Noise Analysis of a CDMS Detector Control and Readout Card

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This project is done in support of the Super Cryogenic Dark Matter Search experiment (SuperCDMS) and involves analyzing the effect that environmental electrical noise has on a Detector Control and Readout Card, or DCRC board. Sources of electrical noise can come from lights, pumps, air conditioning units, electronics, and many other places. The method used in this project takes a signal measurement in the lowest possible noise environment and compares that to various situations of different noise. The power spectral densities of various signals were analyzed. Once it is understood how noise affects the board, steps will be taken to eliminate removable sources whether by shielding or otherwise. Ultimately, the researchers of SuperCDMS will be aware of how the signal they receive is affected by noise.

Key words: *dark matter, detector, TES, SQUID, power spectral density*

Background

Why Look for Dark Matter?

When astrophysicists look into the night sky and observe the motion of distant galaxy clusters, the angular rotation of outer galaxies they see is not the same as what they predict. While the actual calculations for gravitational forces on clusters of galaxies are complex, basic principles of gravitational forces illuminate the problem. In a simple gravitational force calculation, the equation,

$$F_g = \frac{GmM}{r^2} = \frac{mv^2}{r}$$

is used, where *v* is the velocity of a body moving about another, *m* and *M* are the masses of the bodies, *r* is the distance between them and *G* is the gravitational constant. We can see that the rotational velocity is proportional to $1/\sqrt{r}$,

$$v = \sqrt{\frac{GM}{r}}$$

however, the observed *v* for galaxies moving about their galactic center is constant with *r* as shown in Figure 1. In this case, the outer galaxies are moving so fast that they would reach the escape velocity needed to be thrown off the cluster. The cluster would rip itself apart. This phenomenon points to the possibility that there is more mass than is visible which has a strong gravitational pull on galaxies and holds the cluster together. But when we estimate the amount of visible luminous mass like stars, gas, and other celestial bodies, there is simply not enough; this is one reason why dark matter is expected to exist.

Since the 1930s physicists have known about the 'missing mass' problem of our universe.[1] Dark matter, a substance that is not made of regular matter such as electrons, proton, or other baryonic particles, has been proposed to account for the missing mass. As its name suggests, it is 'dark' meaning it does not give off light. It has been predicted that dark matter makes up approximately 23% of the matter in the universe while normal matter makes up only 4% and the remaining 73% is said to be dark energy.[2]

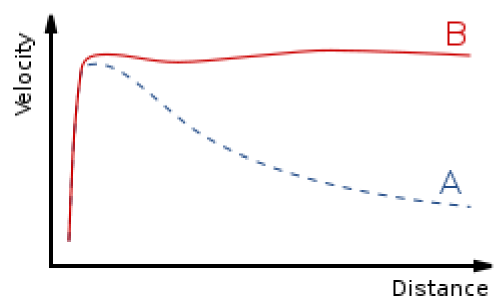

Figure 1: Line A is the expected dependence the rotational velocity of a galaxy with respect to the distance from its galactic center. Line B is the observed rotational velocity.[3]

The Cryogenic Dark Matter Search

With the goal of discovering the secrets of dark matter, the Cryogenic Dark Matter Search was created. The CDMS collaboration took data at Stanford University until 2003 when it moved farther underground to a mine in Soudan, Minnesota; the experiment was then called CDMSII. Now after sensitivity and detector upgrades, the collaboration is called SuperCDMS and includes over eighteen institutions. Soon SuperCDMS will move to an even deeper lab in Sudbury, Canada.

SuperCDMS is looking for dark matter particles dubbed *WIMPs* or Weakly Interacting

Massive Particles. The WIMP does not interact strongly with normal matter making it too elusive for traditional particle detectors, and it is predicted to have a mass of between a few GeV/c^2 and a few hundred GeV/c^2. SuperCDMS uses cryogenic detectors and a combination of detection techniques in their attempt to find WIMPs. So far no conclusive evidence has been found.

Introduction

Detector Technology

In order to detect a WIMP, SuperCDMS uses germanium crystal detectors that are cooled to about 20 mK. When a particle interacts within a detector, the energy of the interaction is transferred to the germanium lattice as well as creating ionization. The event's energy is then measured by a tungsten Transition Edge Sensors (TES). A TES is a device that is kept just below the threshold between superconducting and normal phase transition, $T_{c,}$ so that a small energy fluctuation drives the device normal and a huge spike in resistance results. From there, the current through the TES decreases and the magnetic field within a coil in series with the TES is altered (see Figure 2). The coil is coupled to a magnetometer called a Super conducting QUantum Interface Device (SQUID), and finally the signal is amplified and sent to room temperature electronics outside the 20 mK environment.

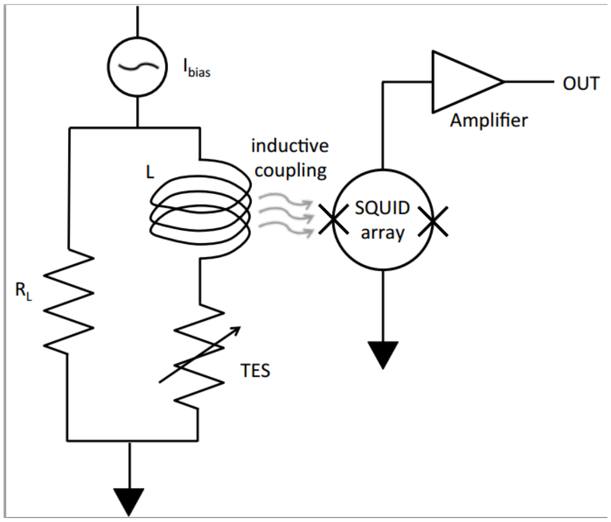

Figure 2: This circuit shows how a TES couples to a SQUID. When the resistance of the TES changes, the current to the inductor L changes, causing an altered magnetic field and this is sensed by the SQUID.

One component of the room temperature electronics is called a Detectors Control and Readout Card, DCRC board for short, and is what communicates with the detectors (see Figure 3). This project analyzed the effect that environmental noise has on the signal it receives. This project did not utilize the actual 20 mK detectors but instead read the signal from a TES and SQUID signal simulator called a Mini Break out Board (MiniBoB). While the SQUID noise can be investigated individually, the TES cannot because of the way it is coupled to the SQUID. The MiniBob has eight channels in total but the project focuses only on a single channel, namely Phonon Channel A.

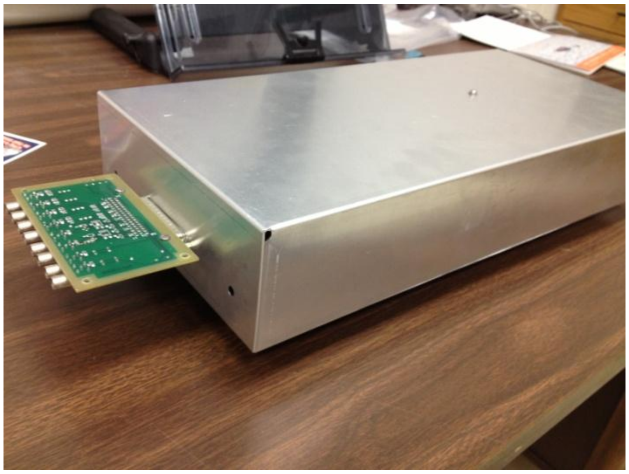

Figure 3: The DCRC board inside its metal shielding box. The green board that is plugged into it is the MiniBoB.

Electrical Noise

The types of electrical noise that were measured in the TES and the SQUID were Johnson-Nyquist noise, shot noise, and flicker noise. These kinds of noise are inherent to all electrical devices. Johnson-Nyquist noise is the measure of electron agitation within conductors; it is also known as thermal noise and "white" noise because it is approximately flat over the frequency spectrum. This type of noise is present regardless of applied voltage. Conversely, shot noise is the result of random fluctuations in current applied due to the discrete nature of electrons. Flicker noise on the other hand, hereafter called 1/f noise, is from fluctuations in condensed-matter materials and dominates in the low frequency region. For example, defects in some metals often account for increased levels of 1/f noise.

Beyond these sources of noise, however, there are others that can affect the resultant signal. Below we will see how surrounding electronics and even a pump affected the TES and SQUID noise signals.

Method

Identifying Sources of Noise

Within the lab, there is a dry dilution refrigerator that uses liquid helium to drop detectors to 20 mK. This means that the lab potentially has many pumps running at once along with the electronics that run the system. In addition, there is a clean bench with a fume hood that adds unwanted vibrations while on and central air conditioning that would be common to any lab.

The usual location where the DCRC retrieves the signal is located on top of the fridge, which is right in the middle of all these sources of noise.

The objective was to see which combinations of conditions resulted in low noise and which resulted in high noise situations.

Data Collection

All of the data was taken in a between April and May of 2012. Some of the conditions altered between measurements were:

- Location
- Shielding
- Lights
- Channel Termination
- Channel Settings

Location involved physically moving the device around to see what lab equipment produced spikes in the signal. Next, The DCRC was first tested without its metal shielding and then with is on to see its effect. Similarly, the effect of having ambient lighting on or off and channel termination with 50 Ohm BNC terminators were also studied. The only variable that was studied that did not concern the physical environment was the board's channel settings. The settings include gain changes and also biasing the SQUID.

Analysis and Results

PSD

A power spectral density, or a PSD, is essentially a time domain signal that has been Fourier-transformed such that it is then in the frequency domain. It shows the power of the signal over different frequencies.

Analyzing the data in this way is effective because it is easy to see at what frequencies disturbances exist. The most common and large disturbances are 60 Hz noise which is the frequency that results from AC power of wall sockets. Any disturbance usually is accompanied by harmonics which are visible at integer multiples of the original frequency.

After being Fourier transformed, the TES data was fit to the following equation,

$$Noise_{TES} = \sqrt{\frac{N_{TES}^2}{1+\left(\frac{f}{f_0}\right)^2} + \frac{A^2}{f} + N_{SQ}^2}$$

where f is the frequency, f_0 is the roll off frequency, A is the 1/f noise amplitude, and N_{TES} and N_{SQ} are the white noise of the TES and SQUID, respectively. The SQUID cannot be decoupled from the measurement so it makes a contribution.

Similarly, the SQUID data was fit to this equation,

$$Noise_{SQ} = \sqrt{\frac{A^2}{f} + N_{SQ}^2}$$

where the parameters are defined the same as above. The SQUID data does not have a TES component in it.

TES Results

Creating the lowest possible noise environment was attempted. Early on in the project, it was determined that ambient lighting did not have an effect on the noise signal so most of the data was taken with the lights on. Figure 4 shows the noise signal for the TES on an evening when the lab did not have any pumps on and all non-essential electronics were turned off. The units of these PSD are units of power, pA/√Hz, and this environment showed a baseline noise level of 1561 pA/√Hz.

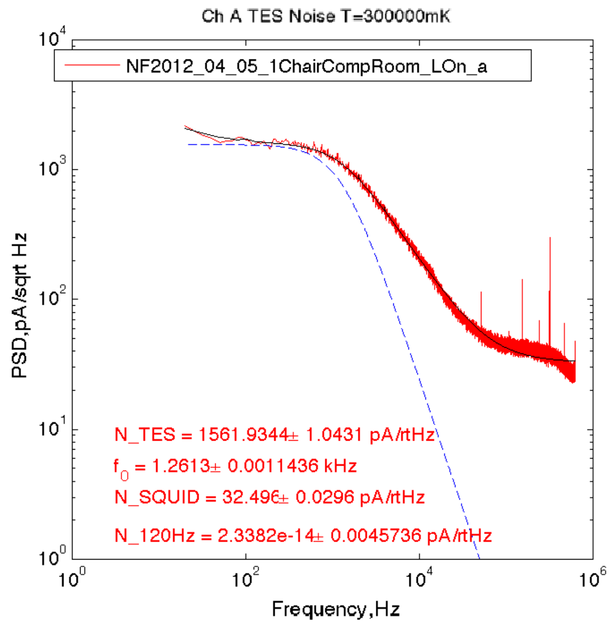

Figure 4: Baseline testing. This noise threshold signal was taken when all lab pumps and nonessential electronics were turned off. The TES noise in this case was 1561 pA/√Hz.

The shape of the curve can be described in sections. The range between 1 Hz and 10 kHz shows the contribution from the TES noise after which the SQUID noise comes into play.

From here, the data plots are categorized by location. The locations each have their own code which signifies the following:

- TableNorthWall—A relatively secluded space that is away from electronics and pumps, yet still subject to the effect of daily routine lab activities and sources such as the air conditioning.
- TopFridge—This location is the place where the DCRC would typically be used because this is where the detector data port is located. This is next to a turbo pump and a lot of wires and electronics.
- TopLSB—Short for the top of the Lake Shore Bridge which is the unit were all of our data and cryostat controls are funneled into. This area was particularly full of 120 Hz noise.

Figure 5 shows the TES noise component of two signals in the "North Wall" location, one with the shielding box on and one without. The noise for the DCRC while shielded was about 150 pA/√Hz less than when it was unshielded.

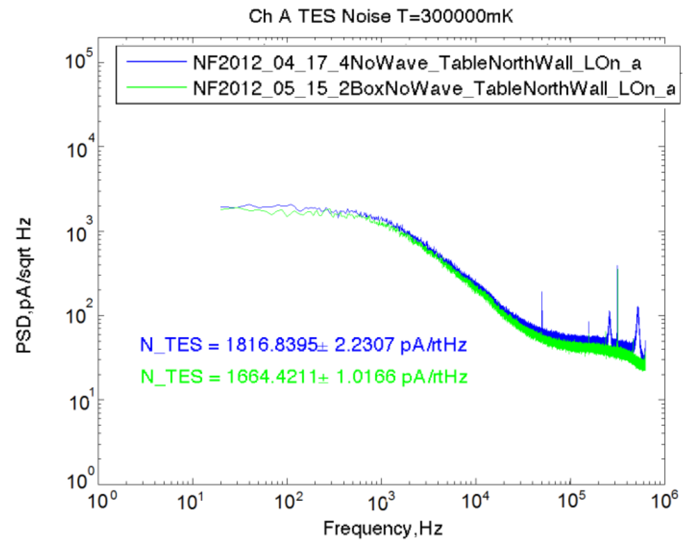

Figure 5: This is the most secluded location. The blue trace is the DCRC's signal without its metal shielding box; meanwhile the green trace is the signal with the box. The noise is reduced in the box.

In another measurement, at the top-of-fridge location where pumps and electronics are, the shielding box did not perform as expected. The shielded signal was approximately 51 pA/√Hz higher than the unshielded signal, shown in Figure 6.

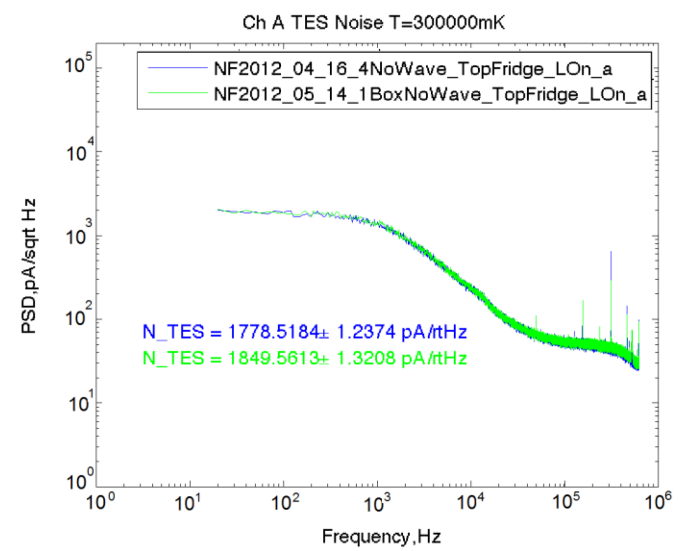

Figure 6: The blue trace is the unshielded signal in the top-of-fridge location, the green is shielded. This location has pumps and electronics around it. Unexpectedly, the shielded signal was higher in noise.

Next, the top of the Lake Shore Bridge position was evaluated. This location is a possible location for the board to operate when it is functioning in an true dark matter application. Figure 7 shows that again the shielding box did not perform as expected. The TES noise for the shielded signal is approximately 23 pA/√Hz higher than the unshielded in this case. This discrepancy is more forgivable but still puzzling.

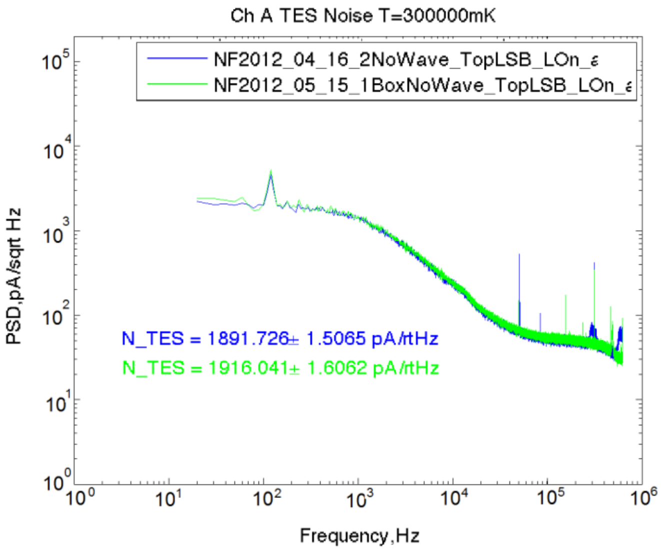

Figure 7: The Lake Shore Bridge location, where many electronics for running the dry dilution refrigerator are housed. Again, the signal for the shielded signal is lower in noise.

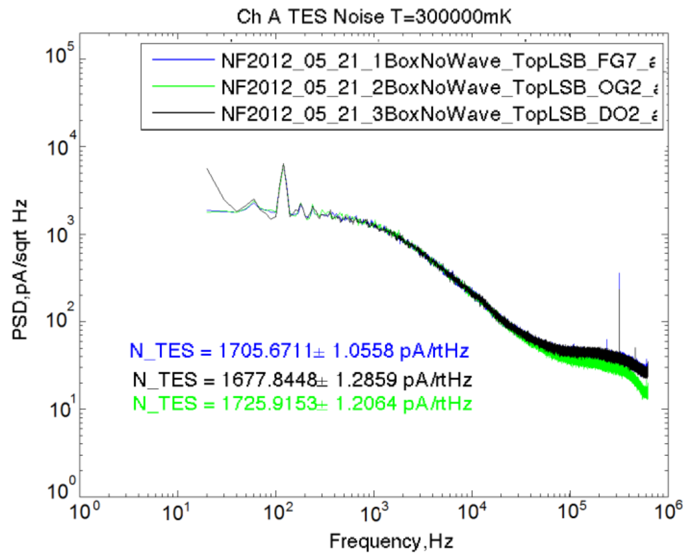

Figure 8: Changing the internal settings of the DCRC board. FG7 means the Frontend Gain = 7, OG2 means the Output Gain = 2, and lastly DO2 means the Driver Offset = 2. This shows that TES noise experiences the biggest decrease by increasing the Driver Offset, however, this also increases the SQUID noise at high frequencies.

It is possible that the shielding box is not a perfect shield and allows RF signal to leak in from the outside and, further, acts in such a way that exacerbates the problem. It was assumed that taking all the data in a four to six week period would be adequate. In a month's time not all that much changes. However, the data for the unshielded signal were taken a month prior to the data for the shielded signal. It is possible that the two locations with higher shielded signals (Figure 6 and 7), simply had more activity going on around them on those dates. The inconsistency warrants further investigation.

The next test involved changing the board's internal settings. For the TES noise, the settings that were altered were the Frontend Gain, the Output Gain, and the Driver Offset. The Frontend Gain ranges from 1 to 100, the Output Gain ranges from1 to 7 and the Driver Offset from 0 to 2. For all of the previous measurements, the gains were set to 1 and the Driver Offset was 0. Figure 8 shows the Lake Shore Bridge position for a shielded signal with these settings altered.

By comparing Figure 8 to Figure 7, here we see that raising the Frontend Gain decreased the noise by 209 pA/√Hz. In the same way, increasing the Output Gain decreased the noise by a similar amount. And lastly, increasing the Driver Offset decreased the noise by 139 pA/√Hz, however, as a trade off, it also increased the SQUID noise at high frequencies.

Further investigation suggested that increasing the Frontend Gain beyond ~10 no longer had any effect on the noise. Ideally, there is a combination of these settings that keeps the SQUID noise low while also minimizing the TES noise.

SQUID Results

The SQUID noise thresholds were analyzed the same way the TES ones were. The SQUID noise signal is different in that it is an order of magnitude smaller than the TES noise. Additionally, the 1/f noise is predominate in the lower frequency range while the white noise of the SQUID dominates after 1 kHz.

Starting with the North Wall secluded location, we see that the shielding box did indeed do its job. The shielded signal is about 5 pA/√Hz lower than the unshielded signal (see Figure 9). A drop of only 5 pA/√Hz seems small but because the magnitude of the SQUID noise is only between 35 and 40 pA/√Hz, it is quite considerable. For the TES, the noise reduction was never more than 10% but the SQUID noise reduction nears 15%.

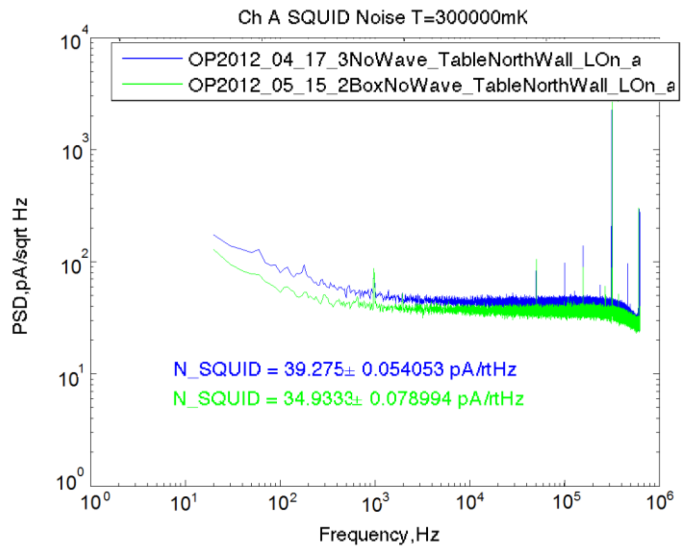

Figure 9: The blue trace is the unshielded SQUID noise signal. The green is the shielded signal which shows a decrease of about 4 pA/√Hz.

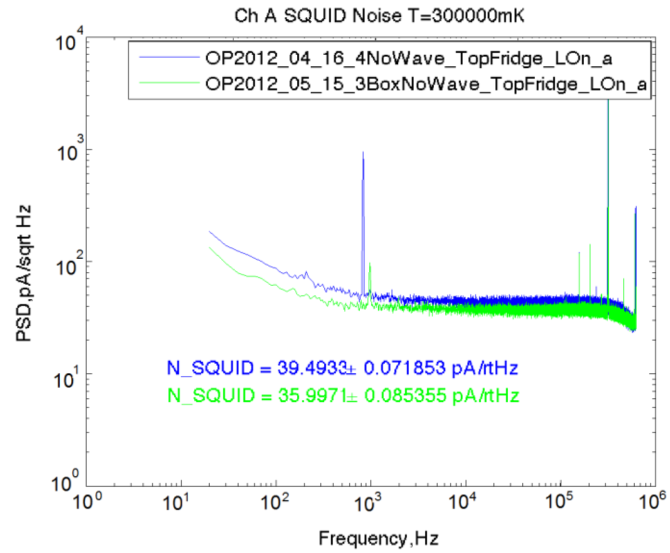

Figure 10: The unshielded signal is in blue while the shielded signal is in green. Here we see the blue trace has a large spike at 880 Hz and a the green has a spike at 990 Hz. The 880 Hz spike is the turbo pump; however, the 990 Hz spike is from an unknown source.

The top-of-fridge location (where some pumps and electronics are) is a bit noisier, but we see again that the SQUID noise is reduced by the shielding box. These plots and Figure 11 show that the shielding box is substantially reducing the pink noise that the SQUID experiences. While this is good for the SQUID alone, knowing this does not mean seeking a better noise insulating shield is necessarily the right path. This is because, in a real dark matter detector run, the signal would still be dominated by the TES noise threshold in that region.

The shielded SQUID signal in Figures 9, 10 and 11, all show a 990 Hz spike. This data was all taken on the same day, however this disturbance has not been accounted for. Alternatively, Figure 10 shows a spike at 880 Hz which is the operating frequency of one of the lab's turbo-molecular pumps which was stationed only 30 cm away.

Figure 11 shows that the shielding box reduced the noise by about 6 pA/√Hz. What is particularly interesting about this data is that the unknown 990 Hz spike is present for both unshielded and unshielded measurements which were taken a month apart.

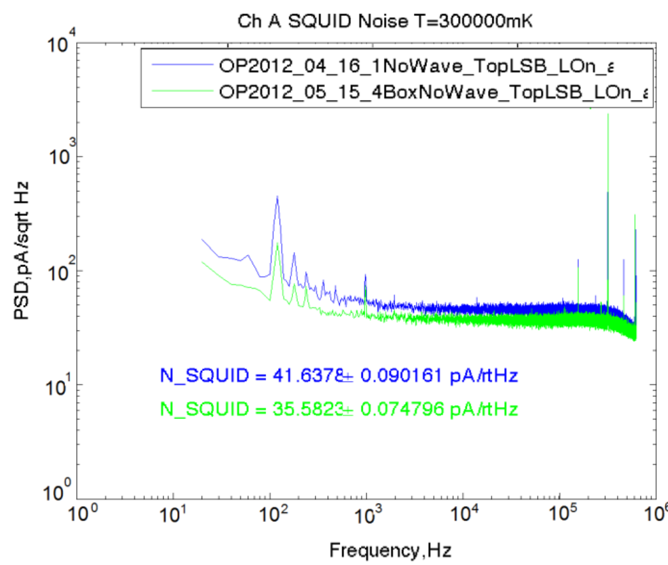

Figure 11: Both traces show the 120 Hz disturbance and it harmonics that are characteristic of the Lake Shore Bridge location.

Next, the channel settings were altered to see what their effect would be. While the Driver Offset increased the noise (not shown in Figure 12), increasing the Output Gain from 1 to 7 halved the noise signal. The Frontend Gain was also changed from 1 to 7 and then to 100. However, this had no effect.

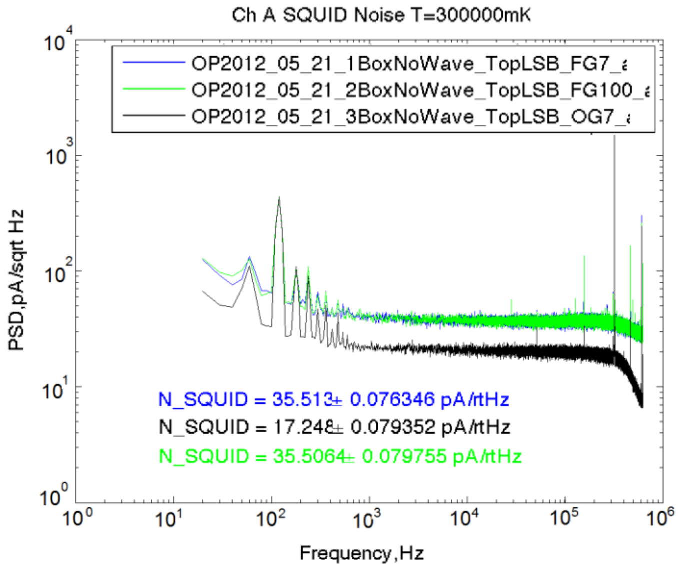

Figure 12: Here the Frontend Gain was switched to 7 and 100, shown in blue and green, respectively. These alterations did not produce any effect on the noise. The Output Gain was switched to 7 which halved the noise.

Input signal testing

Another round of testing that was performed was inputting a 1 kHz sine wave into the Channel A from a function generator. For both the TES and the SQUID the wave acted as expected, having a large spike at the input frequency and showing harmonics at every integer multiple of 1 kHz and gradually tapering off. Figure 13 and 14 show that the signal is well behaved until beyond 10 kHz, where the signal gets fairly distorted from the harmonics and additional high frequency disturbances.

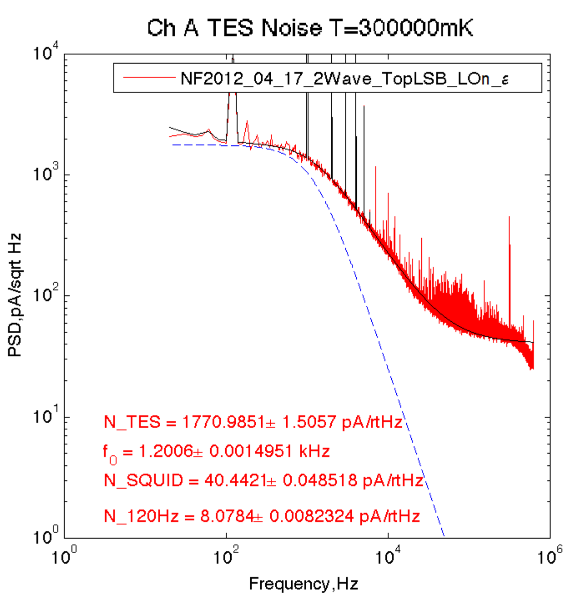

Figure 13: An unshielded TES noise signal with a 1 kHz input sine wave. The wave and its harmonics act as expected.

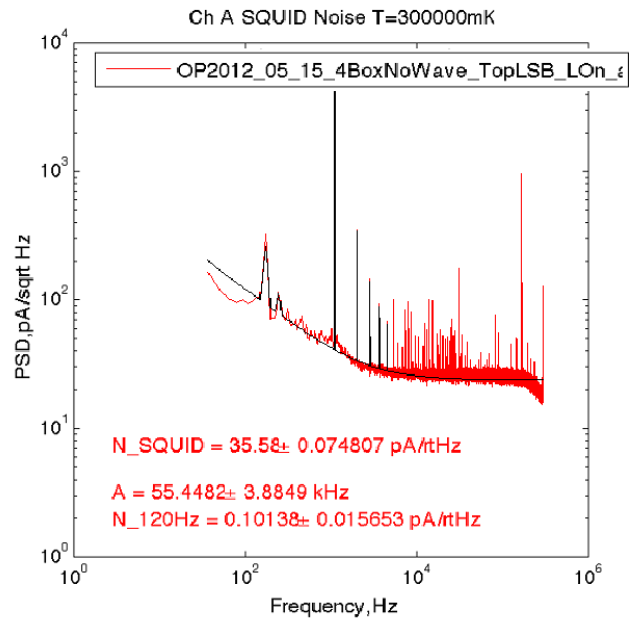

Figure 14: An unshielded SQUID noise signal with a 1 kHz input sine wave.

The harmonics and high frequency spikes are more of a problem for the SQUID. The TES noise is so large in magnitude that it masks the high frequency disturbances until the white noise of the SQUID is reached. Because the SQUID noise starts out small and does experiences 1/f only until 1 kHz, the high frequency spikes show up below 10 kHz.

Conclusion

Of all the differences in conditions, the data suggests that the largest factors in reducing unwanted noise are the location of the DCRC board, shielding, and increasing the Output Gain.

In both the TES and SQUID measurements the signal was altered heavily in the form of 120 Hz noise by exposure to nearby electronics. The SQUID noise was susceptible to pumps and also a second unknown source.

For the TES measurements,

- TES noise dominates between 10 Hz and 1.2 kHz
- SQUID noise dominates from 100 kHz to 300kHz

The SQUIDs are not coupled to the TES in their measurement mode so,

- 1/f noise dominates from 10 Hz to 1 kHz and

- SQUID noise dominates from 1 kHz to 300 kHz.

The shielding box did not reduce the noise for some TES measurements but seemed to help reduce SQUID noise a significant amount especially with respect to the inherent 1/f noise. Raising the Driver Offset for the TES lowered the TES noise but raised the SQUID noise out at high frequencies. The effect of raising the output gain reduced only the SQUID noise.

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