Invisibles21
Poster #262

Novel Active Noise Cancellation Algorithms for CUORE

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Goals of the Project

The Cryogenic Underground Observatory for Rare Events (CUORE) experiment is an ongoing search for neutrinoless double beta decay located at the Gran Sasso National Laboratory (LNGS) in Italy. Recent work has found that the CUORE calorimeters are sensitive to acoustic and seismic events originating from outside the detector at LNGS. To measure the effect of these mechanical disturbances on the calorimeter signals, microphones and accelerometers were installed around the CUORE cryostat. The goal of this project is to implement new algorithms to remove noise from calorimeters instrumented with neutron transmutation doped (NTD) germanium detectors or transition edge sensors (TES) and demonstrate how these algorithms improve the energy resolution of these devices. This is done for devices at UC Berkeley with the intention of ultimately applying these techniques to CUORE data.

Linear Noise Cancellation Algorithm Overview

We assume a linear transfer function from the antenna to the bolometer:

$$X(\omega) \exp[i\omega t + i\varphi_1] \longrightarrow Y(\omega) \exp[i\omega t + i\varphi_2]$$

The transfer function is thus $H(\omega) = X(\omega) / Y(\omega) \exp[i(\varphi_1 - \varphi_2)]$

We use an ensemble of noise events and average the transfer functions from each noise event. Transfer functions with coherent phases should add together in the complex plane. After averaging over several noise events, the transfer function for uncorrelated noise should approach 0.

In reality, we find that this algorithm can introduce parasitic noise at uncorrelated frequencies. This can be remedied by scaling the transfer function by the frequency-frequency correlation coefficient:

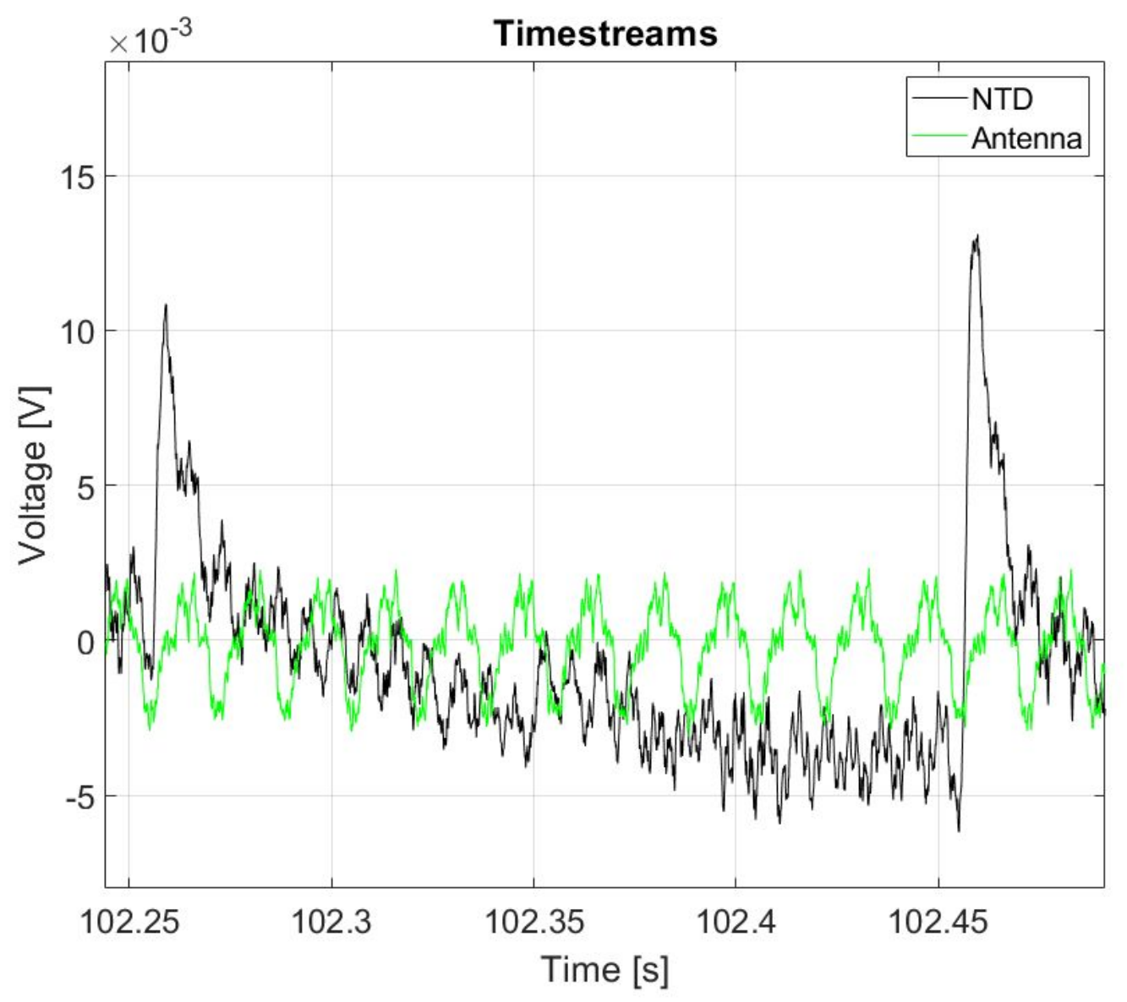
$$\mathcal{R}_{ij} = \sqrt{\frac{\left|\langle X^*(\omega_i) Y(\omega_j)\rangle\right|^2}{\left\langle |X(\omega_i)|^2\right\rangle \left\langle |Y(\omega_j)|^2\right\rangle}}$$

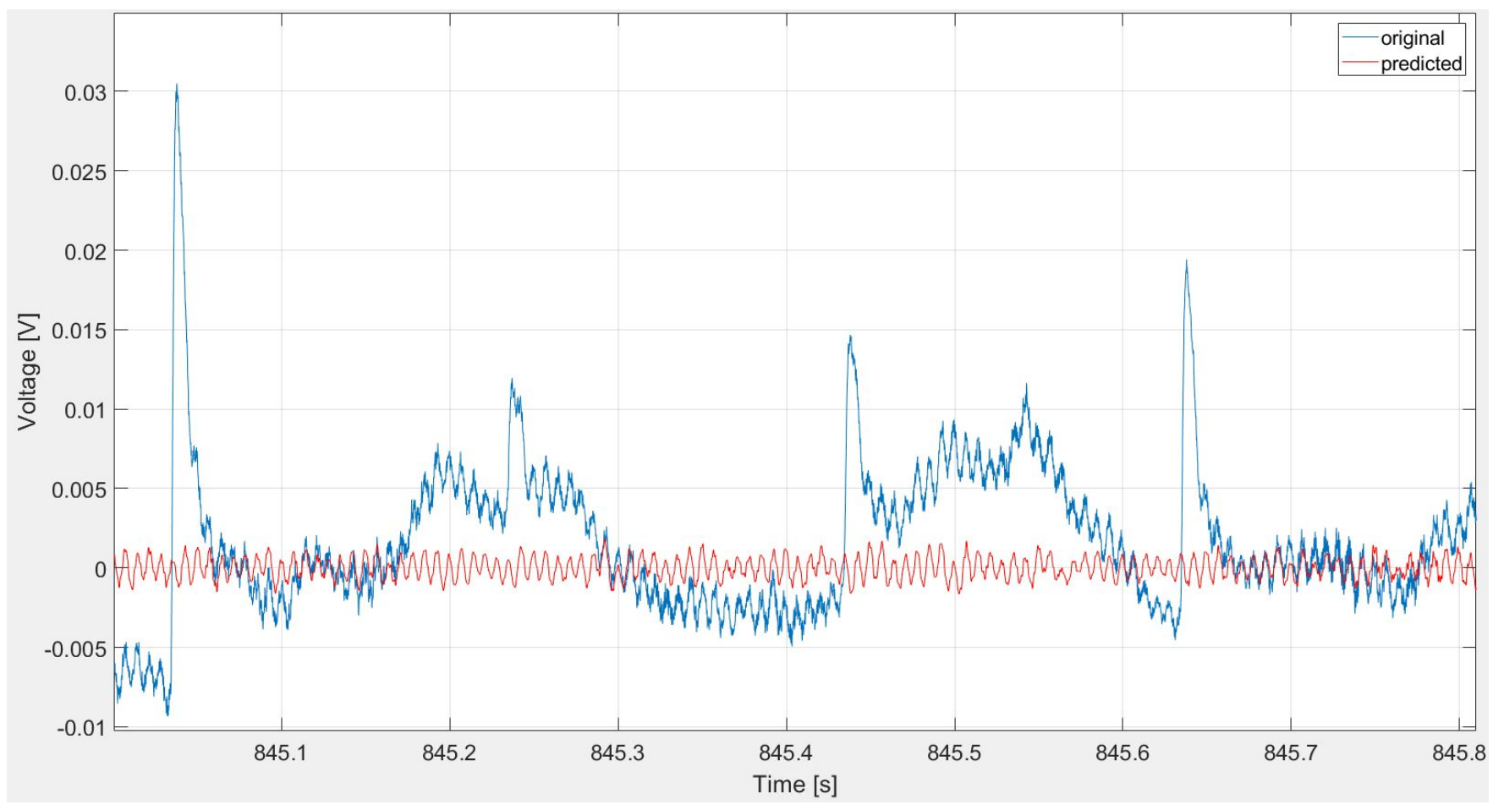
Linear Noise Cancellation in Action

We start with the antenna timestream and the bolometer timestream (right).

By visual inspection, there appears to be a time delay and amplitude scaling for each frequency from the antenna to the bolometer, i.e. a linear transfer function.

We then construct H(ω) as described above and take its inverse Fourier transform. This creates a kernel that we convolve with the original antenna signal to generate the predicted signal.



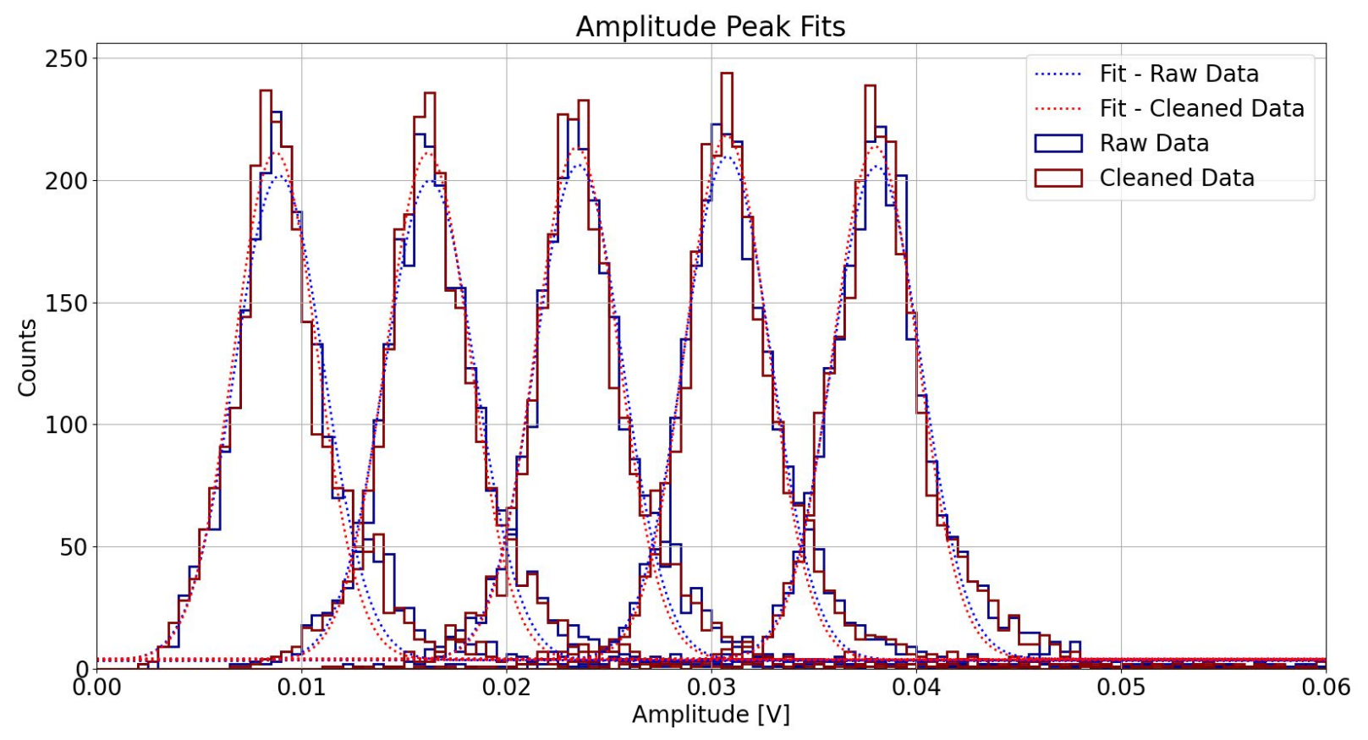


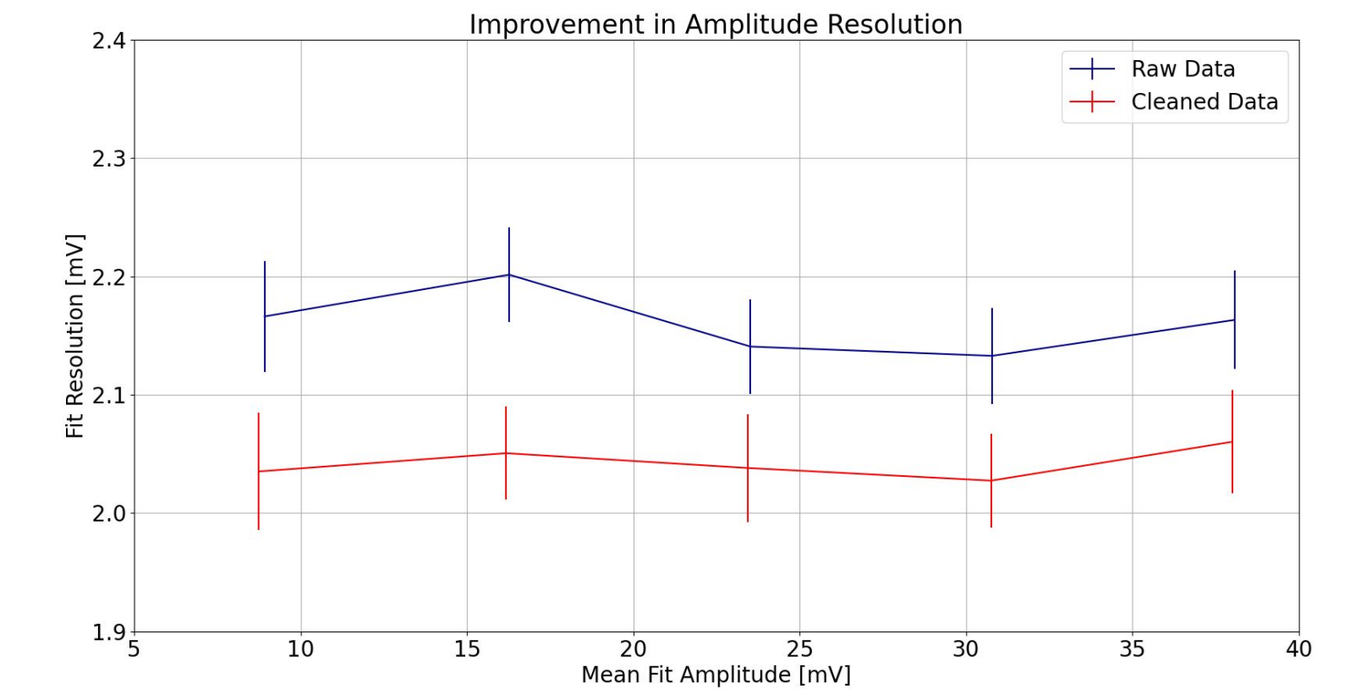
Once the convolution is complete, the resulting signal strongly resembles the electrical noise seen in the data!

By subtracting the predicted signal from the original signal, we are able to reduce the noise, increasing the detector performance.

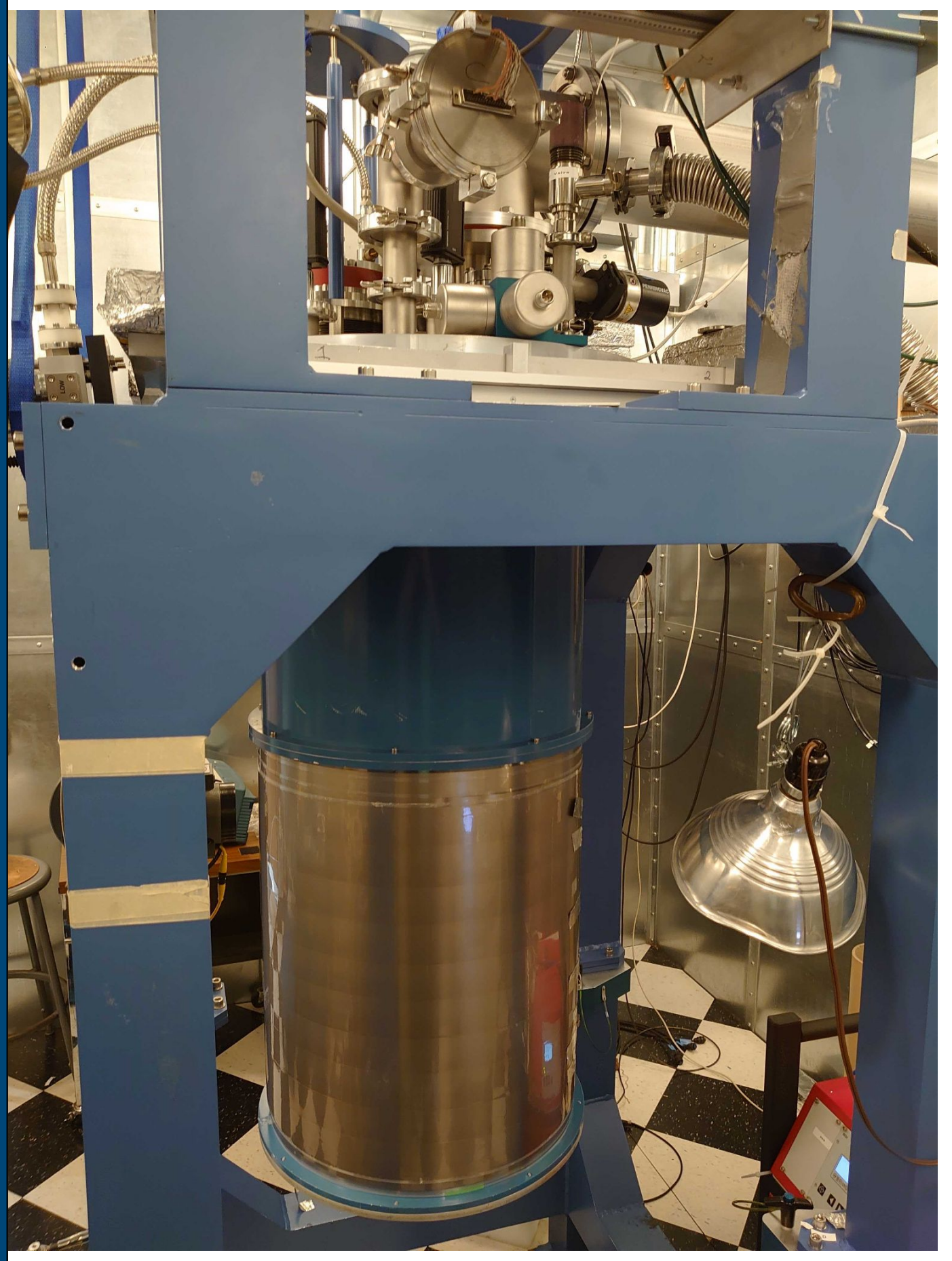
Results of Linear Noise Cancellation

	Raw		Cleaned		Difference	
E	μ [mV]	σ^* [mV]	μ [mV]	σ^* [mV]	$\Delta\mu/\mu_{raw}$	$\Delta\sigma/\sigma_{raw}$
1	8.92	2.17	8.74	2.04	-2.1%	-6.0%
2	16.27	2.20	16.18	2.05	-0.6%	-6.9%
3	23.52	2.14	23.43	2.04	-0.4%	-4.8%
4	30.78	2.13	30.75	2.03	-0.1%	-4.9%
5	38.07	2.16	38.00	2.06	-0.2%	-4.8%



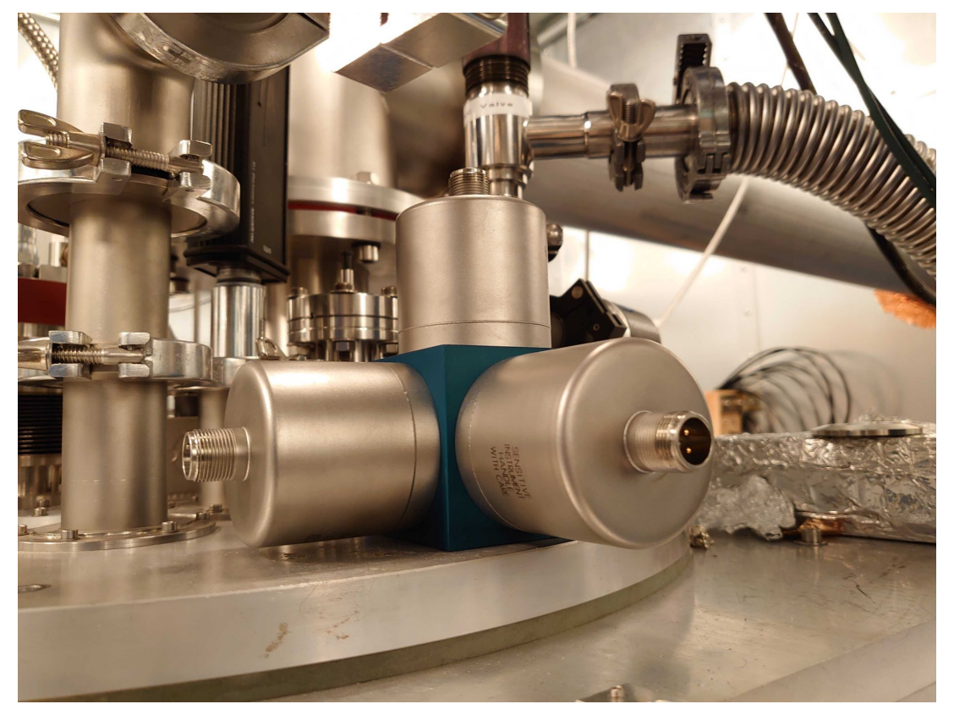


Experimental Setup



In the lab at UC Berkeley, we have a dilution refrigeration unit (left) in which we can cool our devices to ~ 12 mK. We work with both NTD-Ge calorimeters, which are similar to those used in CUORE, and TES-based light detectors as part of research and development for the CUPID experiment.

We monitor the vibrational noise in our system by using accelerometers (below left), which are mounted to the outermost plate (300K plate) of the refrigerator. We also connect a Helmholtz coil antenna (below right) to our DAQ board to monitor electrical noise.

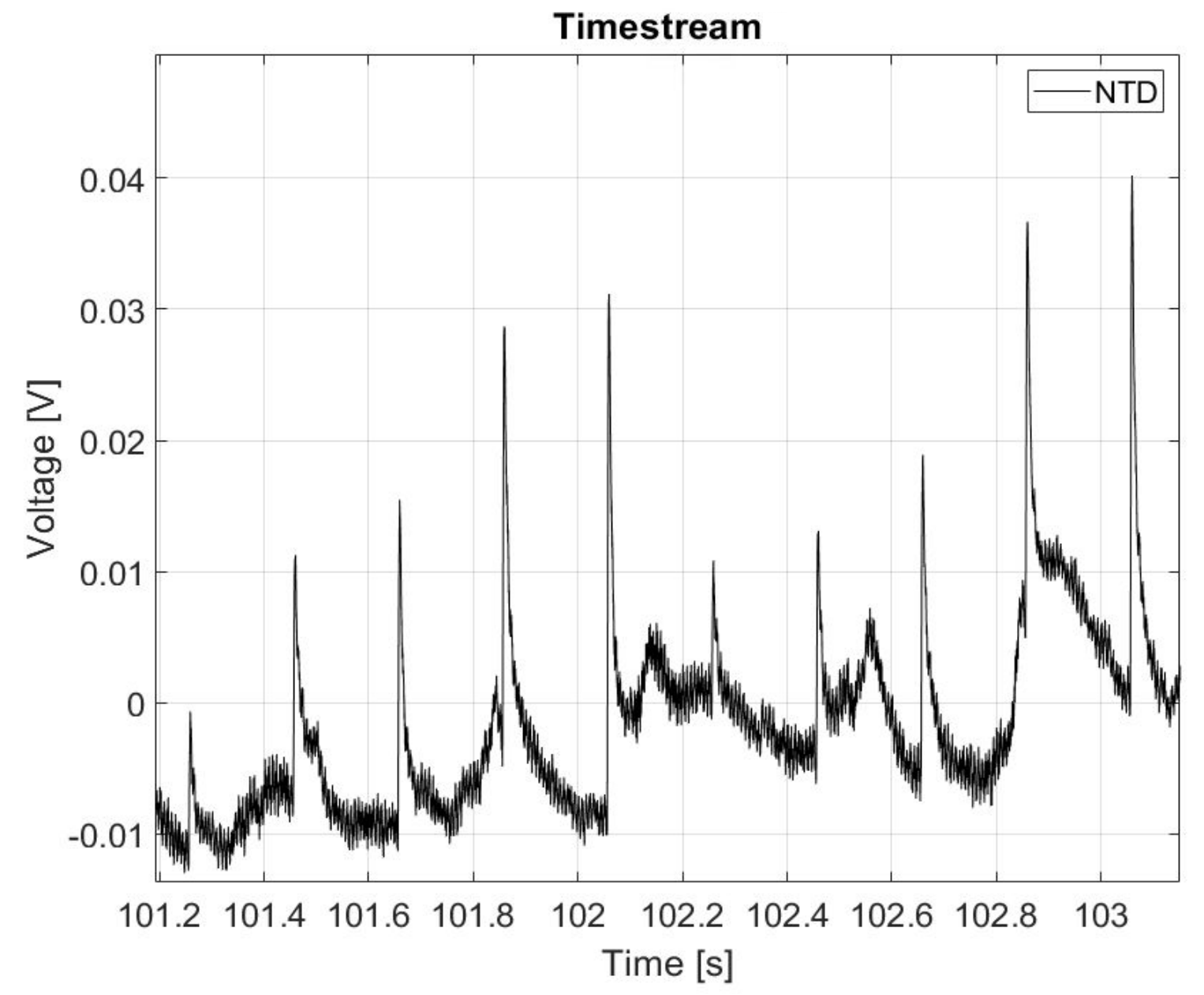


Measuring Device Performance

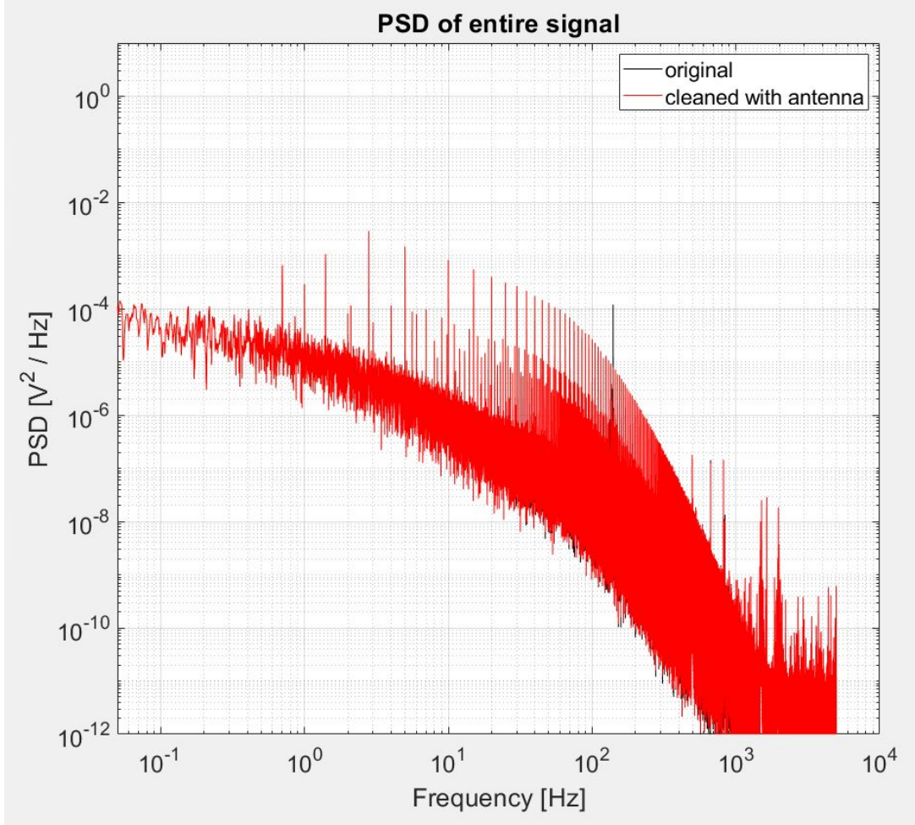
We test the energy resolution of our devices using an LED and a fiber-optic cable which runs into the refrigerator. We then send a train of LED pulses with different widths as proxies for gamma events with different energies.

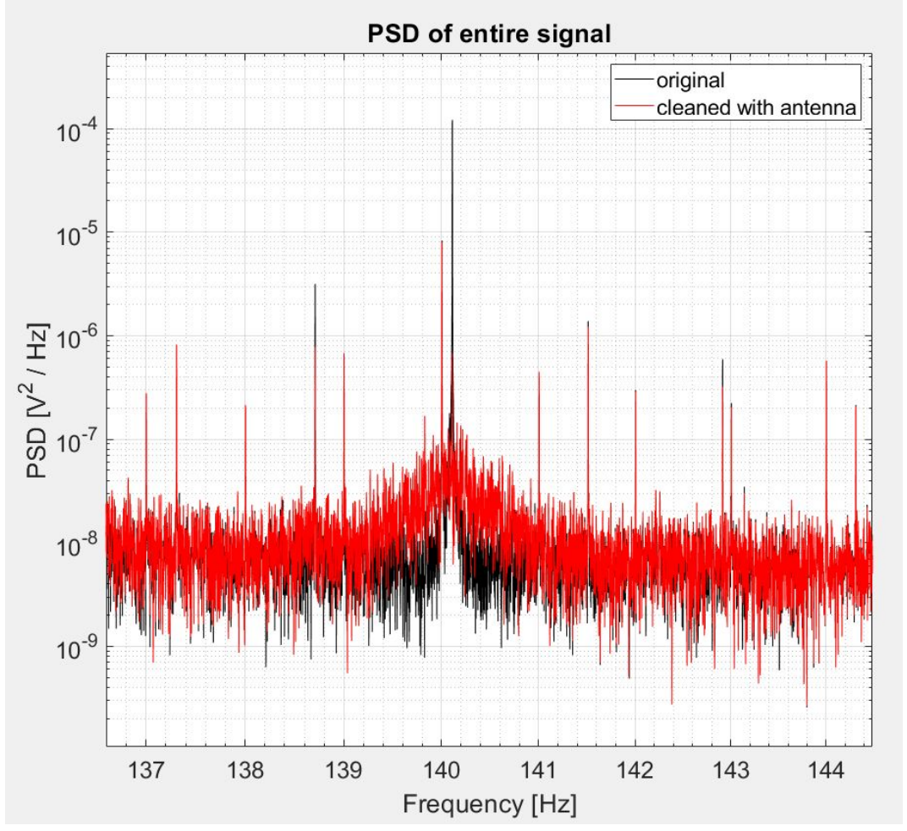
In the example to the right, we have train of five different amplitudes with each pulse separated from the other by 200 ms.

The instability in the baseline is due to a variety of noise sources including periodic vibrations from the pulse tube coolers (PTs) which vibrate with a fundamental frequency of 1.4 Hz. The electrical noise causes the baseline to appear broader in this image.



Noise Removal in Frequency Space

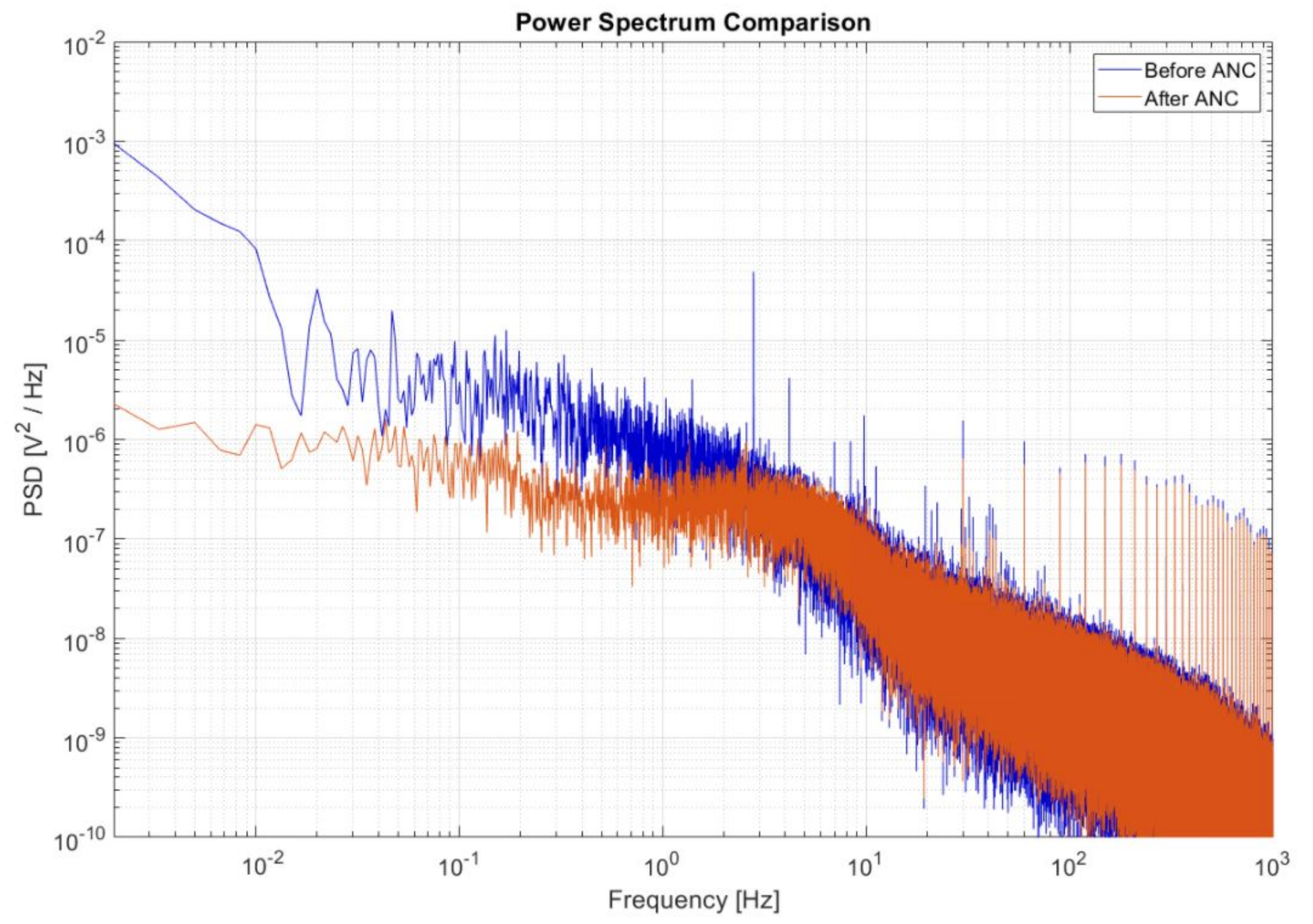




The power spectrum of the bolometer signal before and after the LNC algorithm is shown on the left. A large noise peak at 140 Hz is effectively removed from the signal without injecting other parasitic noise. This peak at 140 Hz is also visible in the antenna data.

When the 30 Hz LED train data is denoised using ANC, we see that there is a significant reduction in the noise continuum at frequencies below 1 Hz. The noise peaks due to the PTs (1.4 Hz and subsequent harmonics) are also reduced or even completely eliminated.

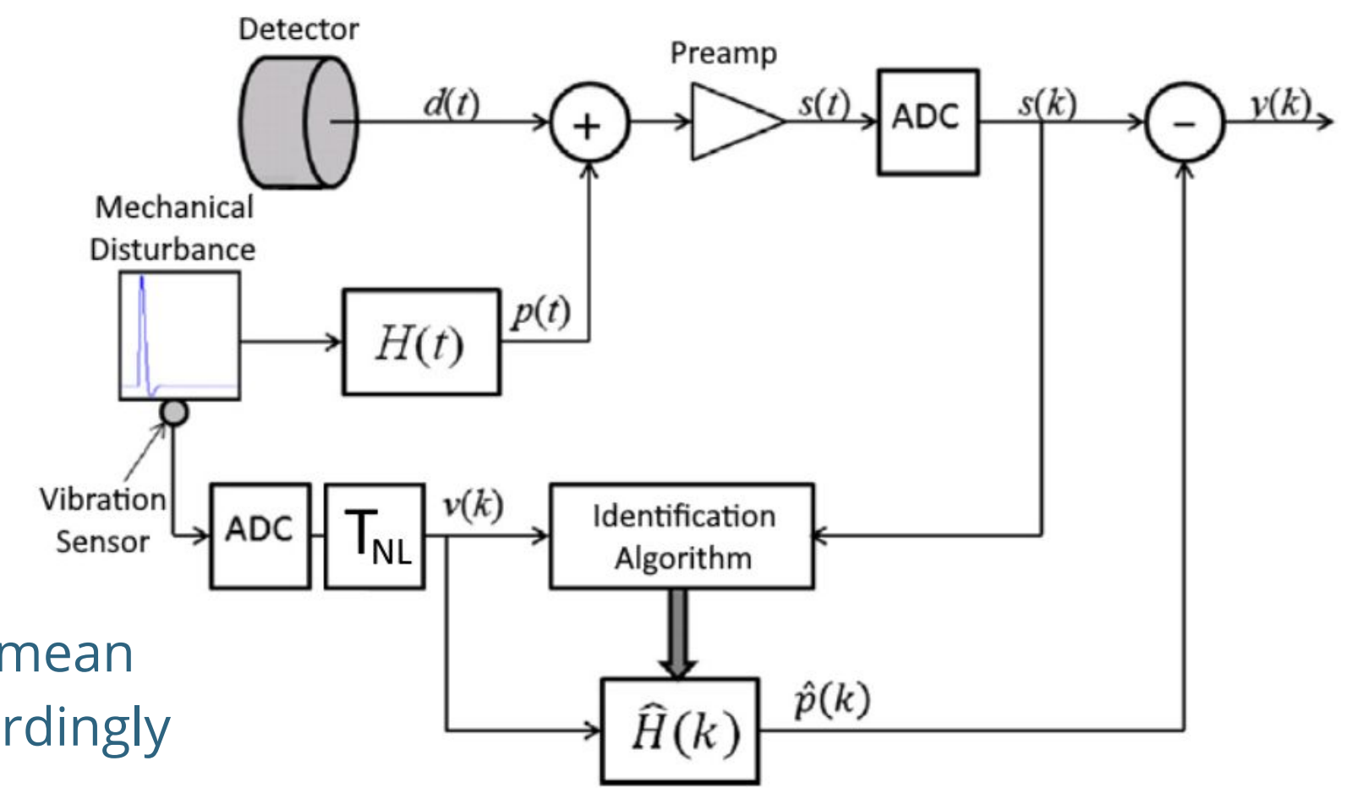
By looking at the signal peaks at integer multiples of 30 Hz, it is clear that there is some degradation of the signal, not just the noise, by this algorithm, though that reduction does not seem to impact the measurement of the amplitude of the LED pulses (See section "Results of Active Noise Cancellation").



Adaptive Noise Cancellation Algorithm Overview

The original algorithm was first implemented by Sergio Zimmermann [1] for charge-collecting detectors but can be adapted to thermal detectors with some slight modifications.

d(t): detector signal without noise
p(t): detector response to the mechanical input
s(k): measured signal in bolometer
H(t): true impulse response of bolometer
v(k): accelerometer response to mechanical input
p̂(k): predicted detector response
Ĥ(k): predicted impulse response

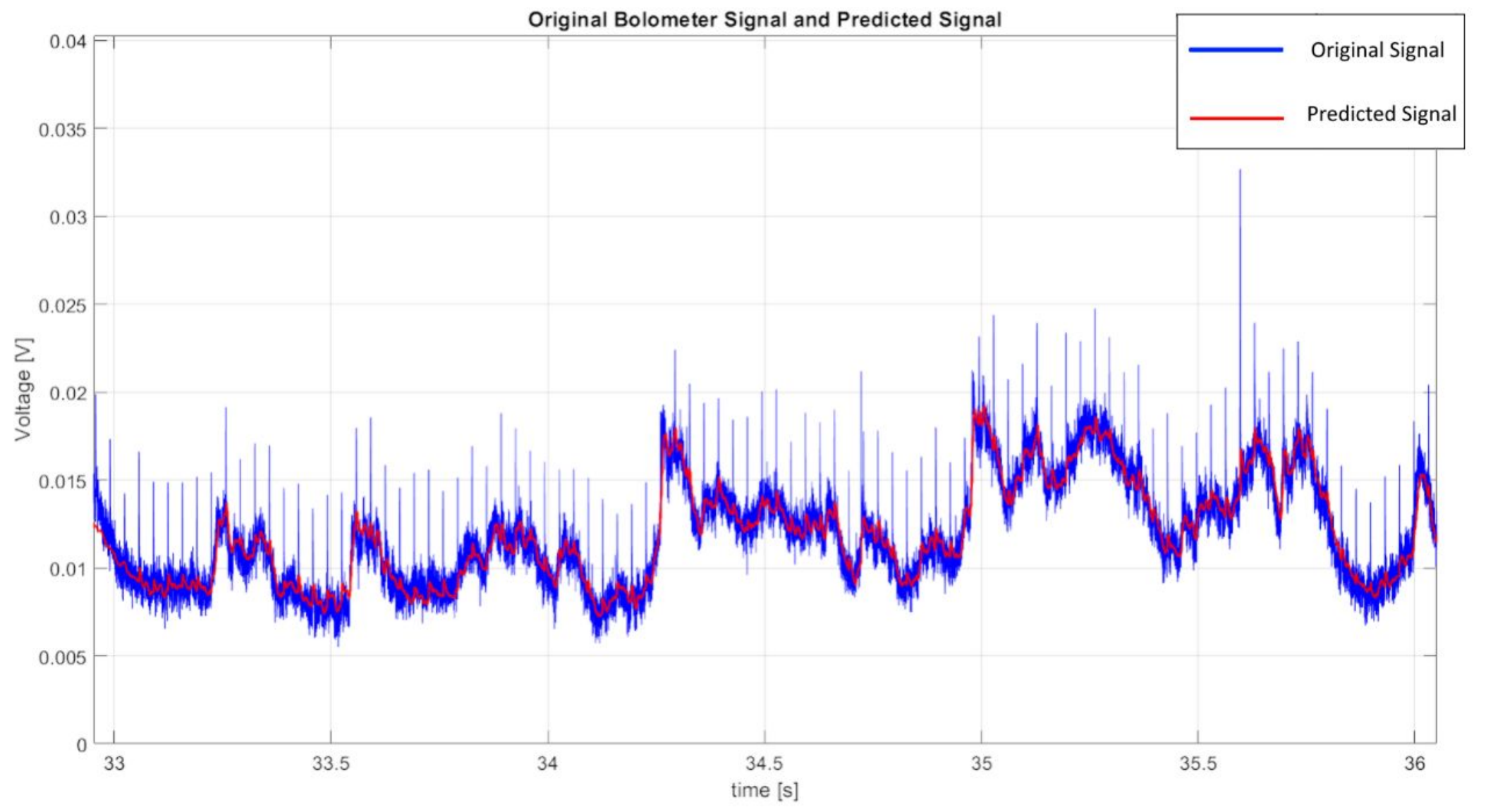


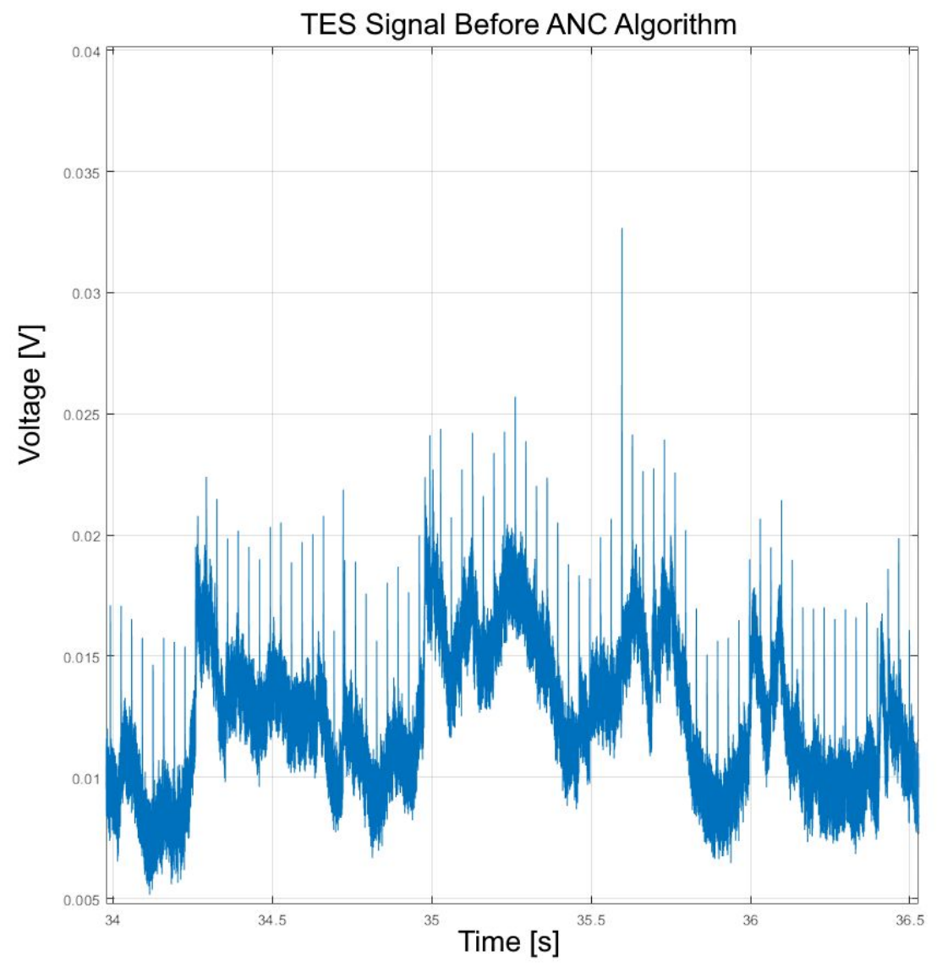
The identification algorithm tries to minimize the least mean square of y(k) and updates the parameters of Ĥ(k) accordingly

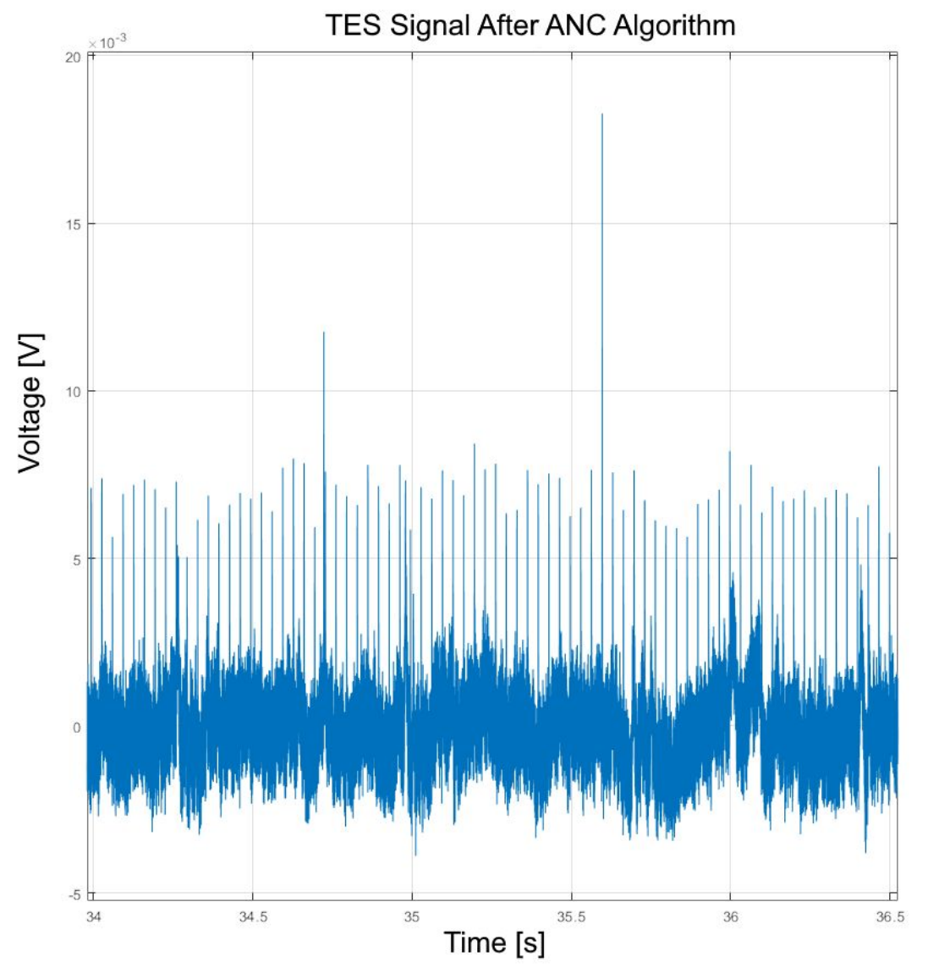
The main difference between this algorithm and that detailed in [1] is the addition of a non-linear transformation $\mathbf{T}_{NL}$. This is a necessary transformation to add because thermal detectors have a unipolar response to a bipolar vibration signal measured in an accelerometer.

Adaptive Noise Cancellation in Action

Similar to the LNC algorithm, the ANC algorithm begins with the raw bolometer signal and the auxiliary device timestream. For the ANC algorithm, we use one of the three accelerometers as the auxiliary device to try to remove the low-frequency vibrational noise in the system. We test this with a train of monoenergetic LED pulses with frequency 30 Hz.



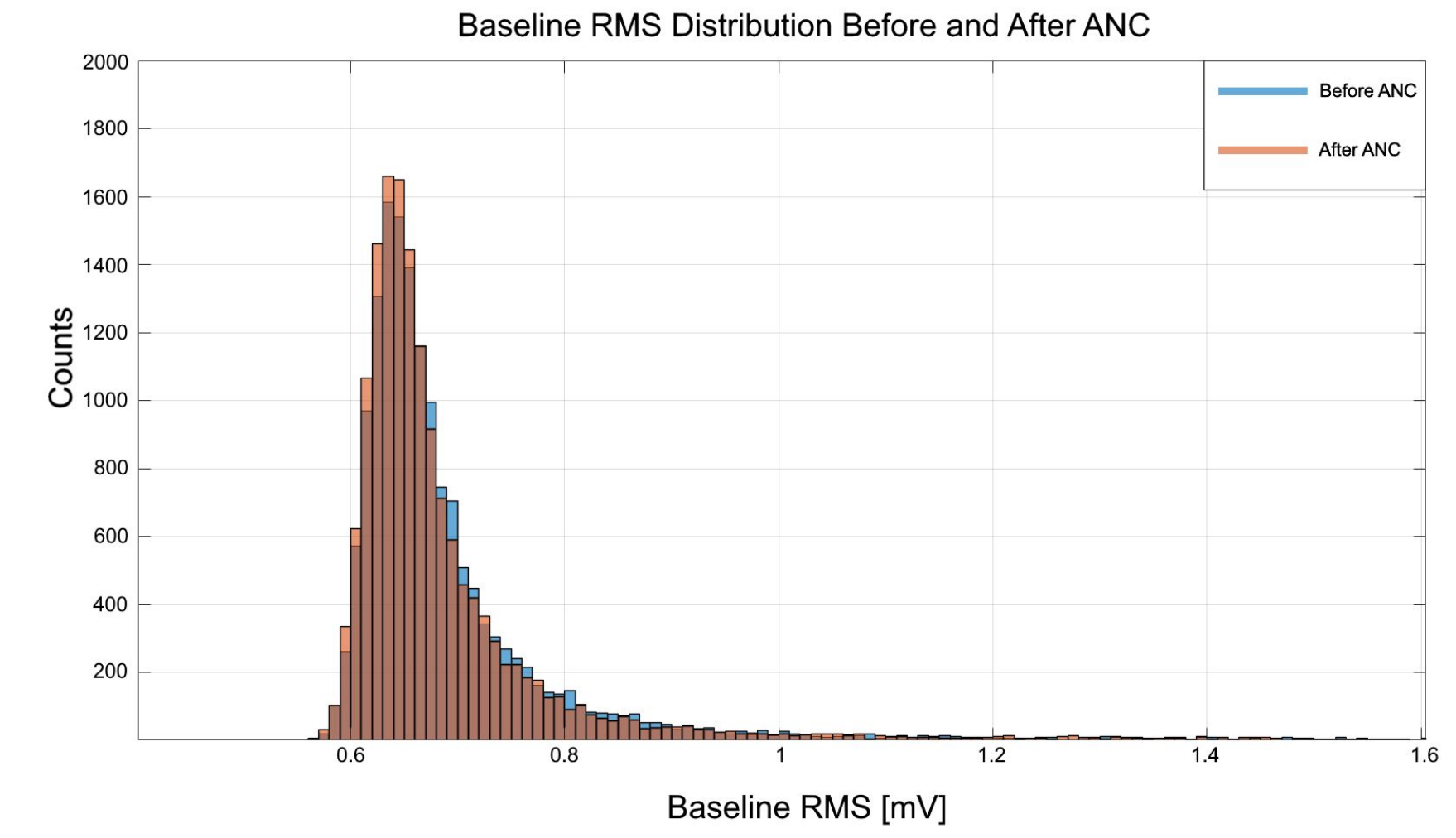


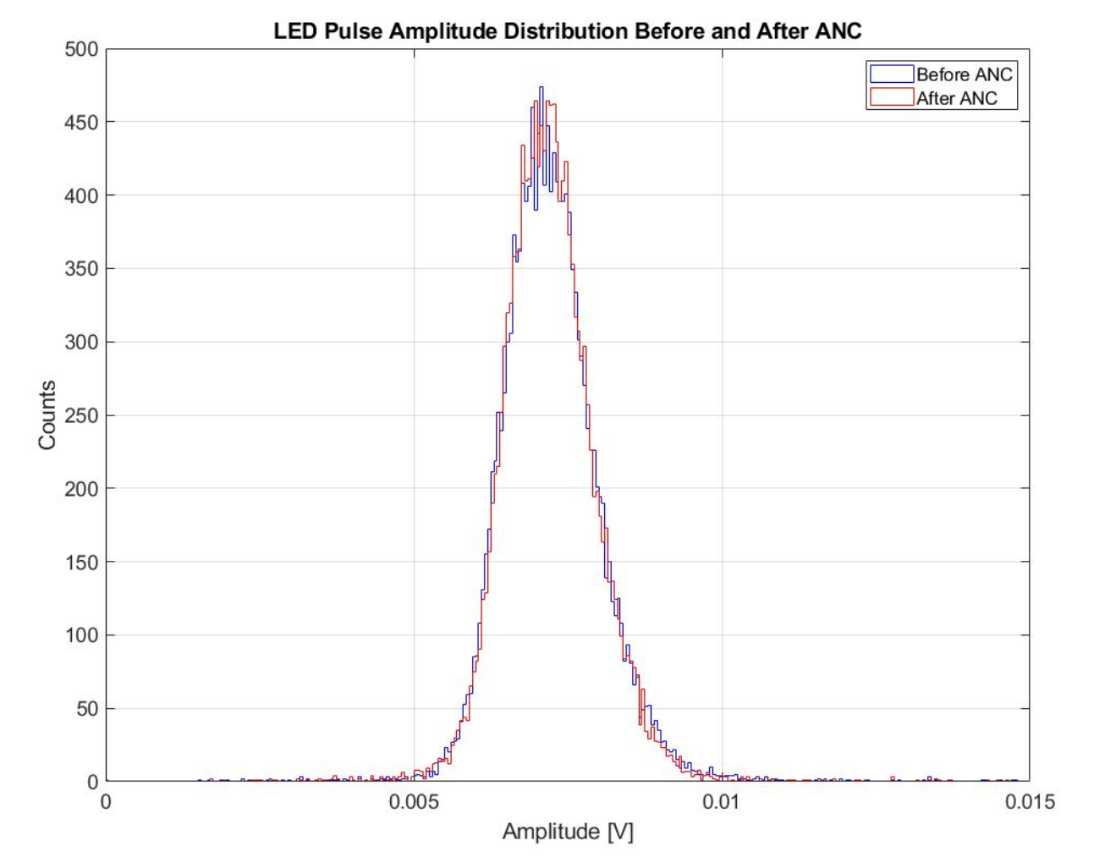


For the ANC algorithm, the convolution happens as the algorithm adapts, rather than at the end of the process as is done in the LNC algorithm.

Like the LNC algorithm, the predicted signal is subtracted from the original signal. The result is clearly less noisy than the original, particularly in the low-frequency regime.

Results of Active Noise Cancellation





This is expected to have minimal impact on the energy resolution of the detectors in this experiment since the detector is much too fast for low-frequency noise to greatly change the detector resolution. There is evidence that this algorithm does slightly change the shape of the detector response function (above right), as well as reduce the average value of the RMS of the baseline of the LED pulses. Importantly, the average value of the LED pulse amplitude is virtually unaffected by the ANC algorithm.

References

[1] S. Zimmermann, "Active microphonic noise cancellation in radiation detectors", Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **729,** 404-409 (2013).