Improving the Detector Fitting Algorithm for the TolTEC Camera and Characterizing its Thermal Behavior

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Abstract

TolTEC is an astronomical camera being constructed for installation on the Large Millimeter Telescope (LMT) with a mapping speed 100 times faster than its predecessor, AzTEC. It is implemented with a cryogenics system containing 7000 kinetic inductance detectors (MKIDs) that reach temperatures of .1K, representing a drastic improvement from the Aztec's 144 detectors. The temperature of the sensors needs to be monitored through thermometers placed in the system's cryostat; since, the system must maintain a constant working temperature. TolTEC's thermometers provide a constant stream of thermometry data to monitor temperature. The thermometry data is normalized through manipulation in Python to create a "health monitor" for TolTEC that will alert operators of any malfunctions. A stable, "healthy" temperature must be established before the MKIDs can function. The MKIDs are used to detect the optical power between 1.1- and 2-millimeter wavelengths. Before TolTEC is commissioned at the LMT, the MKIDs must be extensively analyzed to ensure proper function. The detector fitting algorithm was developed and improved to detect false, duplicate, offset, normal, and nonexistent detections. Without working MKIDS, TolTEC would be blind to the outside world. Overall, the construction of TolTEC will revolutionize the field of millimeter wavelength astronomy.

Introduction

When installed at the Large Millimeter Telescope (LMT), TolTEC will revolutionize astronomy. As pictured in Figure 1, the LMT is a telescope located in Sierra Negra, Mexico at an altitude of 4850 meters. The LMT has a 50 m diameter reflecting primary surface with 180 segments. The LMT's reflecting surface contains 1440 panels that have a rhodium coating, which allow for millimeter wavelength astronomy to be conducted [1]. These features enable TolTEC to image at 1.1, 1.4- and 2-mm wavelengths over three arrays, using a total of 7012 MKIDS [2]. TolTEC's design allows increased angular resolution and sensitivity [3].

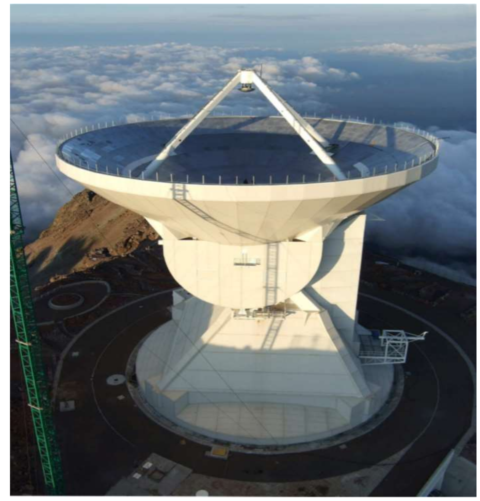


Figure 1: The LMT

The TolTEC camera consists of an elaborate cryostat system, which contains an optics bench and a combination of outer shells known as stages. The stages are kept at separate temperatures.

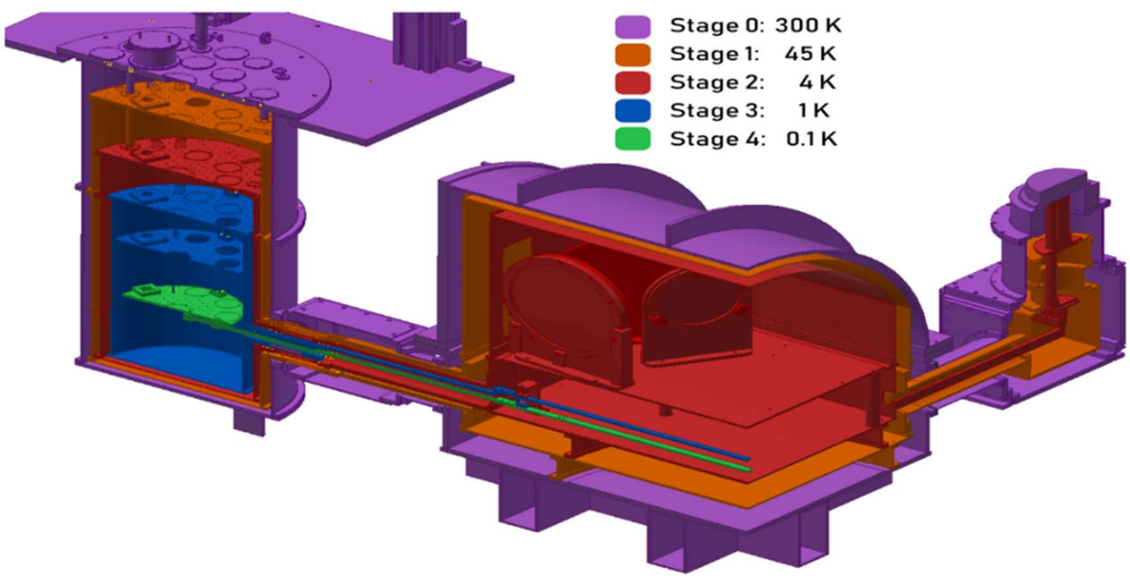


Figure 2: Internal View of TolTEC. Showcasing the stages at different temperatures. The temperatures decrease as you go further into the cryostat.

The TolTEC camera functions by absorbing and filtering photons from the sky. For testing to improve the camera, photons are emitted from a black body source inside the cryostat. The black body source is a metal stand, which features a black, opaque nonreflective square and a copper backing. The black body is an ideal absorber of light at any wavelength, allowing for the amount of light it emits to be extremely predictable [4]. In TolTEC, wires and resistors send specific amounts of electricity to the black body's copper plate, creating a controllable amount of millimeter wave light. The millimeter wave light is distributed onto the MKIDs, so their optical readout is measurable [5]. The MKIDs function using superconductivity, which requires them to operate at very cold temperatures maintained using a cryogenics system (Low temperatures) [6]. The system becomes cold through a dilution fridge and AUX PTC [7].

Figure 3: The 1.1 mm Array

While there is no resistance, a low inductance is detected, allowing for the S_{21} voltage value to become measurable since the pair is moving faster. The S_{21} voltage value is read out electronically on a VNA sweep. In a VNA sweep, the data located on the top shows the gradient of the S_{21} value making it interpretable with each colored peak standing for the detection of a detector, and the bottom part representing the raw S_{21}data [8]. The VNA sweep data is analyzed to ensure the detector finding algorithm can detect all of TolTEC's MKIDs. The analysis of the VNA sweep data is used to confirm that all the MKIDs are functioning.

In addition, 32 thermometers are located throughout the cryostat. The resistance thermometers can read temperatures up to 0 kelvin [9]. Once data from the thermometers is collected, the data is normalized to create a system-wide health monitor, which notifies the operators of TolTEC if the system's temperature is out of the operating range. TolTEC's health monitor is extremely important because TolTEC only reliably works within a standard temperature range.

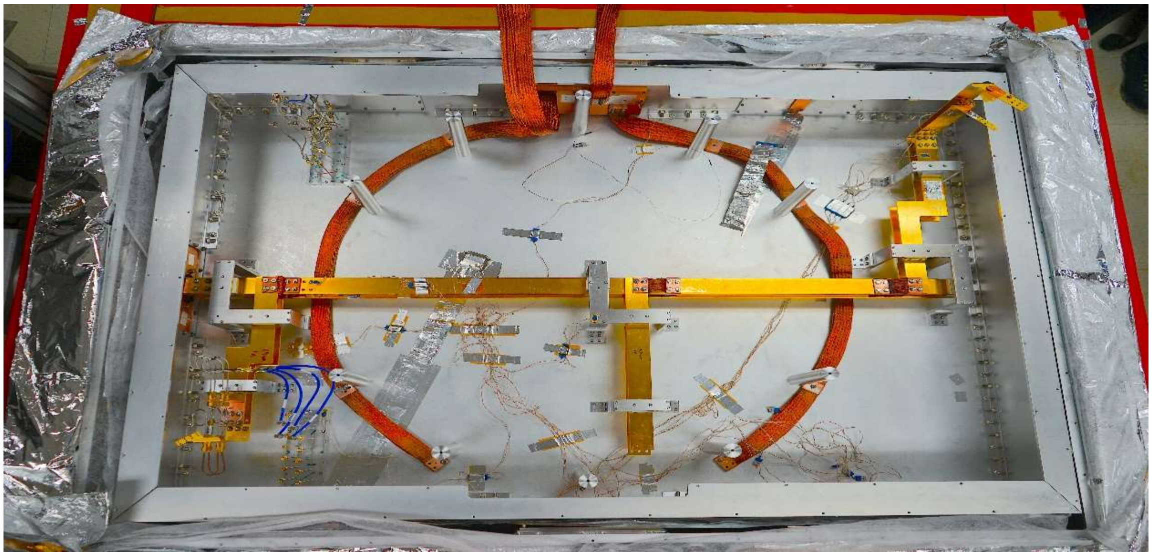


Figure 4: TolTEC's optics bench with 32 thermometers located throughout several positions within the cryostat.

Methodology

Developing TolTEC's Health Monitor:

Figure 5: A Resistance Thermometer

In the cryostat, there is a total of 32 thermometers each in its own channel. For each cooling cycle a data file is complied with each thermometer's recorded temperatures. Images of the optics bench are analyzed to ensure that the position of the thermometers remained the same throughout all the cooldowns. The data files are then analyzed by plotting each channel’s temperature. All channels that do not read any temperatures are classified as “dead” thermometers. The separate channel data from all the cooldowns is plotted against each other.

Afterwards, the data is analyzed, so the start of the cooldowns are aligned, allowing the data to be interpreted. Data interpretation is significant because it allows the known trends to be determined. The known trends for each channel need to be established to ensure the cryostat is running properly. The goal is that an anomaly will trigger an automatic notification to be sent to the operators of TolTEC.

Enhancing the Fitting Algorithm:

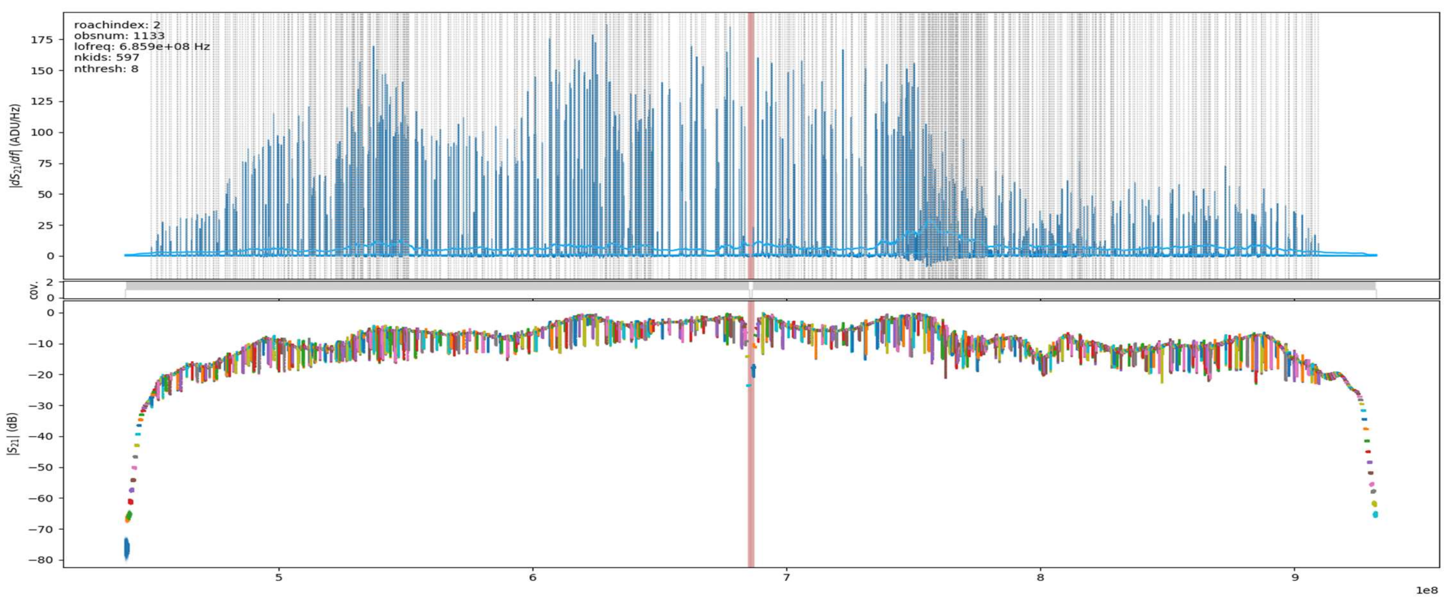
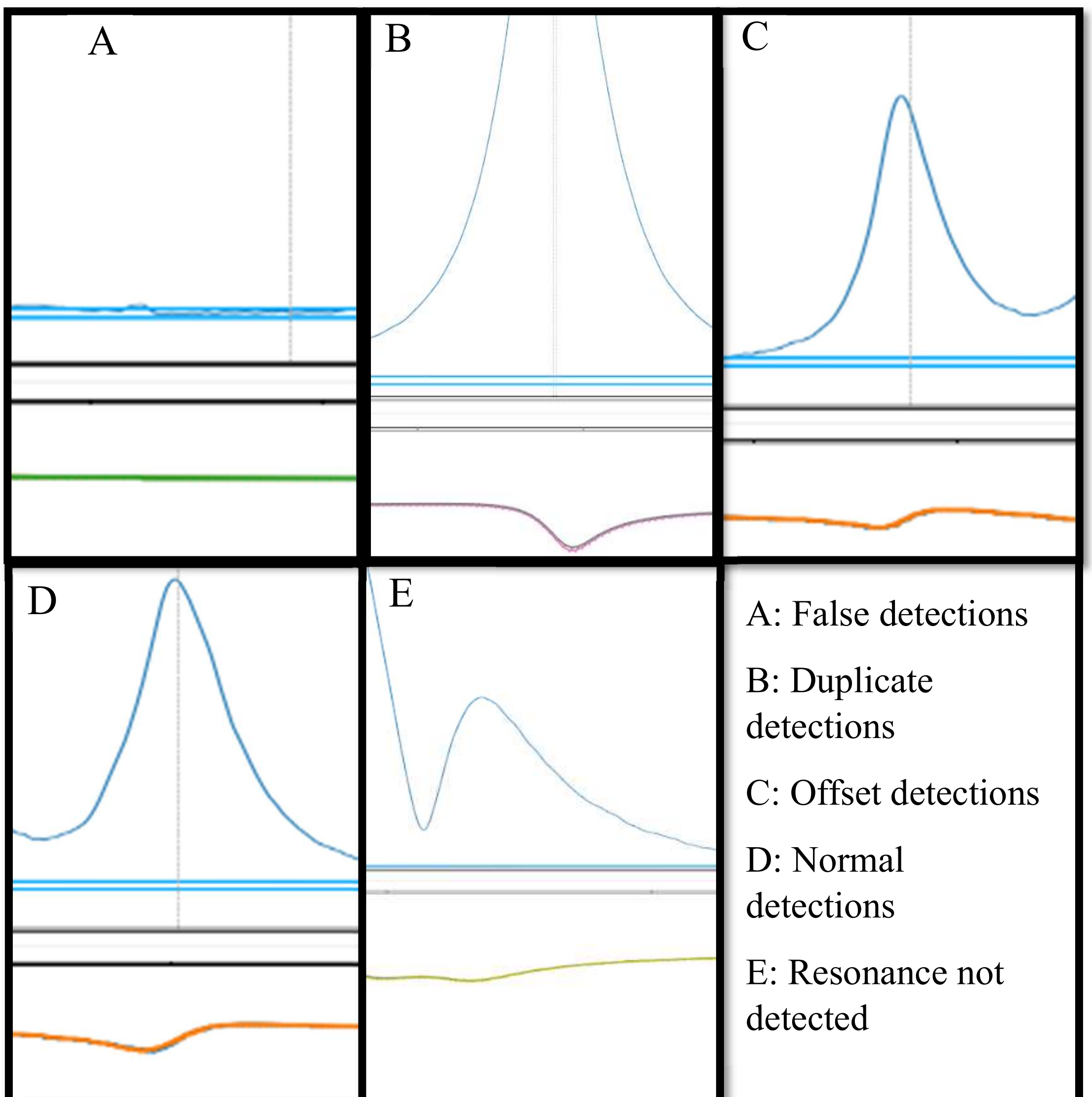


Figure 6: VNA sweep plot of response (absolute value of S_{21}) across full range of detector frequencies. Lines are drawn at resonance frequencies identified by fitting code.

Data from a VNA sweep is processed by the detector fitting code. Then, the detector fitting algorithm characterizes the detections into categories defined by the drawn line. The first type of detection is a false detection, meaning the algorithm draws a line when no detection is made as pictured in part A of Figure 7. Shown in part B of Figure 7, an additional type of anomaly the algorithm creates is called a duplicate detection meaning that two lines are drawn by the algorithm, but a singular detection is made. The next type of detection is an offset detection depicted in part C of Figure 7. The algorithm, makes an offset detection by misidentifying the peak, resulting in a line drawn slightly off center. Next, a proper detection is made when the line is drawn correctly on the peak as displayed in part D of Figure 7. Another anomaly is identified in part E of Figure 7, the algorithm did not identify the detection made by the VNA sweep so, no line is drawn at all.

Figure 7: Types of Detections

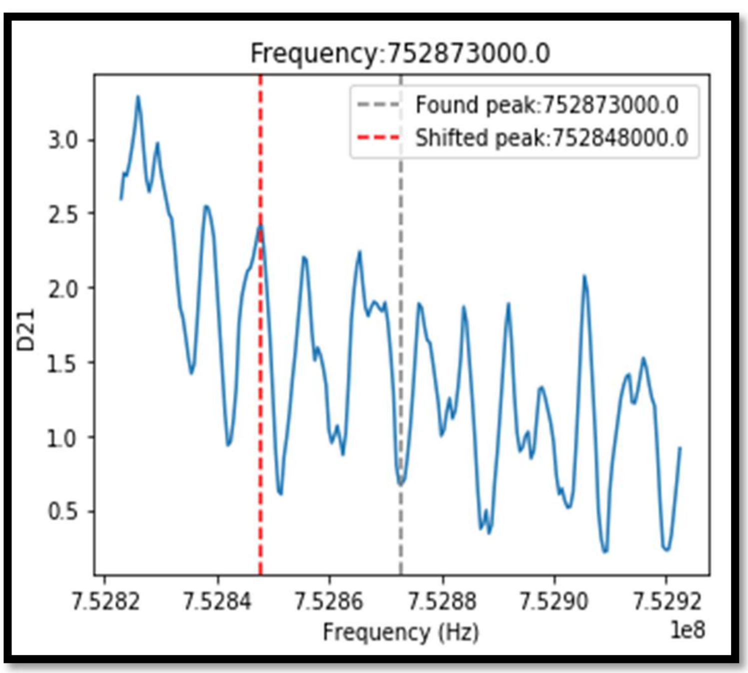


Lastly, when a peak is identified in the VNA sweep with an amplitude of less than 1.5 dB, it is classified as an insignificant peak and not an actual detection. The tiny peak is caused by noise. Using these categories, I compiled the frequencies of each type of detection.

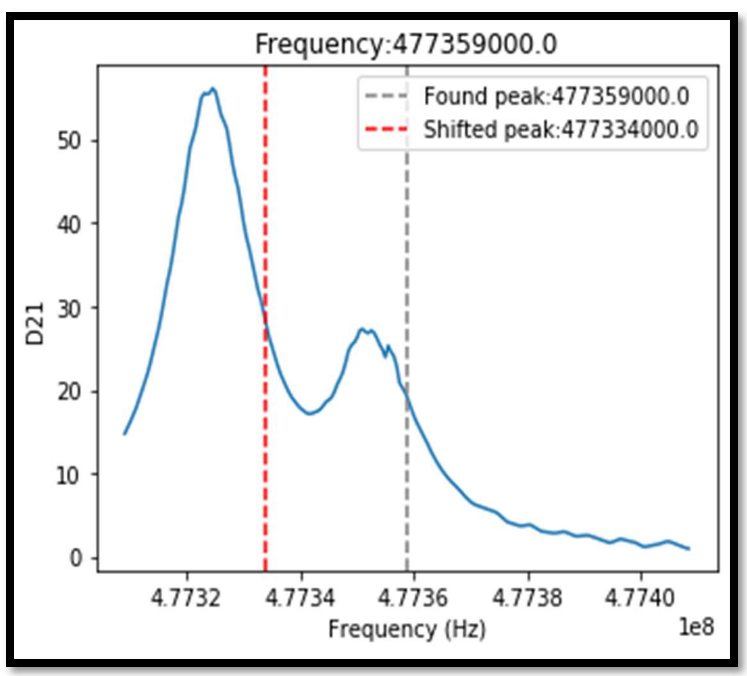
Next, for deeper analysis of the VNA sweeps, a program was written in Python to find the maximum shift values, which are used to find blended peaks. Blended peaks are when one detector is identified by the fitting algorithm, but two disparate detections from the MKIDs are actually present. Since the shift value is considered to be greater than the window size, it can be assumed that the Python algorithm may have not detected one of the peaks because the window of the algorithm was too small. Graphs 1 and 2 are examples of graphs generated to help target blended peaks. Graph 1 was used to identify noise in the data while Graph 2 was used to identify a blended peak. Once the detected frequencies match the designed frequencies, the fitting code will be complete, because it will accurately find all MKIDs.

Finding Blended Peaks

Graph 1



Graph 2

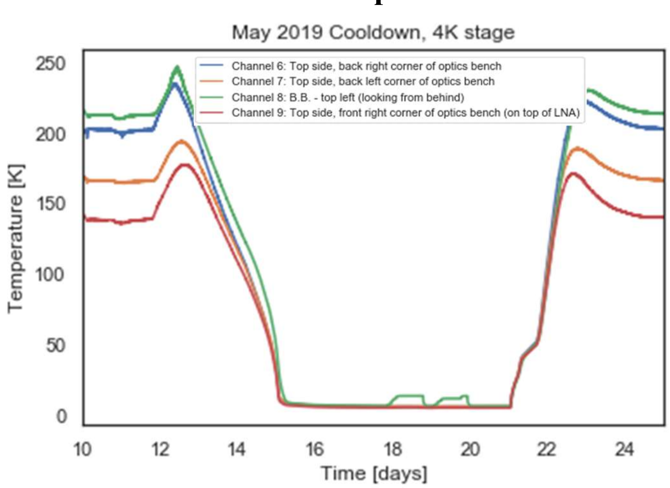


Results and Discussion

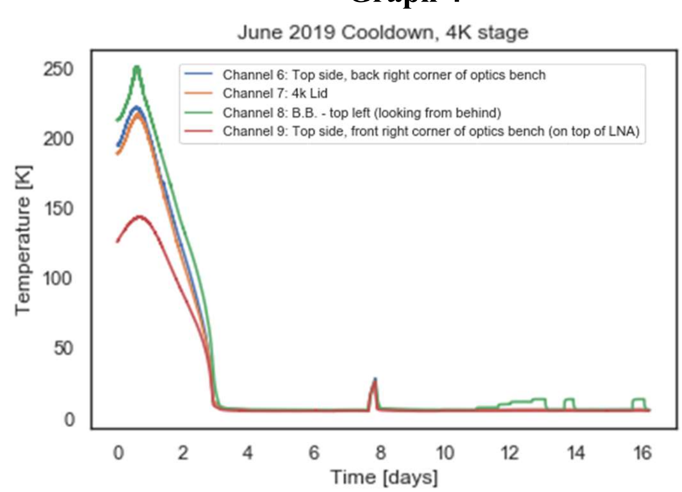
An Implementation Ready Health Monitor:

The results gathered during the examination of the cooldowns have aided in the testing and characterization of the TolTEC camera. Through the analysis of thermometry data, a health monitoring system for the TolTEC camera is being developed. The health monitor is significant because in order for the TolTEC camera to function and read out any data, its cryogenics system needs to work flawlessly. This means that the health monitor is crucial to TolTEC's success. Since the health monitor's algorithm focused on the characterization of TolTEC's thermal behavior, a "normal" standard can be developed. If the thermometers show data outside of the "normal" standard, the operators of TolTEC will be notified, so the problem can be fixed. As seen in Graph 3, the data must be aligned for this "normal" standard to be established for consistent temperatures. In Graph 3, the negative slope line indicates the cooldown of the MKIDs and their constant temperature of .1K on the 4K Stage during the cooldown. The detector testing is demonstrated by the increase of the green line, representing the increase in temperature of the black body during testing, on the bottom followed by a warmup which has a positive slope. These patterns exemplify the normal standards that TolTEC should demonstrate during a cooldown.

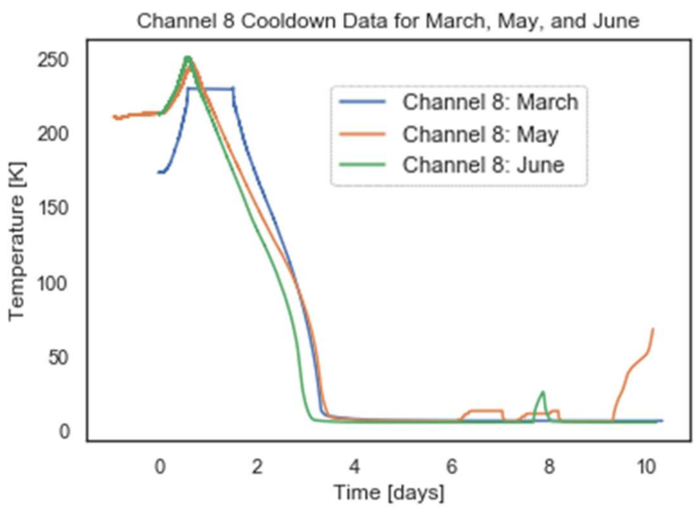
Graph 3



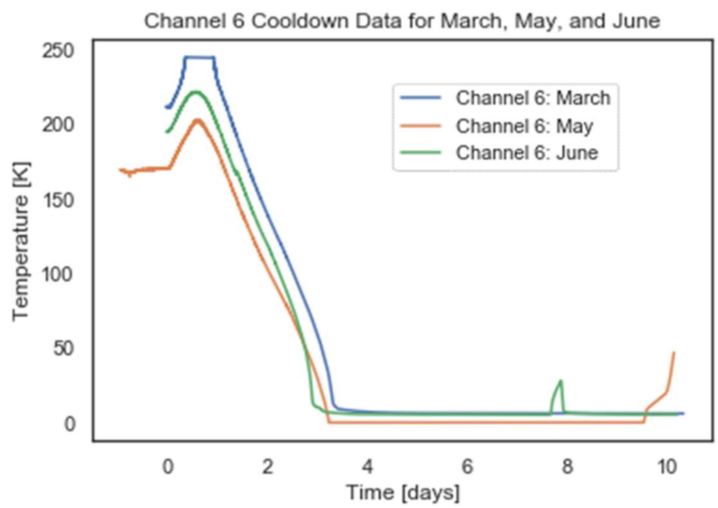
Graph 4



Graph 5



Graph 6



Fitting Algorithm Improvements:

The detector fitting algorithm is crucial to TolTEC's success because the data from each detector needs to be found and interpreted precisely. All MKIDs need to be accounted for so that when TolTEC is deployed for operation it will be able to detect photons. Once the voltage is characterized from the read out, a map will be generated by converting the voltage into optical power and plotting the data from the thousands of MKIDs. The results from the VNA sweep I went through are shown in Data Tables 1 and 2. Data Table 1 shows that networks 0 and 2 have a greater number of missing lines in comparison to Data Table 2. In Data Table 2, the number of both tiny detections and duplicate detections increased.

Data Table 1: Analysis of the Networks' VNA Sweeps

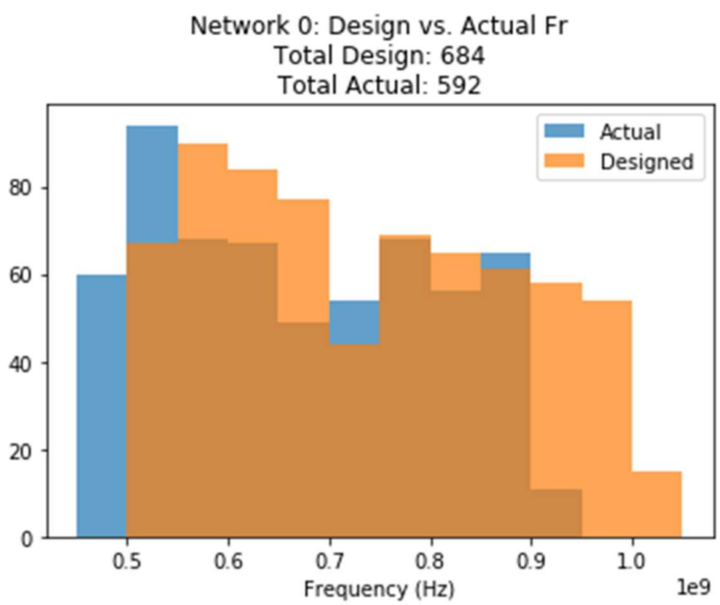
Network Number	Number of False Detections	Number of Resonances Not Detected
Network 0	3	186
Network 2	2	236

Data Table 2: Analysis of the Network 0 VNA Sweep With The Updated Algorithm

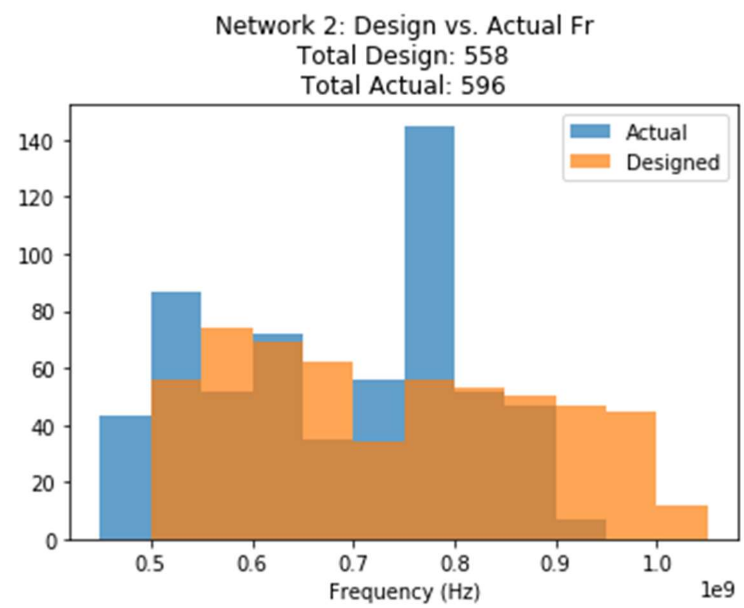
Number of Resonances Not Detected	Number of Offset Detections	Number of Duplicate Detections	Number of Tiny Peaks (<1.5dB)
3	2	52	160

Data Table 2 represents the results of the updated code; the code was altered in a way that improved its ability to find the MKIDs, but now too many detections have been produced. In Graph 7, before the fitting algorithm was updated, the number of detections actually found was lower than the expected number based on the number of MIKDs being tested, but very close to the designed value. In Graph 8, after the algorithm was improved, more detections were made than the designed, showing an increase in actual detections. This demonstrated that the fitting algorithm is close to a hundred percent finding accuracy.

Graph 7



Graph 8



Conclusion

Overall, the detector fitting algorithm has been vastly improved. The improved algorithm finds more detector candidates and the health monitor characterizes thermal behavior for all channels. Both of these advancements have greatly helped progress on TolTEC and will help allow it to soon be installed at the LMT in January of 2019. Once the camera is installed at the LMT, it will be able to accomplish novel research experiments composed of legacy surveys (planned millimeter wavelength astronomical surveys) that will be available to the general public, as well as many other millimeter wavelength astronomy experiments. One of the specific surveys is the Fields in Filaments Survey, which will investigate the role of magnetic fields on star formation [10]. This is just one of the many questions that TolTEC will answer in the coming decade.

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