structure in the universe, allowing us to expand our knowledge of cosmology. The South Pole Telescope detects this background using superconducting bolometers designed for such detection, but the detectors themselves need to be optimized under ideal observation conditions. In particular, the detector response time, responsivity, and intrinsic noise are all unknown as functions of heat, and so a system is required for such optimization. Building this system is the goal of this project. The primary element to this system is a blackbody load, which provides a controlled heat source, emitting a blackbody distribution of photons at any desired temperature in our range of interest. The system will be in a chamber cooled to 4 kelvin, while the detectors are held near their superconducting transition temperature (0.5 kelvin) by a thermal bath. We would therefore like to measure the parameters mentioned as a function of incident heat in the range of 4 to 30 kelvin. In addition, the blackbody load is mounted on a mechanical rotary frame, allowing for future loads (such as a Neutral Density Filter) to be rotated in front of the detector, which can provide additional parameter measurements without the need to re-cool the chamber.

## Introduction

The South Pole Telescope (SPT) detectors are superconducting bolometers held near their superconducting transition by a thermal bath, connected by a variable resistor, shown in figure 1. The detectors function in an electro-thermal feedback loop, in which the superconductors are held at a constant bias voltage. By design, as a photon imparts power to the detector, the temperature rises, causing the resistance to also rise (figure 2). As the resistance rises, the electrical power decreases, compensating for the overall change in system temperature, and this change in electrical power corresponds to a change in the current across the superconductor. The detectors are designed to sense this current change as an indication of incident power transfer.

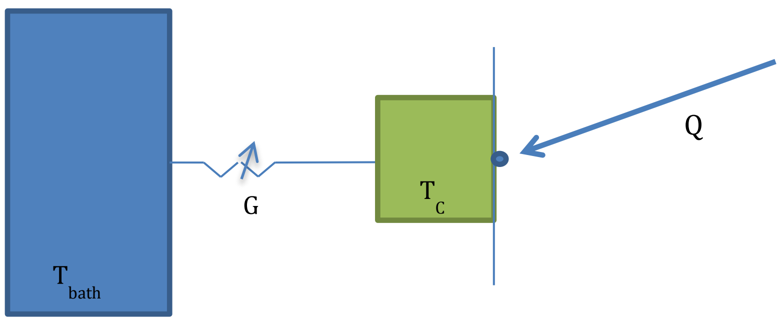


**Figure 1 – Thermal Bath $T_{Bath}$ connected to the superconducting detector held at a bias voltage and fluctuating at $T_C$ due to incident photon radiation, Q.**

The superconductors function properly near their transition temperature, which is around 0.5 kelvin, but the superconductors are not the only reason for operating at liquid helium temperatures. The primary reason we wish to operate in a cold environment is to reduce noise input from three sources: photon shot noise, phonon noise, and Johnson noise.

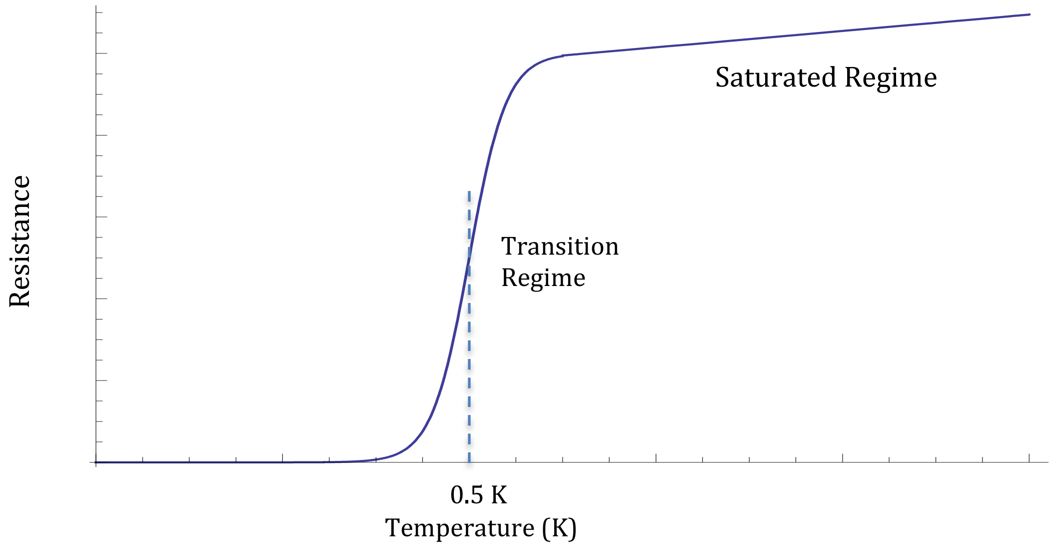


**Figure 2 - Resistance as a function of temperature. As Q increases $T_C$, the resistance moves up this curve, and as it does so the electrical power through the device, $P_e$, decreases, thus acting to reduce $T_C$, keeping the device within the transition regime. In the limit that $P_e$ goes to zero, the device can no longer compensate, and the superconductor enters the saturated regime. Note, also, that the resistance values here are omitted, as this is a qualitative graph.**

Blackbodies are objects that radiate heat in the form of photons by the Planck distribution [1].

$$B(\nu, T) = \frac{2\,h\,\nu^3}{c^2}\frac{1}{e^{\frac{h\,\nu}{k\,T}} - 1} \tag{1}$$

Figure 3 shows this distribution for several temperatures. For the SPT detectors, the

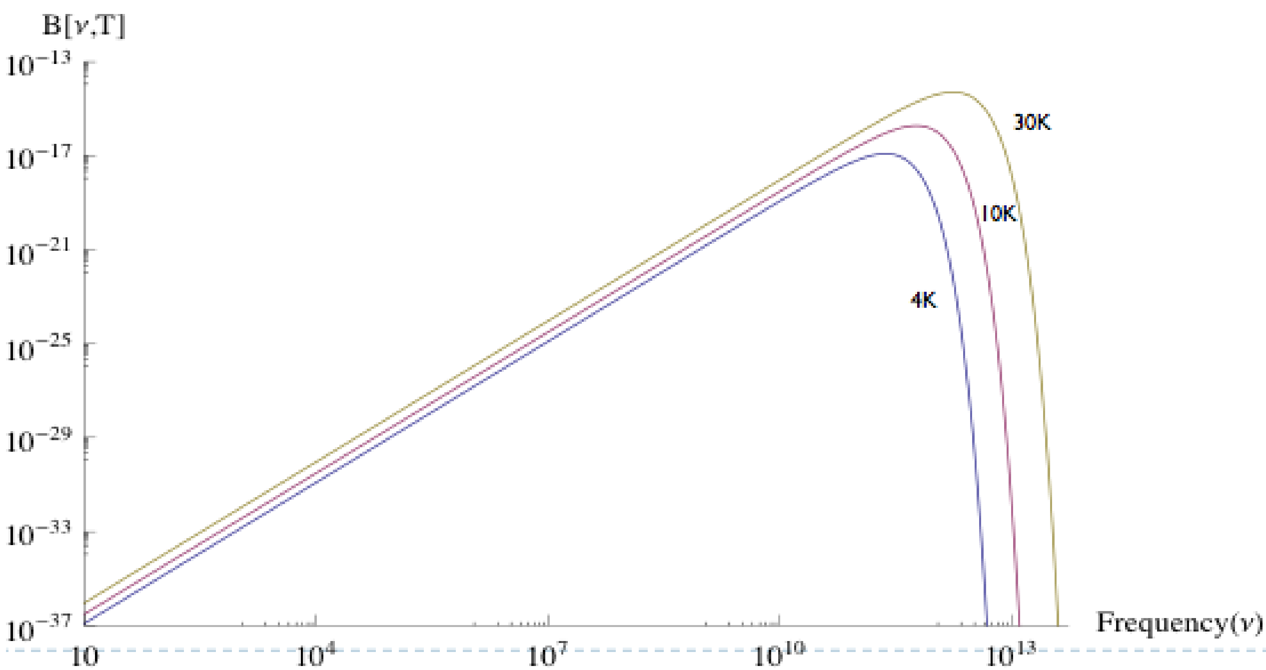


**Figure 3 - Plotted are three blackbody distributions, for T = 4K (Blue), T = 10K (Red), and T = 30K (Gold).**

relevant frequency regions are 75 to 105 GHz, and 130 to 170 GHz. From (1), we can obtain the total power by multiplying by the area of the detectors (For single mode antennas, the area is the wavelength squared), dividing by two (to account for photon modes), and integrating over the relevant bounds.

$$Q_{90} = \int_{75\,GHz}^{105\,GHz} \frac{h\,\nu}{e^{\frac{h\,\nu}{k\,T}} - 1} d\nu \tag{2}$$

$$Q_{150} = \int_{130\,GHz}^{170\,GHz} \frac{h\,\nu}{e^{\frac{h\,\nu}{k\,T}} - 1} d\nu \tag{3}$$

With this, we can numerically determine how much power is imparted to the detectors by the blackbody's radiation at a given temperature. The goal of the project is then to design a system for detecting the imparted heat described above.

**Objectives**

The objectives of this project, then, are to design and fabricate a blackbody load for use in SPT detector optimization, and to implement the blackbody into a mechanical rotary frame. For design ideas, we turned to similar work in the field. In 2004, the ARCADE instrument utilized a calibrator that functions on the same principle. Their method was to use an array of pyramid shaped teeth that would act as a blackbody cold load. These pyramids were then coated using Eccosorb CR-112, a resin designed for absorbing microwaves. [2] Similarly, a group at Tohoku University in Japan used CR-112 and pyramid arrays. [3] For similar purposes, we will adopt a similar strategy: the bottom surface of the aluminum will be cut into an array of pyramids, which will then be coated in an absorptive resin (Eccosorb CR-112).

**Methods**

The first, most important fact about blackbodies, as far as design is concerned, is that a blackbody emitter is equivalent to a blackbody absorber. This allows us to design a blackbody load as a blackbody absorber, and then use it as a blackbody emitter. However, our blackbody need not be perfect: we only need to produce a rough blackbody spectrum, and so a load that is anywhere above 85% black will do the trick. The challenge in our design is to make an absorber that is thermally synced to an aluminum backing, such that the surface temperature may be controlled. The first objective then, is to get a surface that is absorbing in the microwave regime that can also be thermally synched. An inadmissible method of absorbing is to use millimeter wave foams. These are great for absorbing, but cannot be controlled thermally. So we need to adopt a resin surface that adheres to an aluminum backing.

**Eccosorb CR-112 Optical Properties**

Eccosorb CR-112 is an absorbing resin designed for use in optical systems. Its exact chemical structure and composition are proprietary, but its implementation sheds some light on its properties. Its data sheet suggests that in our frequency range, the material will have around 80% incident power reduction (~20% reflected). For our purposes, this is a great start. However, in order to be sure of its optical properties, first I needed to test a slab of the resin for its reflectiveness. In order to do this, I used a Gunn Oscillator to measure the relative reflected power of the resin compared to a flat aluminum surface. The test was performed at multiple angles; the setup is shown in figure 4. For each test, I compared the aluminum's reflection to the resin's reflection; the ratio of the two was taken as the reflected power percentage of the resin. The tests were only performed at a frequency of 137 GHz, because our objective was to observe a very rough reflected power percentage. The reflection would not appreciably change over our frequency band, and so we only used a characteristic frequency near the middle of the band. Yet again, for our purposes it is not necessary to have high precision, so the tests were performed at five different angles. The results are plotted in figure 5. Unfortunately, the results of these tests show that the resin reflects approximately 50% power at lower angles, decreasing at higher angles. This reflection is higher than expected. However, as it decreases with angle, it will still be usable for a load, as the incident angles will generally be in the 45-35% reflection range. With a surface of acceptable optical properties, the next objective was to attempt to further attenuate incident power.

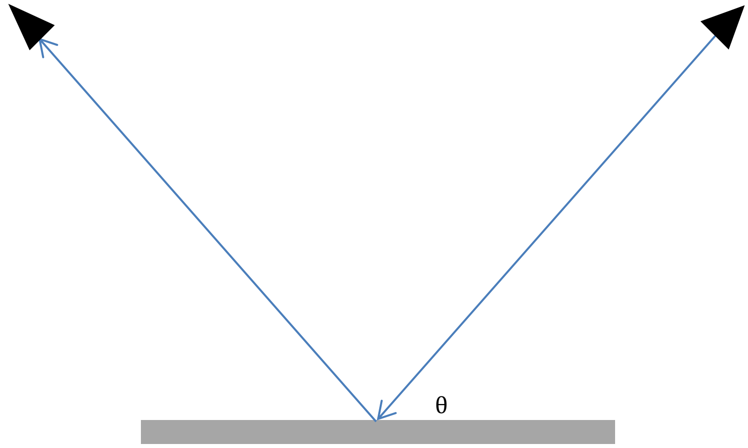


**Figure 4 – Gunn Oscillator setup used for measuring the reflected power of incident photons at 137 GHz. The Gunn Oscillator generates radiation at a desired frequency (emitted from the right), as we read out the incident radiation (of the set frequency) into the left horn.**

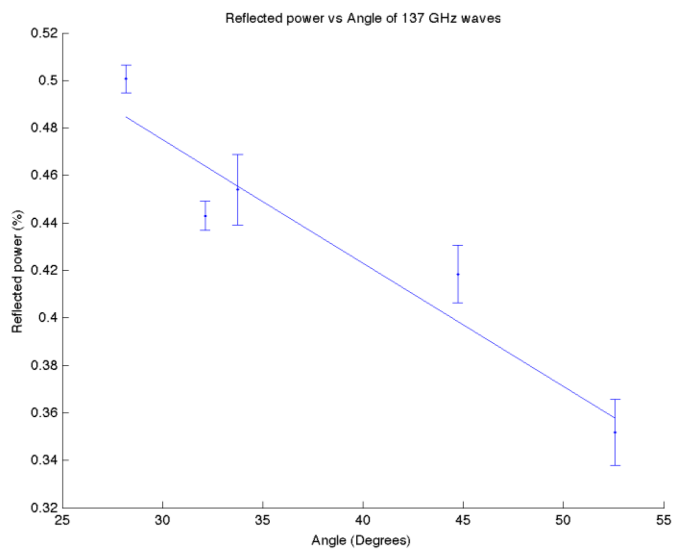


**Figure 5 – Reflected power against incident angle. There are large uncertainties in these values, and the linear line is simply to show a decreasing reflected power with increasing angle. It is not a stringent fit.**

**Parameterizing Blackbody Surface Geometry**

As the incident radiation is reflecting off of the surface, it is possible to control the reflection dynamics by altering the reflection surface. In particular, by using a pyramidal array, radiation is forced to bounce multiple times before eventually traveling onto a detector. This causes multiple interactions with the resin, further decreasing the reflected power. In accordance with the ARCADE and Tohoku University groups, we used this pyramidal structure on the surface of the blackbody load. As the optical properties of the proposed surface are known, all that is necessary is to know the number of bounces incident radiation will experience when entering the load. Using a ray-tracing program, I modeled the effect of placing a point source of rays a certain distance away from the blackbody. This is effectively the time-reverse of our setup, in which radiation follows the rays coming from the outside and bounces down onto the point (the ray paths are identical in both cases). Figure 6 shows the ray trace. From this program, the number of bounces encountered by 10,000 randomly distributed rays originating from the point source (the source only emitted rays within a 70 degree cone angle, so that all 10,000 were in the direction of the model) can be determined and plotted against incident angle (onto the detector, plotted in figure 7).

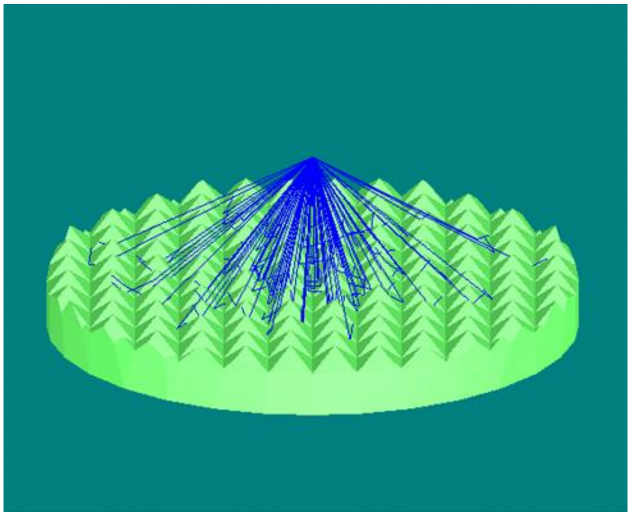

**Figure 6 – Ray trace of rays incident onto the blackbody load model.**

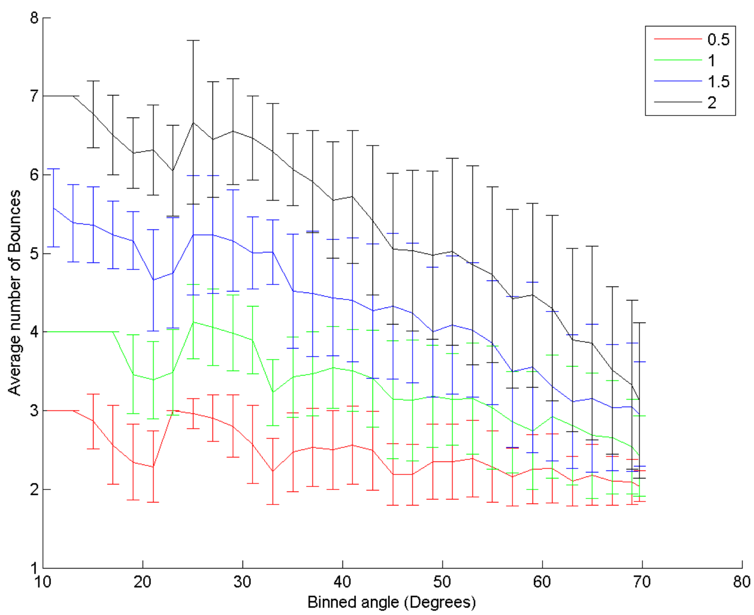


**Figure 7 – Average number of bounces against blackbody models of varying height against the incident angle (onto the point source). The legend is in units of half-inches (red is quarter inch tall, green is half inch tall, etc).**

The objective here is to determine the optimal shape of the pyramids. Due to the x-y symmetry of the system, square pyramids were chosen, with height as the varying parameter. The ray trace was then performed on multiple models all of varying pyramid height, shown in figure 7. From this

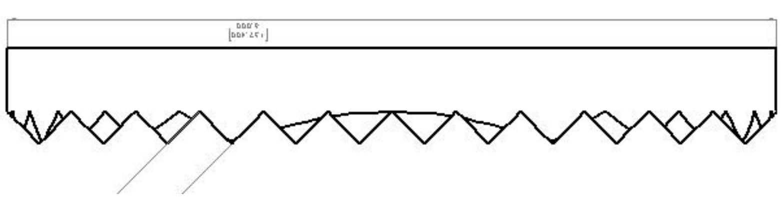

**Figure 8 – Cross section of blackbody load. Diameter is 6"; pyramid height is 0.25 inches, with 90-degree angles.**

analysis, pyramids with height equal to half their base length provide between two and three bounces. With two bounces at 50% power lost, the total reflected power is at 25%. Three bounces leads to 12.5% reflected, and so on. This analysis determines that creating a load with pyramids of height half their base will be sufficient for creating a blackbody load for our purposes. Figure 8 shows a cross section of the design.

**Creating the Blackbody Load**

The next objective was to create the object itself. First, the aluminum backing for the load needed to be prepared. Second, the resin needed to be poured onto the backing. Third, the resin needed to be cut to conform to the surface geometry described in the previous section. Because the resin would be eventually cut, it needed to adhere fairly well to the aluminum backing. In order to avoid the resin breaking off entirely from the aluminum, the backing must be cut to conform to the same geometry as the resin.

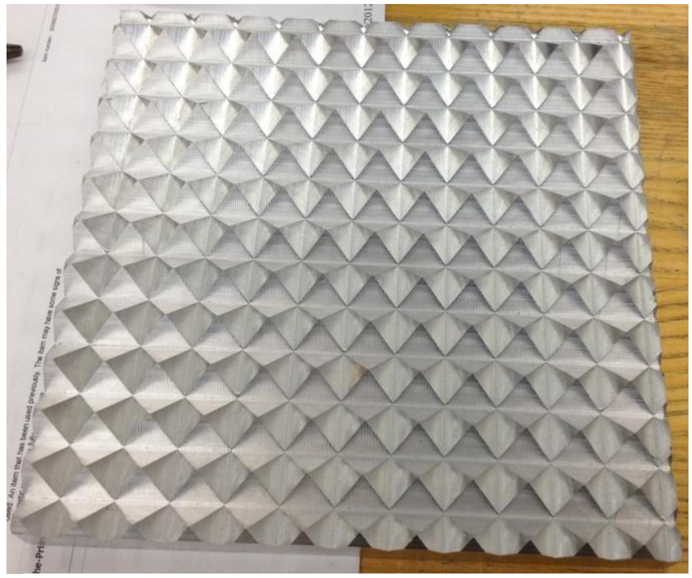

Figure 9 – Prototype of aluminum base for the blackbody load. The piece is 6x6 inches.

In order to cut the aluminum backing, a plate of thickness 5/8” was cut lengthwise with a precision mill tilted at 45 degrees. The virtue of using square pyramids with height equal to have their base is that the valley between pyramids forms a right angle. This allowed for a greatly simplified machining process, as the mill could simply cut along straight lines on a grid, progressively performing deeper cuts until the surface in figure 9 was produced.

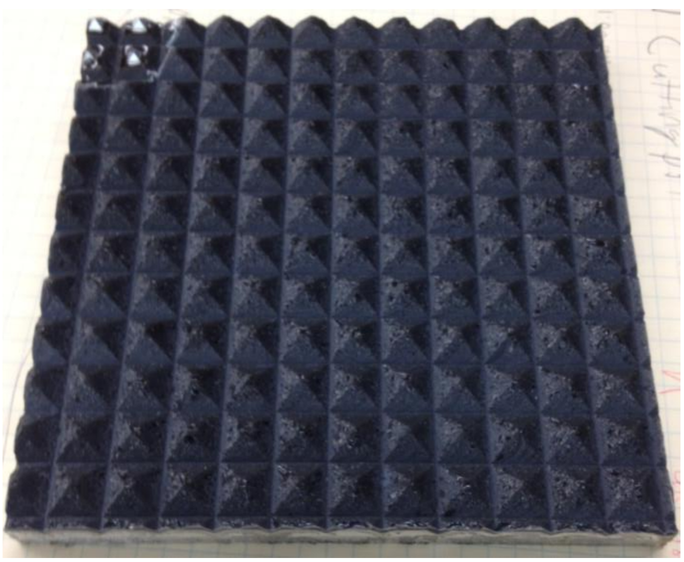

Figure 10 – Prototype blackbody load, after curing and recutting. Again, the part is 6x6 inches.

The next step in the process is applying the resin. From the manufacturer, it comes in the form of two liquids. The mixing ratio of the two liquids determines the type of resin produced. Before applying to the part, the composite mixture must preheat with the part itself to around 66 degrees C. One concern in applying the resin was that the resin may have a density gradient upwards due to gravity. In order to compensate for this, we used a method of mixing in Cabosil, a powder used by other groups to increase the viscosity of the resin in liquid form. The Cabosil has no effect on the electrical properties of the resin, or the curing process. [2] In order to pour the liquid onto the part, aluminum tape was applied along the edge to act as a retaining wall. Once preheated, the resin was poured onto the part, allowing adequate volume above the pyramids so that the part could be cut properly. After pouring, the part is left in the oven to cure until solidified. Upon curing it can be cut in the exact same manner as the aluminum, except using a carbide end mill. An early prototype using this method is shown in figure 10.

Figure 11 – Later blackbody model. This object is about 7x6.8". The surfaces are much smoother than previous models due to vacuum evacuation. In this particular attempt, there was a lack of resin on the surface, so the pyramids could not be fully cut, as can be seen by the square flat surfaces at each pyramid tip.

As can be seen in figure 10, there are many chips and holes along the surface of the resin. This is due to entrapped air remaining in the resin after curing. To remove this, later designs vacuum evacuated the part after the resin was poured. In liquid form, the resin easily allowed for the entrapped air to escape under high vacuum. Using this method, a much smoother surface is produced, shown in figure 11.

### Rotation Frame

The next objective was to design a method of holding the blackbody load above detectors. As mentioned in the introduction, the detectors are cooled to millikelvin temperatures. However, the area above the detectors is held a little warmer, at 4 kelvin. Because of this, it would be convenient if the blackbody load could be moved away from the detectors so that other tests may be performed without taking the time to recreate a cold environment. This is accomplished with a rotational frame mechanism. The objective was to design such a system for use at 4 kelvin.

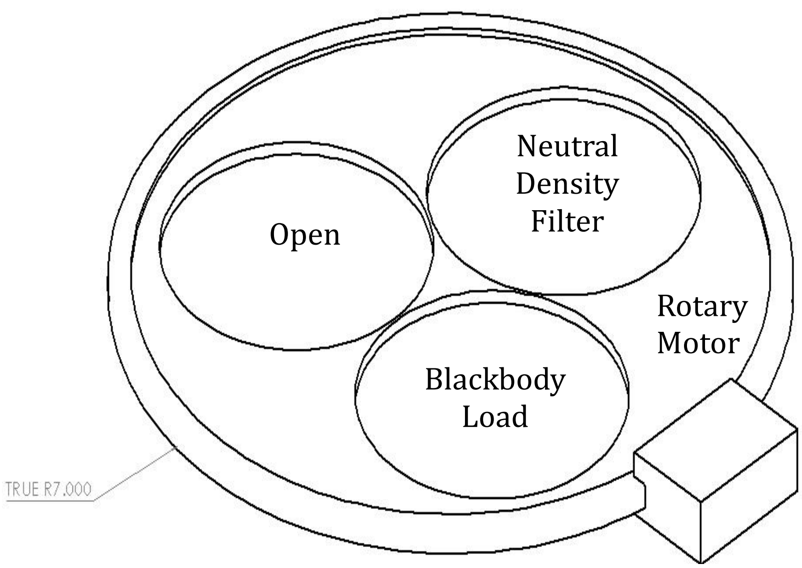


Figure 12 – Schematic diagram of the rotary frame. Three holders are in place for the blackbody load itself, along with a future planned Neutral Density Filter, and an open window. The frame is 14" in diameter.

Fortunately, a rotational system for use

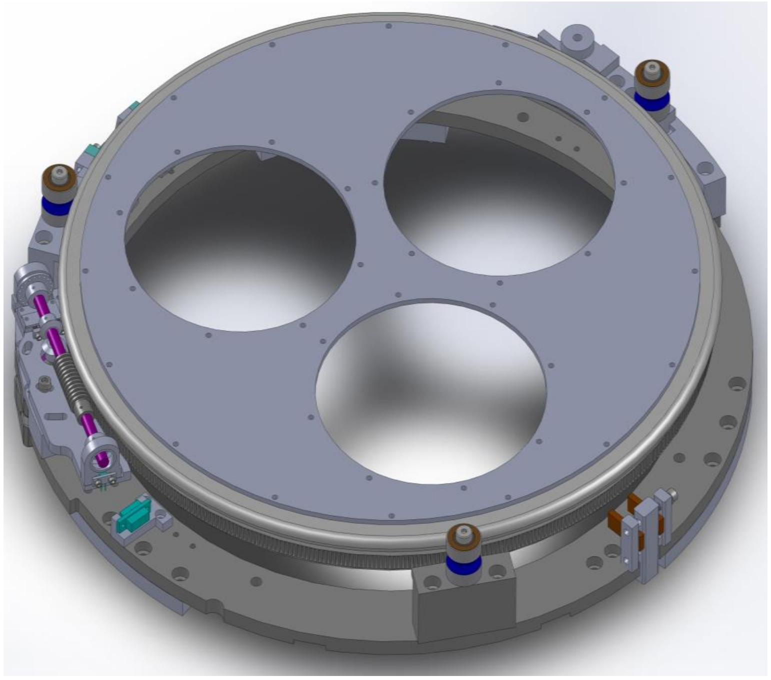

Figure 13 – Model diagram of the rotational frame. Primary designers for the rotation motor are Sean Bryan and Thomas Montry

at 4 kelvin already exists in the lab from a previous project. Graduate student Sean Bryan and PI Thomas Montry have constructed a rotational frame that as initially designed for holding a sapphire wave-plate for use in SPIDER operations. As the mechanism is no longer in use, it has been adapted for use with the blackbody load. In order to fit the load in addition to other future objects, a single cut aluminum plate was designed to be applied to the rotation system. Figures 12 and 13 show the schematic of the system and the model of the system, respectively.

## Conclusions and Future Work

Through a process of design work and machining, this project has constructed a method of creating blackbody loads with ease, as well as a method of holding various objects in a frame suspended above detector arrays while being held at 4k. In the short scope of this project, things that need to be completed are combining the rotation disk with the frame, as well as cutting the blackbody into a circle shape, which can then be bolted into the rotation disk. In the long run, with this system in place, various parameters may now be measured. Because the blackbody radiates in accordance to figure 3, a filter must also be designed and placed in front of the load, so the detectors are only receiving radiation at the frequencies we are interested in. In particular, the bands are 70-105 GHz, and 130-137 GHz.

Using the blackbody load as a variable radiation source, noise in the system may be measured at different blackbody temperatures, varying the optical power loading on the detectors. In addition, we may measure the DC responsivity and compare it to the ideal responsivity calculated from theory, applied from the introduction section, giving us the optical efficiency of the system. We may also modulate the electrical power loading on the detector at various blackbody temperatures, measuring the detector response speed.

In the rotary frame, it is also proposed to place a Neutral Density Filter (NDF), which is a filter that reduces power equally across all radiation frequencies. Without an NDF, the incident power from the room (at 300K) is enough to overload the detectors, sending them out of the transition regime and into the saturated regime. Using an NDF, we can determine the full bandwidth of the detectors by reducing the room's optical power. This may also allow for measuring the detector response speed using a modulated optical signal instead of a modulated electrical signal. It is also possible to gain information about the detectors looking into the room without and NDF, as the NDF may alter the incident polarization of radiation.


## Acknowledgements

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