Noise Characterization and Elimination in Microwave SQUID Multiplexing CMB Detection Systems

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ABSTRACT

Microwave SQUID multiplexing is a next-generation detection and readout scheme that could increase the number of pixels in current CMB cameras by 50-fold[2]. The noise in a model microwave SQUID chip channel at 250mK was measured using a homodyne demodulation scheme and digitized using an oscilloscope. It was determined that the cryogenic pulse tube cooler microphonically coupled $\sim 700 \frac{\mu\Phi_0}{\sqrt{Hz}}$ of noise into the system. Additionally, we determined the system was susceptible to AC magnetic field pickup at $\sim 54 \frac{\mu\Phi_0}{\sqrt{Hz}\,\mu T}$. Both of these values are an order of magnitude larger than what has been previously acheived[3]. As a result, a niobium foil magnetic shield has been designed for the SQUID housing and a mechanically isolating bellows will isolate the pulse tube vibrations from the cryostat. These improvements hope to reduce the noise in a microwave SQUID chip environment and validate our test setup.

INTRODUCTION

Since its discovery by Arno Penzias and Robert Wilson in 1964, the cosmic microwave background (CMB) radiation has been a gold mine for astronomers and cosmologists looking to learn more about our universe. At 13.8 billion light years away, radiation from the CMB is the oldest, most-distant light we can observe. Scientists have relied on data from the CMB to study everything from gravitational lensing and inflation to neutrino masses and the shape of our universe[6]. More precise CMB images will allow astrophysicists and cosmologists to make even stronger claims about the origin and evolution of our universe.

Our ability to take deep (low noise) images of the cosmic microwave background is limited by the number of detectors we can connect to form an array. More detectors mean more pixels, which yields higher quality images of the CMB and more data for scientists. However, each detector adds another wire traveling from room temperature into the cryogenic detection and readout system. This means as array sizes increase, the thermal loading from the large number of wires becomes technically and cost prohibitive to cool.

To solve this problem, we use a technique called multiplexing, which allows many signals to be read out on a common wire. Multiplexing is common in telecommunications systems and a well-established technology in room temperature electronics[7]. However, multiplexing to read out CMB pixels must be done at temperatures where the detectors operate (100-500mK) using superconducting electronics and much work can be done in this area.

A multiplexing scheme is characterized by its multiplexing (MUX) factor which corresponds to the number of detectors read out on one carrier line. The current best ground-based CMB measurement system, AdvACTPol, has a MUX factor[8] of 66. This paper focuses on experimental noise characterization and reduction in a next-generation microwave SQUID multiplexing readout system. If properly implemented, the microwave SQUID multiplexing technique is predicted to be able to achieve MUX factors[3] as high as 4000.

What is a SQUID?

A superconducting quantum interference device (SQUID) is a superconducting loop interrupted by one or more insulating barriers called Josephson junctions[3] (figure 1).

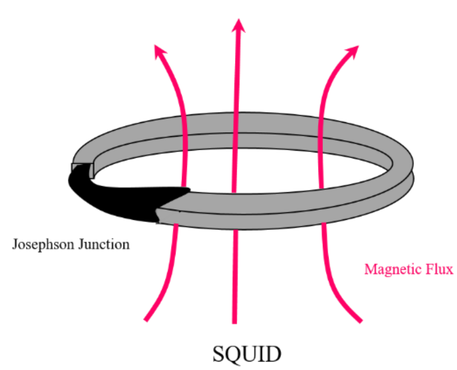


Figure 1: An artistic representation of a SQUID in a magnetic field.

SQUID technology began in 1962 when Brian Josephson discovered that the superconducting loop current tunneling through an insulating barrier is a periodic function of the current's phase difference across the junction[2]. This means that as flux increases through a SQUID, the current response is periodic (figure 2). Furthermore, A 2π phase difference across the junction corresponds to one magnetic flux quanta, denoted $\Phi_0 = \frac{h}{2e} = 2.068 * 10^{-15} Webers$, through the SQUID[2] (figure 2).

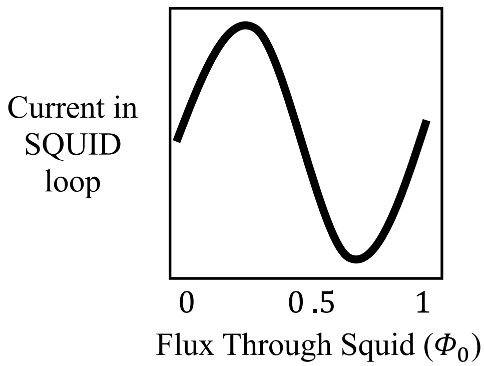


Figure 2: A generalized SQUID response to increasing flux.

In general, SQUIDs are used to sense magnetic flux and are widely used in modern cryogenic readout systems for their high sensitivity and low noise[4]. The system described later in this paper uses dissipationless radio frequency (rf) SQUIDs, which are characterized by a capacitive Josephson junction with no resistive shunt (figure 3). Thus, these SQUIDs dissipate very little power because they are purely reactive[3].

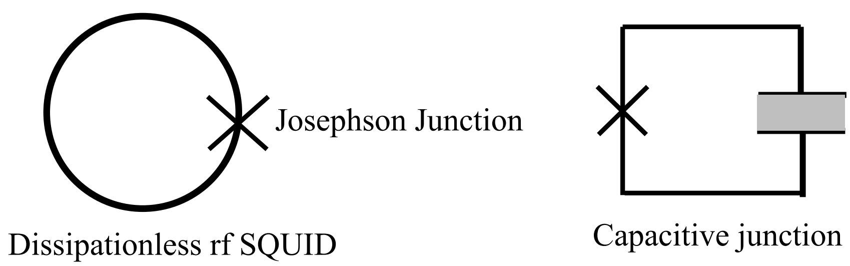


Figure 3: Circuit model for a disipationless rf SQUID and capacitive Josephson junction.

Transition Edge Sensors

Transition edge sensors (TES) are the current state of the art CMB detectors. They rely on the sharp change in resistance when they undergo a phase transition to a superconducting state[3] (figure 4).

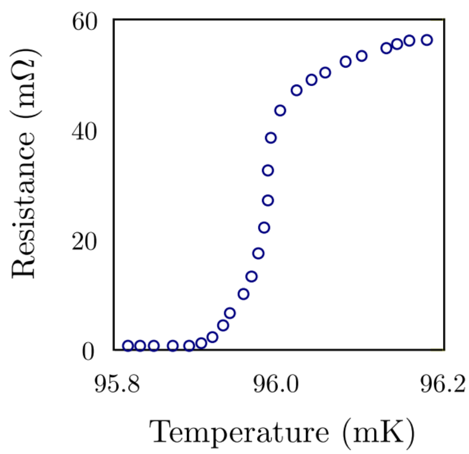


Figure 4: Resistance through a TES's superconducting film as a function of temperature [Mates, fig 1.2]. The transition temperature is 96.0 mK.

The TES is a perfect detector for microwave SQUID multiplexing because it naturally operates at mK temperatures, is very sensitive, and outputs a current signal that can be amplified by a SQUID.

Microwave SQUID Multiplexing

Next we will examine a microwave SQUID multiplexing setup in the context of CMB detection. First, an incoming CMB photon is registered by a TES, which produces a current pulse that is seen by a SQUID as increased flux (figure 5).

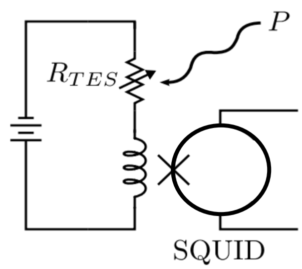


Figure 5: An incoming photon interacts with the transition edge sensor inductively coupled to the SQUID circuit [Mates, fig 1.5].

The SQUID is inductively coupled to a microwave frequency quarter wave resonator, a TES detector circuit, and a flux biasing line (figure 6). Any flux into the SQUID from signals on the TES or input on the flux bias line change the SQUID's inductance. This change in inductance changes the impedance to ground for the microwave resonator, thus changing the resonant frequency.

A radio frequency (RF) input signal is fed in on an RF feedline, consisting of a coaxial cable and coplanar waveguide (figure 6). If this signal is close to a resonance, it will be absorbed by the resonator. If the input tone is far away from resonance, all of the power—minus the system attenuation, will be transmitted. Various detection and reconstruction schemes can be used to detect the change in output tones and reconstruct a CMB map (appendix B).

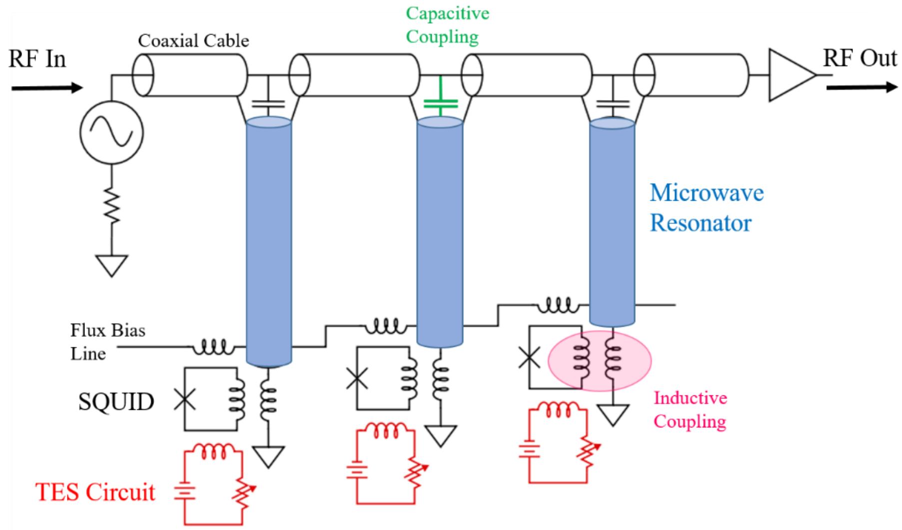


Figure 6: An overview of the microwave SQUID multiplexing hardware system

Flux Biasing

SQUIDs' sensitivity makes them an excellent choice for amplifying a TES signal—however, their native response is non-linear and periodic, which makes the signal difficult to reconstruct. The microwave MUX system is linearized by applying a periodic or 'ramped' flux directly to the SQUID. This line ramps through multiple Φ_0 of flux (the SQUIDs are ½ Phi_0 periodic) which generates multiple periods of the SQUID response curve. This response curve with no input signal is used as a reference so when a signal arrives from the TES circuit and couples some additional flux to a SQUID, we observe a phase shift from the original SQUID response curve (figure 7). The phase offset between the two curves is linear in time and so by measuring this offset we can easily reconstruct the signal (figure 7).

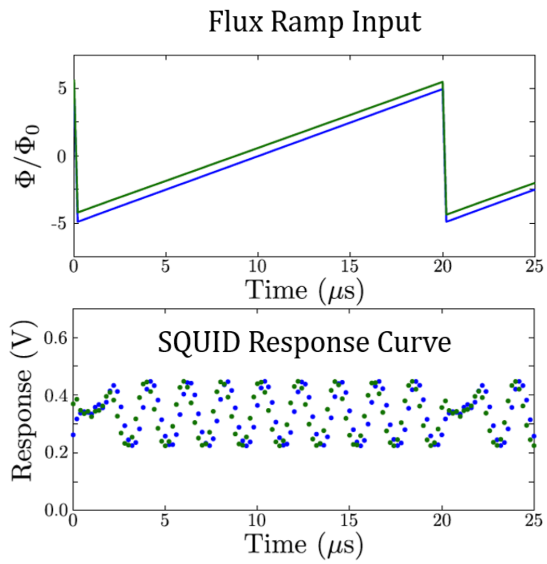


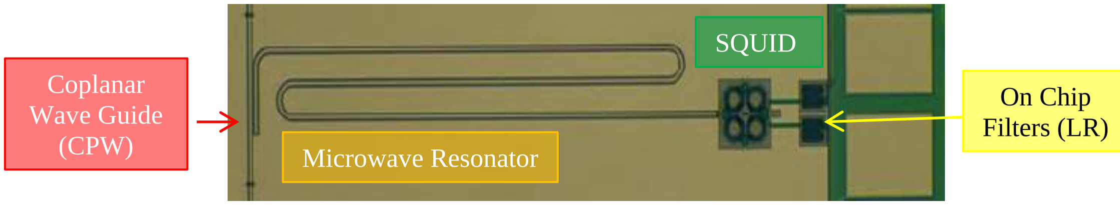
Figure 7: SQUID response in volts to an increasing flux in magnetic flux quanta. The blue and green lines on the upper plot represent different flux ramps through the SQUIDS. The lower plot shows the SQUID responses to the two ramps are linearly offset.

METHODS

Above we laid out the theoretical idea behind microwave SQUID multiplexing. To experimentally characterize the noise in the system, we obtained a 32-channel SQUID chip[1]. Our microwave SQUID multiplexing setup does not include the TES and uses an Agilent 3340A function generator to supply the input ramp to the flux bias through the SQUIDs. The input rf band is a single 11.0dBm, 5.0872 GHz (corresponding to a single resonant frequency) supplied by a HP 83711B source. The flux ramp line and RF input go into the cryogenic setup and interact with the microwave multiplex (μMUX) chip (Figure 8). The output signal is processed by a room temperature homodyne demodulation circuit and read out on a Rhode & Schwarz RTE 1104 oscilloscope (figure 12).

[1] fabricated by Gene Hilton and designed by Ben Mates at NIST in Boulder, Colorado

Single Resonator/SQUID



32 Channel Chip

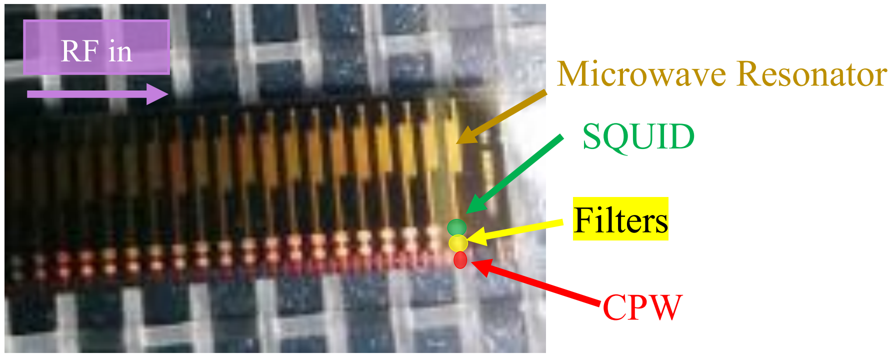


Figure 8: A zoomed in (above) and zoomed out (below) picture of the elements on the µMUX chip.

Choosing a Resonator

In order to examine the inherent noise of the SQUID/resonator system, we chose to interrogate a singular resonator by inputting only that resonator's resonance frequency. We used an Agilent E8363B vector network analyzer (VNA) to examine all 32 resonators on the chip. We connected the VNA to the system as depicted in figure 9 and measured the signal transmission through the chip (S21 channel) for a variety of input frequencies to obtain the data in figure 10. We wanted a resonator with a high quality or Q factor and looked for a deep, steep dip, unimpeded by collisions with other resonances on the VNA spectrum. We choose the 5.8072 GHz resonator because it fit this criteria (figure 10)

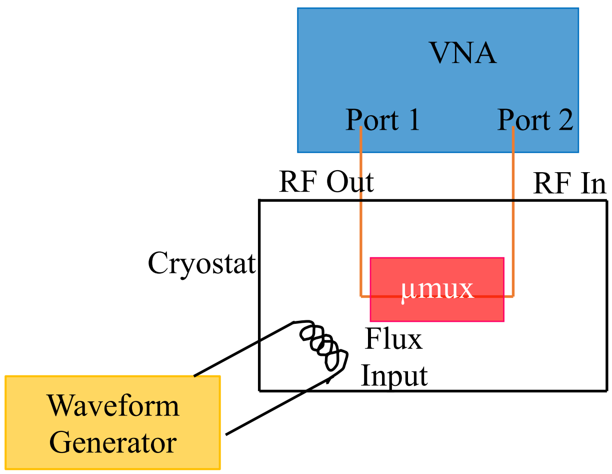


Figure 9: A schematic diagram of the vector network analyzer (VNA) resonator quality measurement.

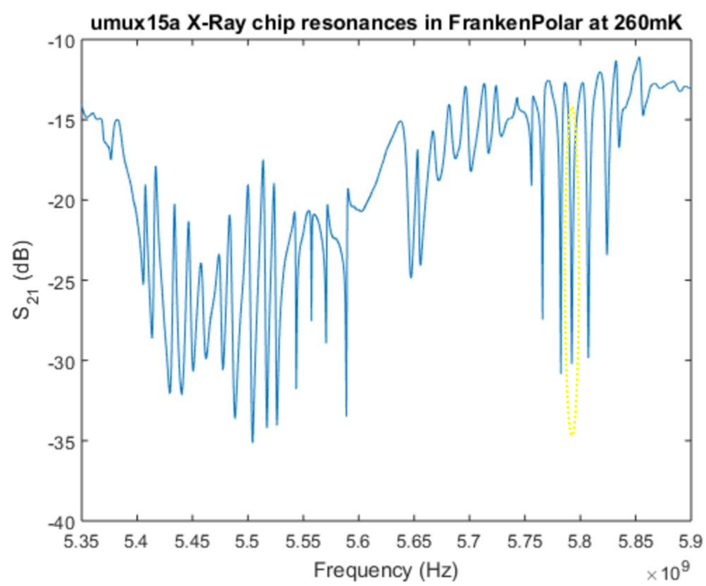


Figure 10: S21 transmission through the chip in dB vs. frequency in Hz for the 32 resonators on the chip. The resonator at 5.8072 (yellow) was chosen because it appears to be steep, deep, and is in a region of with a flat background and no collisions with nearby resonators.

Cryogenic Setup

The system is first cooled to 50K and 4 Kelvin with a Cryomech Model PT415 2 stage pulse tube cooler. A series of four copper mounting stages, called “the wedding cake,” are mounted on the 4K stage and further cooled to 2 K, 350 mK, and 250mK using a Chase Berkeley He-10 (2 He-3 pots & 1 He-4 Pot) adsorption refrigeration system. The µMUX chip is housed on the ultra-cold or UC plate at 250 M (figure 11).

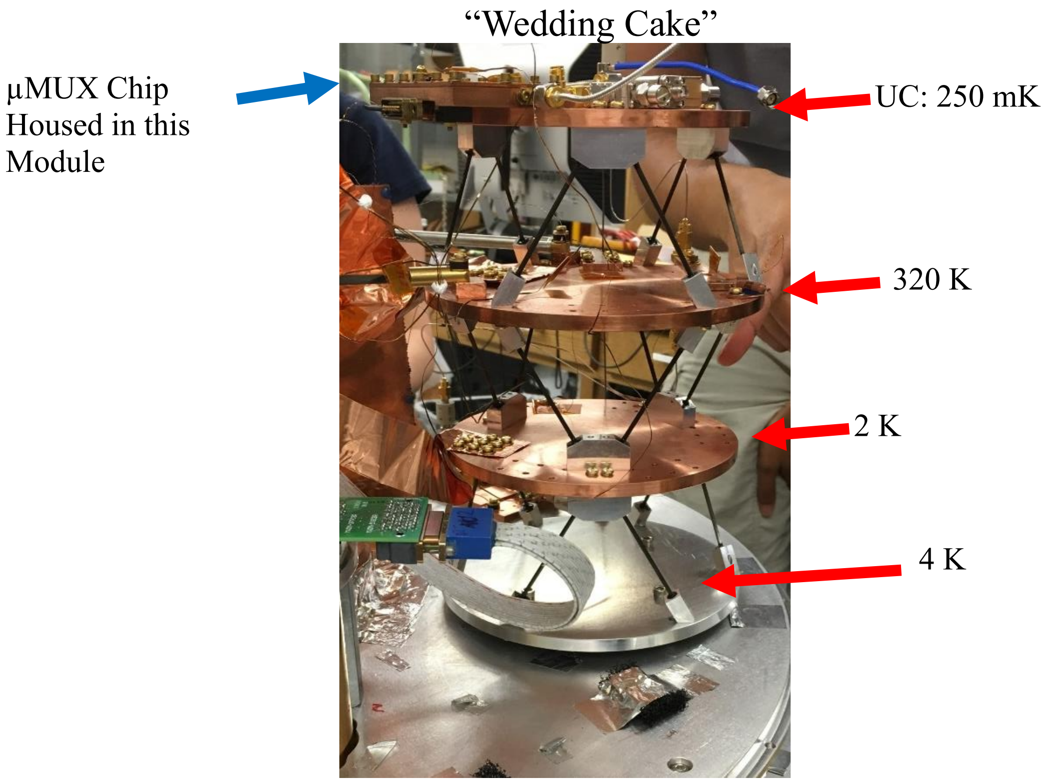


Figure 11: A picture of the wedding cake structure housed within the cryogenic system.

Homodyne Setup

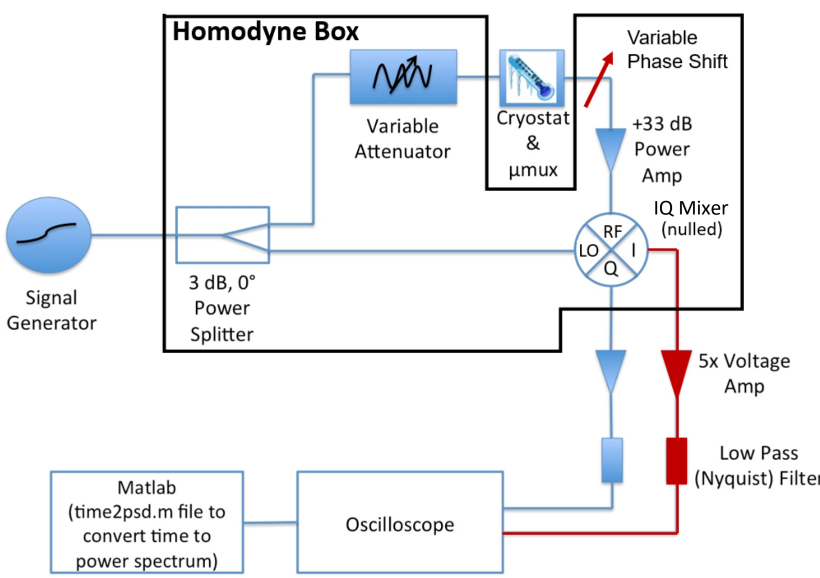


Figure 12: A schematic diagram of the homodyne setup.

Our homodyne setup is a room temperature readout device used to measure the noise level in the system (figure 12). The input RF signal is first split by a power splitter, one signal is fed into the cryostat to interact with the µMUX chip, while the other goes straight to the local oscillator (LO) port of the IQ mixer. The signal traveling into the fridge is attenuated before the sample and amplified after—so as to not overload the cryogenic system in-between, and finally fed into the RF port of an I/Q mixer. The I/Q mixer consists of two mixers: one takes the two input signals and outputs the difference between them, the other applies a 90-degree phase shift and then takes the difference. The first mixer yields the I quadrature output, which corresponds to the real component of the difference signal. The second produces the Q quadrature output, which corresponds to the imaginary component of the difference signal. Our system contains many components along the RF line which produce phase shifts, leaving the signal into the RF port at a random phase. This means our final signal gets spread randomly between the I & Q output ports. It is more computationally convenient to process the signal if it all resides in one quadrature, so we include a variable phase shifter inline before the RF port. This allows us to manually rotate the signal phase until it resides totally in one quadrature. The resulting signal amplitude is then recorded as a time stream on a R&S RTE 1104 oscilloscope. Finally, the time stream is processed in matlab to generate a power spectral density vs. frequency dataset.

Noise Measurement

The following procedure is used to take a noise measurement

1. Rotate noise into Q quadrature
    a. Display the I and Q output on a X-Y plot and rotate the manual phase shifter until all of the signal resides in the Q quadrature.
2. Take a calibration curve
    a. Using a NIST BB332 clean DC voltage source connected to the flux ramp input line, step through ~-1V to +1Volts in ~100mV increments and record the DC offset of the Q channel coming out of the homodyne setup. Convert the voltage source to units of magnetic flux quanta to obtain a mV vs. Φ_0 curve (figure 13). Calculate the slope of the curve at 0 (note that 0 is arbitrary for noise measurements we can bias at any flux point, optimal would be the max slope point). This corresponds to no initial flux through the SQUIDs and will be used later to refer the noise data collected on the oscilloscope back to the flux through the SQUIDs.

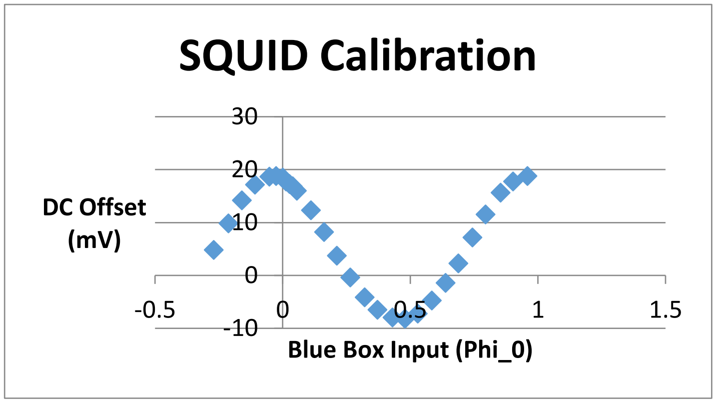


Figure 13: A sample mV vs. Φ_0 curve taken as described above on 7/20/2016.

3. Take a noise trace
    a. Place a shorting cap on the flux ramp line going into the cryogenic system.
    b. Using a Rhode & Schwarz RTE 1104 oscilloscope, record 25, 5 second sweeps at 200,000 KSa/s.
4. Analyze data
    a. Convert the time stream to power spectral density (psd) in $\frac{\text{V}}{\sqrt{Hz}}$ using the time2psd.m matlab function.
    b. Average the psd's and convert the psd from $\frac{\text{V}}{\sqrt{Hz}}$ to $\frac{\Phi_0}{\sqrt{Hz}}$ using the slope from the calibration curve.

We performed a baseline measurement using the above protocol and then took noise traces in the configurations depicted in figure 14 to test microphonic and magnetic pickup (see appendix A).

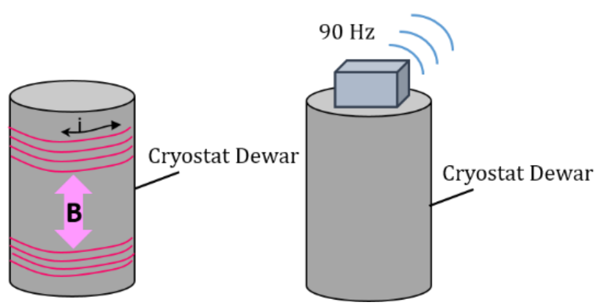


Figure 14: A schematic of the various noise configurations. Left: A Helmholtz coil setup was wrapped around the cryostat (10 turns about sample, 7 below) and a $17 \pm 10\ \mu T$, 51Hz AC magnetic field was applied. Right: A Cambridge Soundworks speaker was placed on the cryostat and used to play a 90 Hz tone at half volume.

To test microphonic pickup, we placed a Cambridge Soundworks (SN: SW 10009400005052) speaker on the outside of the cryostat shell and played a 90 Hz tone at half volume and recorded the noise in the system (figure 14, left). To test magnetic pickup, we wrapped 10 turns above the sample and 7 below the sample of 14-gauge copper wire around the cryostat in a Helmholtz coil setup. We powered the coils with an Keysight 33500B function generator outputting a 10Vpp, 140mA, 51Hz sine wave and collected a noise trace (figure 14, right).

RESULTS

Our baseline noise trace shows that our current noise level is about one order of magnitude above the noise inherent in a typical TES detector (figure 15). The pulse tube beats at 1.4 Hz and this can be seen in our spectrum along with 60Hz and 120Hz pickup from A/C power (figure 15).

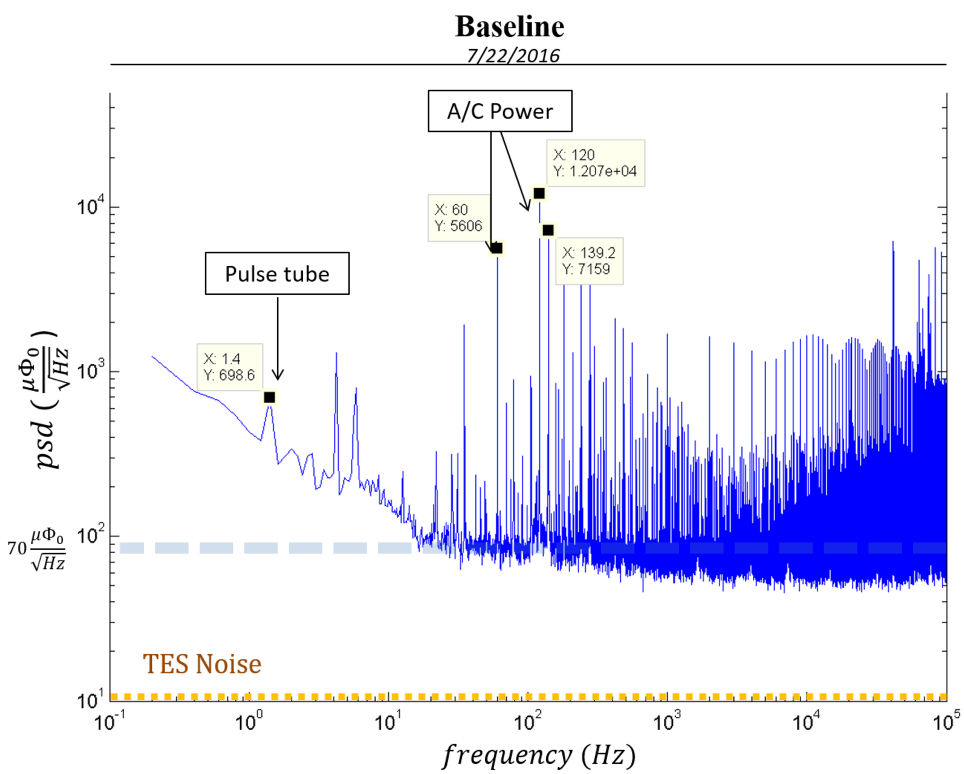


Figure 15: A baseline noise trace showing the power spectral density (psd) in $\frac{\mu\Phi_0}{\sqrt{Hz}}$ vs. frequency in Hz on a log-log scale. The noise floor is marked with a blue dashed line and the noise level inherent in a TES is marked with the yellow dashed line.

Our system also shows sensitivity to magnetic fields with a $17 \pm 10\mu T$ field corresponding to a $925\,\frac{\mu\Phi_0}{\sqrt{Hz}}$ pickup (figure 16).

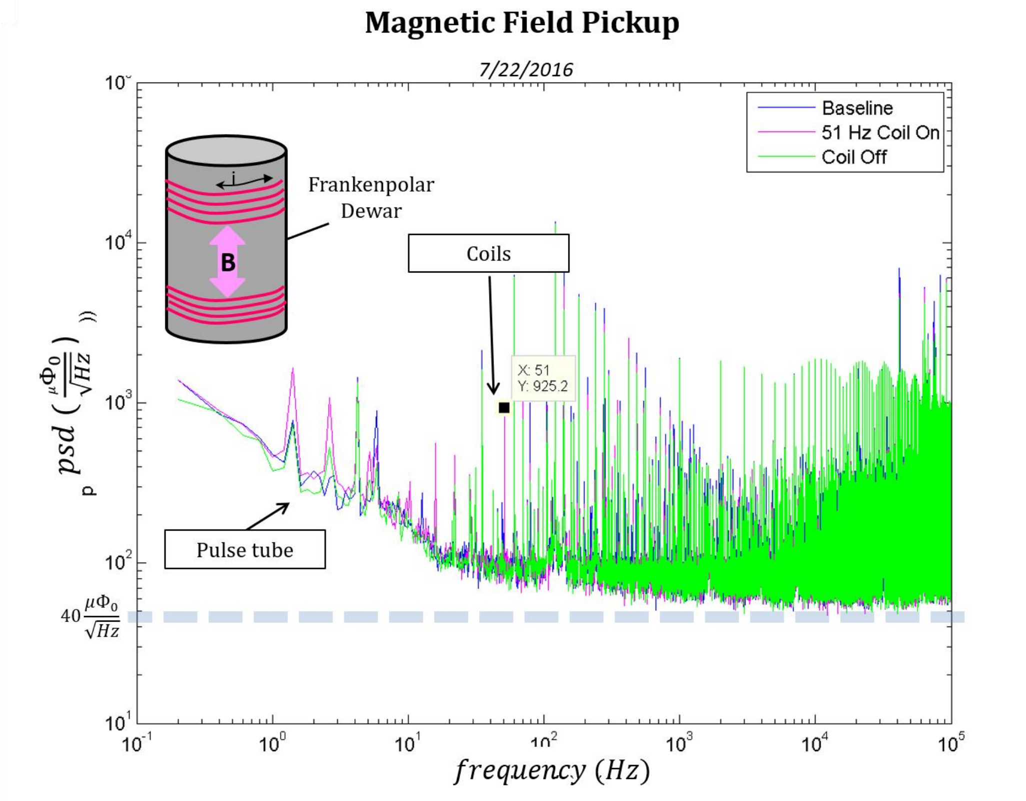


Figure 16: A power spectral density (psd) in $\frac{\mu\Phi_0}{\sqrt{Hz}}$ vs. frequency in Hz log-log scale overlay. The blue curve is the baseline after cycling the fridge and before turning on the coils. The magenta line is with the coils on and the green line is after we turned the coils off and unplugged them. The noise floor is marked with a blue dashed line.

The µMUX system also showed sensitivity to microphonic pickup. The 90 Hz tone from the speaker can clearly be seen in the noise trace as well as additional harmonics from the 1.4 Hz pulse tube (figure 17).

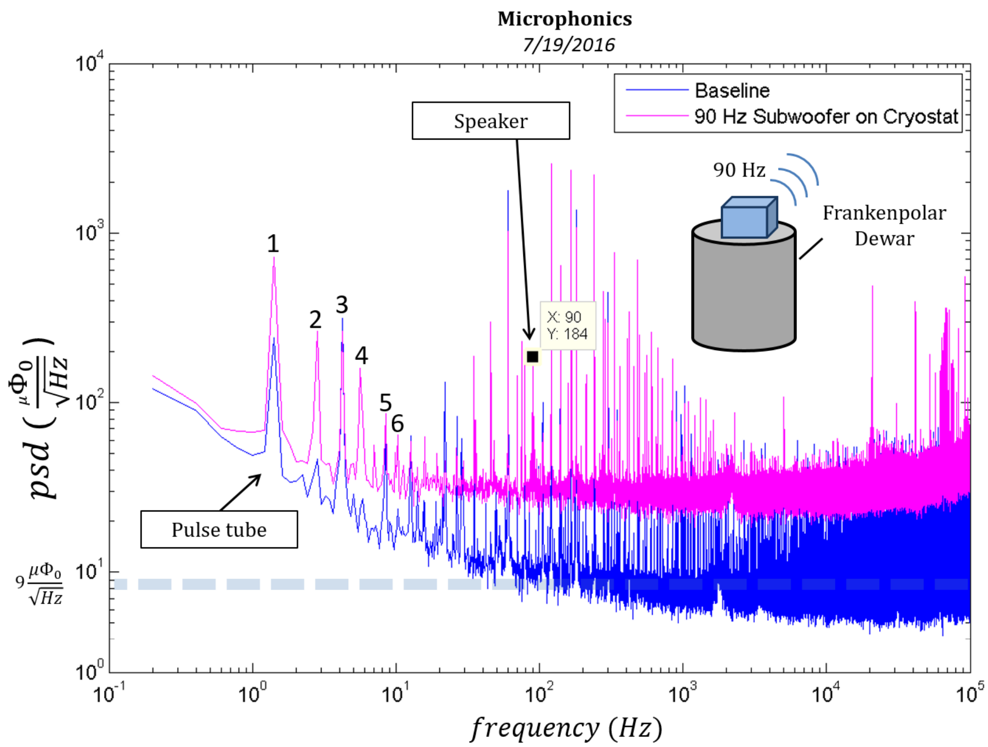


Figure 17: A power spectral density (psd) in $\frac{\mu\Phi_0}{\sqrt{Hz}}$ vs. frequency in Hz log-log scale overlay. The blue curve is the baseline and the magenta line is the noise with a 90 Hz subwoofer vibrating the cryostat shell. The numbers above the peaks mark the different harmonics of the 1.4 Hz pulse tube. The noise floor is marked with a blue dashed line.

Furthermore, certain large noise sources—such as a 139.2 Hz peak all together disappeared when we took a noise trace with the pulse tube and a loud, nearby fan (used for another setup in the lab) turned off (figure 18).

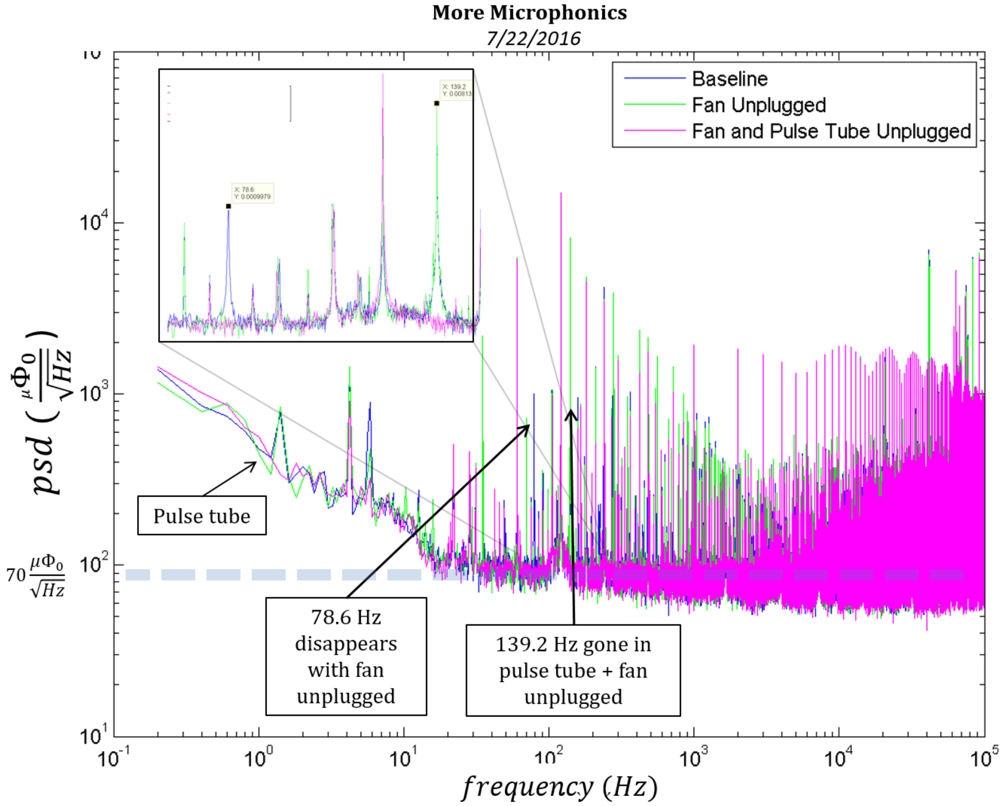


Figure 18: A power spectral density (psd) in $\frac{\mu\Phi_0}{\sqrt{Hz}}$ vs. frequency in Hz log-log scale overlay. The blue curve is the baseline, the green line is with a nearby loud fan unplugged, the magenta is with the fan and the pulse tube unplugged. The noise floor is marked with a blue dashed line.

DISCUSSION

Our long-term goal is to reduce the noise in the system below the inherent noise in the TES. Our baseline noise trace in figure X shows we are still about an order of magnitude from this goal. We suspect the noise floor could be inaccurate due to inconsistent calibrations, which vertically scale the data. The inconsistent calibrations are most likely caused by not flux biasing the SQUIDS. In other words: we are calculating the slope of the $\frac{V}{\Phi_0}$ calibration curve at zero, which is an especially non-linear region of the SUID response curve and is difficult to constrain. Going forward, we will include a flux biasing line in our measurements to optimally bias the SQUIDs.

We also learned that the microwave SQUID multiplexing system is sensitive to magnetic fields. We are currently in the process of installing a 0.5mm niobium foil magnetic shield over the µMUX sample box. We plan to run the same Helmholtz coil test after closing and cooling the fridge to test the shield's efficacy.

Our noise trace data also shows the system is sensitive to internal and external vibrational noise. Interestingly, more pulse tube harmonics appear in the spectrum with the speaker on than with it off (figure 17). This indicates there is a mechanical coupling mechanism being excited by the speaker. Furthermore, the 1.4 Hz pulse tube and its harmonics are evident in all spectra, suggesting a microphonic pickup between the pulse tube and electrical system. Based on these results, we are in the process of designing and obtaining mechanical isolating mechanisms for the pulse tube.

Lastly, we are installing a 1:100 current divider on the flux input line. This allows us to shunt away 99% of the noise that is being injected on that line from room temperature electronics and pickup. We bump the input current up by a factor of 100 as well so that we can still put a multiple phi_0 ramp signal in while keeping all noise that is not signal power dependent suppressed by this 100:1 factor.

CONCLUSION

Overall, the noise in our microwave SQUID multiplexing environment is currently about one order of magnitude higher than what has been achieved[3]. We found some of the noise is caused by microphonic and magnetic signals being transduced into our system from the lab environment. Moving forward, we are fabricating a niobium foil magnetic shield to protect the μMUX sample box and designing and obtaining mechanical isolating mechanisms for the pulse tube cooler. We are also incorporating a current divider and resistive shunt to maximize the signal to noise ratio entering the μMUX chip. We will perform the same noise measurements after installing these improvements and quantify the effects on noise levels. We expect the improvements to reduce the system noise and increase the feasibility of microwave SQUID multiplexing technology in cosmic microwave background detection and readout systems. Ultimately, we hope to validate our test setup for future reliable measurements of μmux chips. These reliable measurements will help us establish the use of microwave SQUID multiplexing to read out CMB signals and help take the deepest pictures of our universe yet.

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APPENDIX A

Excess noise in any detection and readout system can compromise the integrity of the signal and usefulness of the device. The purpose of this project was to characterize and eliminate noise in our microwave SQUID multiplexing system. Some intrinsic noise sources include: Thermal, 1/f, and TES noise, see Mates section 2.5 for more detail. For the purpose of this project I will focus on the two noise sources below.

1. Microphonic pickup
   a. Microphonic pickup is the general process where vibrational or auditory signals get translated into electrical signals. For example: vibrating one end of a parallel plate capacitor could transduce the mechanical signal into an electrical signal. Mechanical isolating mechanisms are often used to combat microphonic pickup.
2. Magnetic pickup
   a. Magnetic pickup occurs when stray magnetic fields produce extraneous electrical noise in the system. This can occur if a magnetic field penetrates a loop of wire in the system and induces an extraneous current. Magnetic shielding and twisted pair wiring can help minimize magnetic pickup.

APPENDIX B

In a finalized readout scheme, all resonances on the RF line are simultaneously measured and a comb of tones is synthesized with each tone corresponding to a chip resonance. Feedback is used to move the tones in time to track the resonant frequency. This frequency shift can then be calibrated to correspond to a signal from the TES which can be used to reconstruct a CMB map.

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