

## Mu-Metal Shielding Factors in a Static Magnetic Field & An Investigation of 3D Printing

### ***Introduction***

Under the direction of my mentor Dr. Michael Niemack, I have been privileged to contribute research work towards furthering precise measurement and analysis of the Cosmic Microwave Background (CMB) radiation. Part of the research I conducted was measuring interior magnetic field changes resulting from mu-metal shielding in cylindrical cavities. The goal of this experiment was to determine shielding factors of mu-metals and examine the variability of shielding factors by region.

I was additionally tasked with developing 3D printing methods and best practices for possible future cosmological related application or design. 3D printing is potentially an industry changing technology that has recently been made accessible and affordable to non-manufacturing study in academia. As a still maturing technology, 3D capabilities and limitations with current software and hardware support are useful insights for maximally on some reported benefits such as cost/material reduction and on-demand production features.

### ***Mu-Metals and Motivation***

Mu-metals are ferromagnetic alloys mainly composed of nickel, iron, copper, small proportions of less common transition elements, and sometimes non-transition metals such as silicon. Mu-metals are also highly engineered during processing which enhance their unique properties, granting them a reasonable solution to mitigating static or slow varying magnetic fields. Conventional shielding techniques using conductive enclosures are only effective against changing magnetic fields  $>100\text{kHz}$ , by effectively canceling the applied fields via eddy currents developed in response. Mu-metals however, accomplish effective shielding against slower varying and static fields due to their high magnetic permeability - the ability of a material to support the generation of a magnetic field within itself. This property enables shielding not by blocking external fields, but by drawing fields into themselves effectively creating pathways for redirection of field lines around the shield. Although the method of action displayed by mu-metals is not a novel behavior, it is a property influenced by many factors difficult to precisely determine or quantify. Shape, manufacturing variations, age, and even past material histories such as physical shock, can cause variations of expected shielding factors which create difficulty in simulating precise field effects.

The cylindrical cavities employed in Dr. Niemack's laboratory are designed to encase cryostats containing extremely sensitive electromagnetic detectors required for precise CMB measurements. Cylinder shaped cryostats suspended from mounts to an overhead cryogenic housing assembly require a shield design of a single open-end cylinder to allow the shield to slide over the cryostat exterior from the bottom.

The cryogenic environment inside the cryostats is highly regulated with liquid helium, roughly maintaining a temperature of  $200\text{mK}$  – *two thousandths* of a Kelvin above absolute zero.

This extreme temperature is to control parameters in detectors known as a Transition-Edge Sensors (TES), and Superconducting Quantum Interference Devices (SQUIDS). TES's are based on the highly temperature-sensitive superconducting phase transition when a material is on the edge of normal conduction and superconducting phase change. Near this phase shift, variance in electrical resistance of the detector is exaggerated due to small temperature changes. This gives rise to a high precision measurement when the TES is heated by CMB photons. The TES circuit also requires coupling to a SQUIDS for accurate signal readout. SQUIDS exploits quantum behaviors through a Josephson Junction and are extremely sensitive to tiny magnetic fields. The sensitivity of SQUIDS can achieve detections of fields 12 orders of magnitude smaller than the magnetic field produced by the Earth. The background magnetic fields such as the Earth's can obscure precision data gathering, leading to a conclusion that a comprehensive understanding of mu-metal shielding factors will likely lead to increased reliability and precision in CMB data gathered in the outlined method.

### ***Shielding Factor Experiment Setup and Results***

A Helmholtz coil is a device that can produce nearly uniform magnetic fields in an experimental area. By measuring the field distribution produced at a specific strength for a region large enough to contain the target shield size, a route for analyzing field changes and calculating shielding factor is realized; first without any objects in the region for a baseline measurement, then inside the mu-metal shield in the center of region. However, due to unknown shield histories of magnetic exposure, possible physical shocks, and current visible structural deformities, a single measurement inside the shield cavity at center may not reveal accurate or precise results. Multiple measurements in every test shield should be performed in a consistent and iterative procedure at many locations.

To accomplish this, a magnetometer was mounted on a vertical adjustable rod that can be lowered or raised in the shield cavity. This vertical rod is then mounted on a horizontal assembly coinciding with the diameter of the shield. Such a setup allows for a 2D map of squares for cross-sectional viewing of field changes. Using 5 cm increments of measurements horizontally and vertically, 25 cm<sup>2</sup> resolution was achieved. At each measurement increment, field direction was also reversed by switching Helmholtz coil current direction. After 15 increments of measurements, the magnetometer was removed from field and recalibrated to reduce residual magnetization error. This process was repeated on the field with direction rotated by 90 degrees as well, in attempt to view variations in shielding when field direction coincides with cylinder diameter.

After aggregating data, all measurements showed shielding factor range of roughly 200-600. This factor was obtained by measuring a theoretical field strength of 10.5 Gauss in a Helmholtz coil region without shield, and then inside shielding cavity in coil region. By dividing the latter by the former, the previously calculated shielding factor was obtained. On the 2D map there were not any easy to distinguish patterns other than an average decrease of shielding factor as the measurements approached the open end of the shield cavity, which was expected. While the shielding factor determinations do not seem precise, all measurements did lead to a shielding factor in the same order of magnitude, which is significant for reducing the 12 orders of magnitude field strength difference between maximum SQUIDS sensitivity and Earth's magnetic field.

Error sources were most likely caused by: no available fixing of shield to center of Helmholtz coil field, no mounting of magnetometer probe assembly causing judgement errors and movements of probe from its intended position, open-ended cylinder allowing for magnetic fields to enter interior cavity, structural mu-metal discontinuities such as weld joints, and unknown previous physical histories of the mu-metal.

### ***3D Printing***

3D printing is a relatively new manufacturing technology which has been steadily gaining attention, due to a potential to revolutionize existing manufacturing techniques and structure. 3D printing is a colloquial term attributed to a subset of additive manufacturing technologies that has permeated consumer markets due to maturing technology support and decreasing costs. Bringing 3D printing to market required the integration of several technologies, leading the exciting ability of publicly shared designs to be built within the user's physical printer limitations. 3D printing also features an additive building process which reduces material use, a wide array of materials to use as building substrates with environmentally friendly options, active communities surrounding most printing platforms, and substantial varieties of free software programs dedicated to assisting in model optimization.

Traditional manufacturing techniques such as subtractive removal of material or casting and pour, have historically provided the essential supply of products required to support a growing population. These techniques existing since man first chipped away a rock to reveal an arrowhead, have been slowly evolving tools and methods over history to simplify and automate production to the magnitude seen today. 3D printing contrastingly adds thin layers of melted material by layer, which procedurally adheres to previous layers, eventually summing to the final specified product. Refinements of 3D printing processes, design methods, and best practices have not had such lengthy maturing times for holistic saturation into current manufacturing industries. This relative immaturity in its implementation clouds 3D printing's impact on future industry infrastructure.

### ***Goals & Resources***

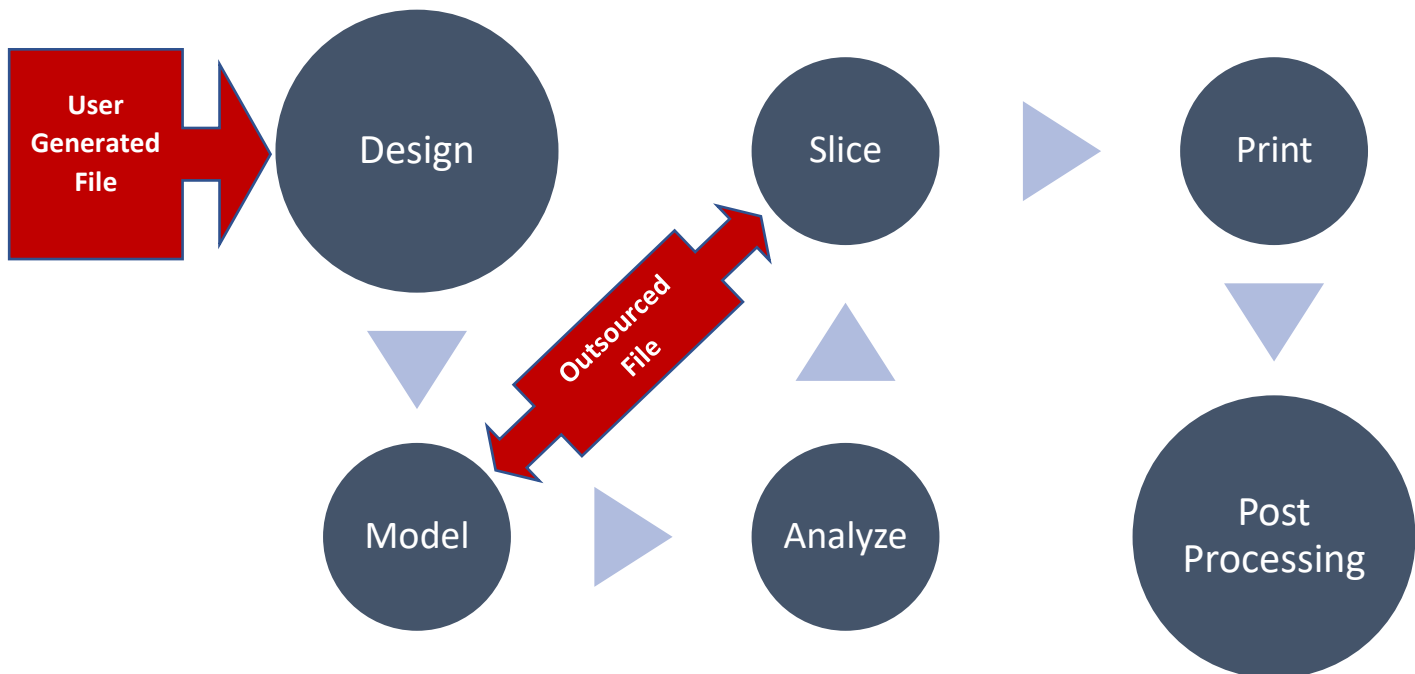
Create accurate scale models of the Atacama Cosmological Telescope (ACT), and the proposed Simons Observatory Small Aperture Telescope. These will be attempted to be 3D printed using existing or incomplete modeling files provided.

Resources available to accomplish these goals contained various hardware and software tools. The hardware consists of an Ultimaker 2+ printer, various colors of polylactic acid (PLA) – a robust, recyclable, biodegradable, and renewable polyester, and polyvinyl alcohol (PVA) – a water-soluble synthetic polymer ideal for printing supporting structures enabling seamless and quick removal. The software used to create and edit model geometry consists of SolidWorks 2017 and Autodesk CAD. Additionally, two non-native model files were provided containing geometries of the telescopes. 3D printing requires additional software to analyze the model to be printed by 'slicing' the model horizontally into thin sheets, conveniently dubbed 'Slicing Software.' The software chosen to use was Ultimaker's own collaboration with developers in its community named Cura. This software is purportedly designed to maximize support and proper configurations of Ultimaker products, as well as introducing over 100 additional parameters for

tweaking global printer settings, adding supporting features, model scaling or positioning on build plate, and basic geometric mesh repairs.

### *Process*

After two months of model creation, optimizing existing models, and comparing completed prints to the original specifications, it is retrospectively obvious to see patterns and categorizations of general procedures. It is helpful to break the 3D printing process into various phases of development seen below. I have illustrated a description which I think properly details and encapsulates the process, which helps describe some of the intricacies which are not immediately apparent when approaching the subject of 3D printing.



*In the process flow above, the red boxes consist of inputs into the system. Outsourced files may have alternate flows depending on if they were previously optimized to be ready for slicing and printing. A detailed breakdown of each phase follow.*

**Design** – Here, decisions must be considered that include the size of the product, material type, function, and complexity. These properties must fall within constraints set by the model of 3D printer such as maximum printing size, material compatibility, and print time availability. Furthermore, depending on the modeling software to be used, designing an object for print should include considerations of how it can be modeled in the simplest and most accurate way. For example, creating a model with smooth features should not be expected to be modeled in a software package that does not allow for polygon resolutions able to correctly represent a curved surface. Additionally, creating a model demanding a cosmetically pleasing external surface but also requiring support structures, may require use of a dual-extrusion printer to use a dissolvable material as supports which would enable maximizing external appearance.

**Model** – In the modeling phase, various software programs are available for creating and editing models. Each of them has capabilities and limitations that can present issues, especially with

importing and exporting supportive filetypes. An imperative feature is the ability to export a model to a format that is compatible with slicing software. In a specific case of software difficulty encountered, SolidWorks had a difficult time properly converting the .igs file extensions. Although the intended geometry was preserved, editing the geometries using SolidWorks proved to be impossible, requiring additional conversions to AutoDesk and back again. Oddly enough, this proved to fix the issues, but not before multiple hours of frustrating research into the issue.

It is important to select the right software that synergizes its strengths with the models most detailed and critical components. Software versatility of supported filetypes is also a desired ability. Depending on this factor, there may even be situations where an outsourced file should be only used for reference, as creating a new model based on reference could prove to be a quicker and less work intensive process.

**Analyze** – This phase consists of checking for inconsistencies in the model that may interfere with desired print outcomes. Gaps between separate features may become fused together, especially when they approach the size of the printer’s extrusion head resolution. A model that has sub-millimeter spaces between separate faces may get fused together, as most printer heads extrude material around 0.4mm. As with any manufacturing specifications, there are ranges of precisions which limit resolution of fine structures. Intersecting solids can also cause confusion in the software interpretation of the model geometry, causing inconsistent interpretation and unpredictable results in consequent phases.

**Slice** – Similar to the Model phase, many different software platforms exist dubbed ‘Slicing’ programs. Their purpose is to provide tools for importing and making final adjustments to models and exporting the model to a file format containing machine instructions for the printer to execute. The conversion of model geometry to build instructions is accomplished by horizontally slicing the model into layers, which is then converted into movement instructions for the printer for each layer. The slicer also enables modifications of hundreds of parameters directly relating to printer settings. It is here that a layer-by-layer visualization can be examined, as well as the estimated printing time. Another feature is the analysis of the model to determine where build supports are needed to assist overhanging structures. Orientation, scaling, and rotation of model can also be modified for positioning on the printer build plate. Post-scripting instructions is also achievable here, allowing for such mechanics such as layer dependent pauses in printing for color changes. This is especially useful in creating multi-colored models, but only when color changes across the model apply at a certain layer.

Slicing software should be chosen based on supported printer models of the software. Until industry wide standards are created for file formats and methods, certain software and hardware compatibilities are relegated to the individual printer manufacturers.

**Print** – After obtaining the machine instruction file from the slicer, it can be loaded into the printer via removeable storage media, or in some cases direct connection with the printer. Before printing begins, the material type and color should be loaded into the machine, as well as ensuring a clean build plate for maximal material adhesion and stability. At the start of a print, the build plate will heat up, as well as the printer head extruding element, to preset parameters dependent upon type

of material or custom requisites. After printing has begun, periodic checking of progress in long prints is good practice. In the cases of printing failures, this progress checking can help determine failure causes, as well as minimizing wasting of material. The printer is not designed to determine quality or minor failures, so aborting a print early after undesired deformities can mitigate waste. Monitoring the printing can also help give insights into how exactly the model was translated into mechanical instructions. This can help one see how certain complex areas were resolved into physical structure and movement.

**Post processing** – After removing the finished product from the build plate, removal of material that is used to help adhere the product to the build plate is needed. In situations where supports were necessary, they are then removed as well. This can require significant manual dexterity and tool use depending on the amount of supports needed, as well as their density specified in the Slice phase. Removal of supports is best done with needle-nose pliers for hard to reach areas. In some cases, undesired ridges remain that cannot be further removed with pliers. In these cases, improvising with other tools can help mitigate the noticeability. A hot glue gun nozzle provides a useful temperature range to melt those striations back into the model. It does not give perfect results but can significantly reduce their appearance. If a dual extrusion printer was used, and supports were provided with a water dissolvable material, then the model can be submerged until the supports are gone.

### ***Encountered Obstacles and Hidden Limitations***

After about a week of modeling program tutorials, research into 3D printings inner workings, and frustratingly glitchy model behaviors, progress was made by exporting the model file to one of the supported file formats supported by the slicer software known as \*.STL. After successful preparation in the slicing software Cura, the \*.STL file is then converted to a numerical control programming language used in machine controls known as G-code, a file with extension \*.gcode which can be executed by the printer. Part of the encountered difficulties was most likely due to the imported base geometry file of the ACT, which had to be repeatedly converted into other modeling programs and back to be able to edit basic features correctly.

During times of ACT model printing requiring roughly 35 hours for completion, I managed to modify the other file of the Simons Telescope to obtain an acceptable representation. The interior part assemblies were removed, as they were not necessary. The very in-depth design of this model introduced severe increases in model calculations, causing a cascade of lag in the software response and deathly slow wait times every time a feature was modified. This highlighted another possible limitation with the modeling process, though this could be software dependent. There were also situations where I wished to add on to a previously printed model, but as of now there are no mechanisms to have slicing software and printer support to navigate that obstacle.

### ***Summary and Conclusions***

I have found that researching shielding technologies and 3D printing for use in cosmological applications to be exciting, intellectually stimulating, challenging, and fruitful. It

was an enlightening experience to see real research in action from scientists and graduate students, while also being able to contribute what I could. It gave me great insights into the sheer number of hours of work and research that goes into some of the seemingly easiest of tasks. Taking measurements of the magnetic fields inside the mu-metal shields was extraordinarily tedious and required teamwork to complete effectively. When I first was assigned the 3D printing goal, I was convinced I would have it completed in a few weeks at most. Little did I know that even using technology that isn't absolutely novel, I entered down a rabbit hole of obstacles and steep learning curves that required many hours of work to navigate efficiently. I am grateful for these experiences though, as it was a humbling reminder of how the magnitude of the phrase, "standing on the shoulders of giants" truly applies. I also am grateful for the opportunity to probe the nuanced 3D printing technology, especially after having a background in computer science. I was able to discern the many improvements that is needed to truly unlock the capabilities of 3D printing, while also appreciating the monumental integrations that has already been pioneered to make it possible.