Novel Noise Cancellation Algorithms for Low-Temperature Detectors

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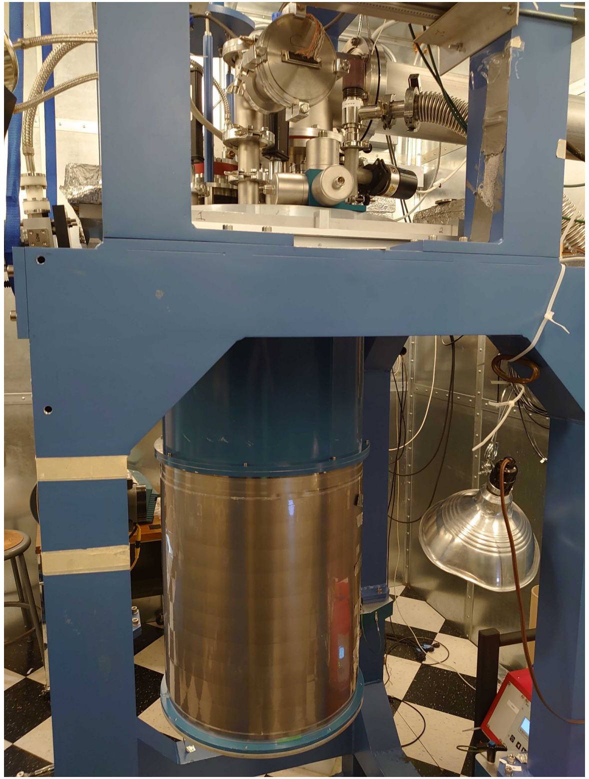
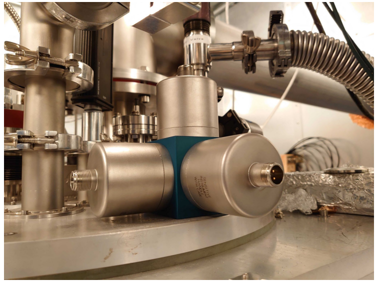
The Experimental Setup

Our refrigerator cools detectors (NTD calorimeters & TES-based light detectors) to ~ 12 mK.

We have connected accelerometers (top right) and a Helmholtz coil antenna (bottom right) to measure vibrational and electrical noise.

Our goal is to remove vibrational and electrical noise from our detectors using these “auxiliary” devices.





Approaching the Problem

Method 1: "Linear" Noise Cancellation (LNC)

- Assume a linear transfer function from auxiliary devices to bolometers
- Done in Fourier space rather than Laplace space (IIR filter, not FIR filter)
- Algorithmically similar to building an Average Noise Power Spectrum

Method 2: Adaptive Noise Cancellation (ANC)

- First implemented by S. Zimmerman for GRETA (NIMA, 2013)
- Assumes a finite impulse response from auxiliary devices to bolometers
- Employs a gradient descent algorithm to find the transfer function adaptively

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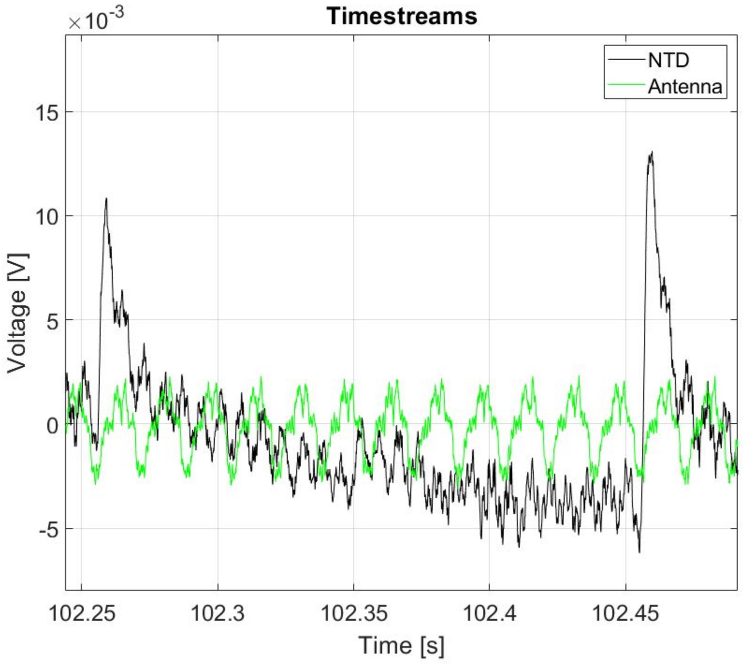
Linear Noise Cancellation (LNC)

Linear Noise Cancellation

- Original motivation: electrical noise in local Berkeley detector data
- Noise should be independent of thermal noise
- Measure the noise with helmholtz coil antenna attached to our DAQ board
- Time delay and amplitude scaling for each frequency from aux to bolo, i.e. a linear transfer function



Removing Electrical Noise

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

$$A_1 \exp[2\pi i f + i\varphi_1] \longrightarrow A_2 \exp[2\pi i f + i\varphi_2]$$

The transfer function is thus $H(f) = A_1 / A_2 \exp(\varphi_1 - \varphi_2)$.

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.

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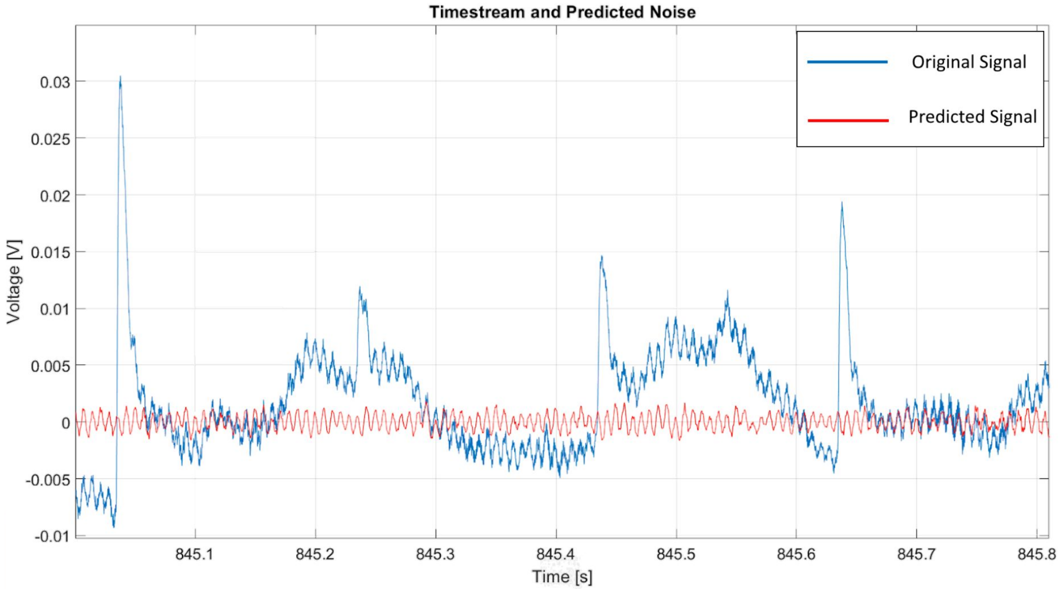
LNC Using Berkeley Data

We predict the noise by performing an IFFT of the transfer function to get a convolution kernel.

Convolving this kernel with the antenna gives the predicted signal.



Subtracting the predicted signal from the original reduces the electrical noise

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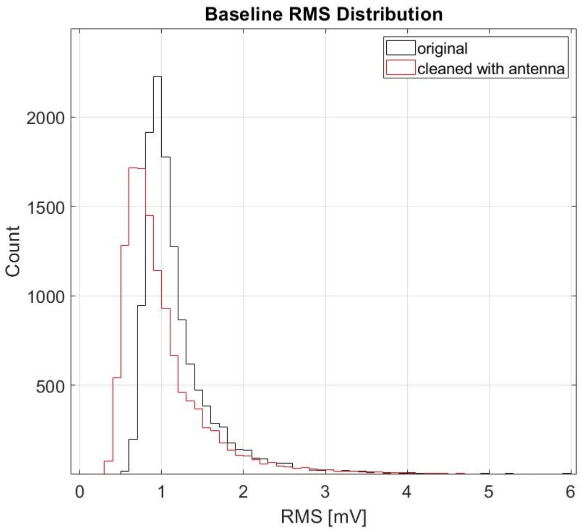
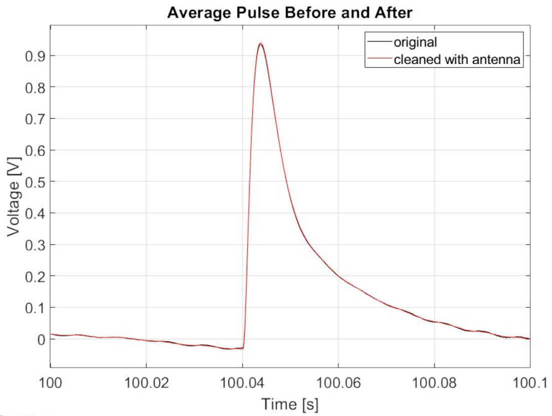
Berkeley Data LNC Results

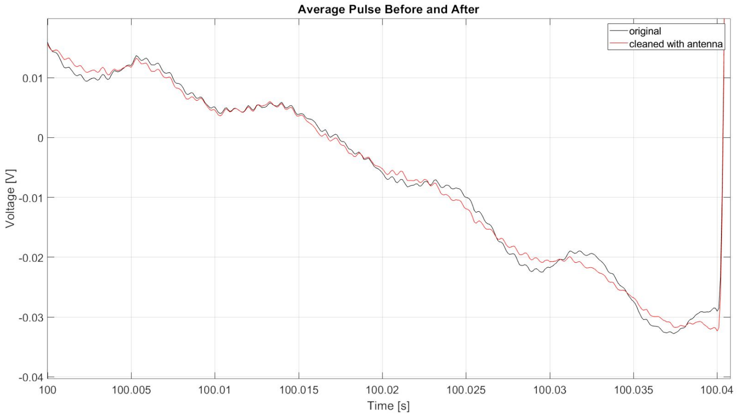
Baseline: first 30 ms of the 40 ms prepulse

Mean of baseline RMS decreases by 11.3% (from 15.9 mV to 14.1 mV)

Amplitude of Average Pulse increases by 0.5%







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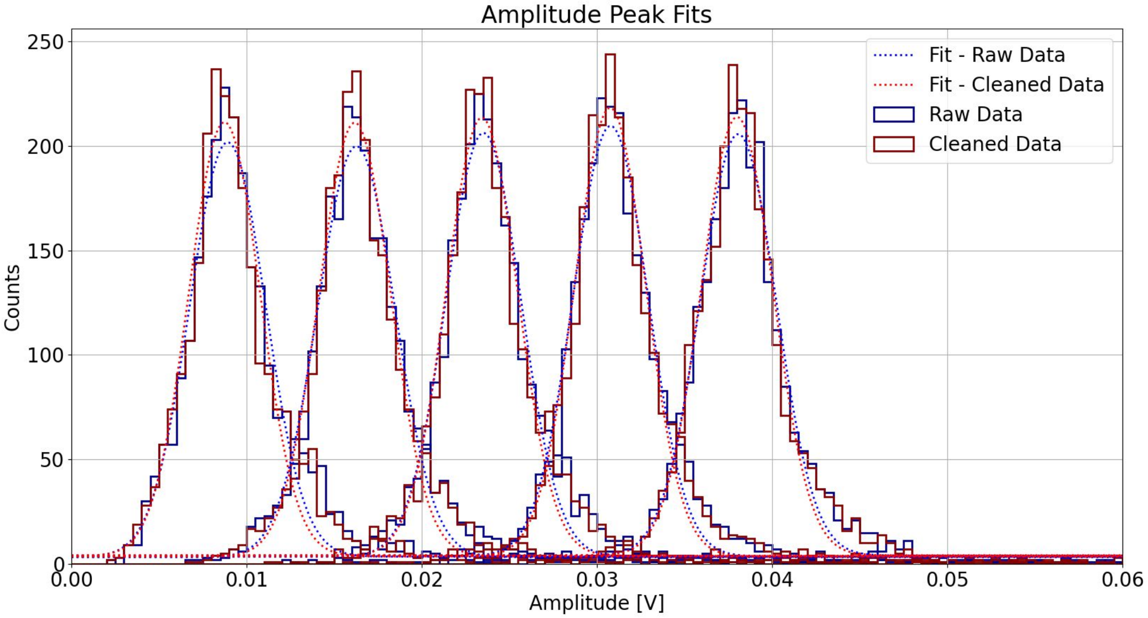
Improvement in Energy Resolution

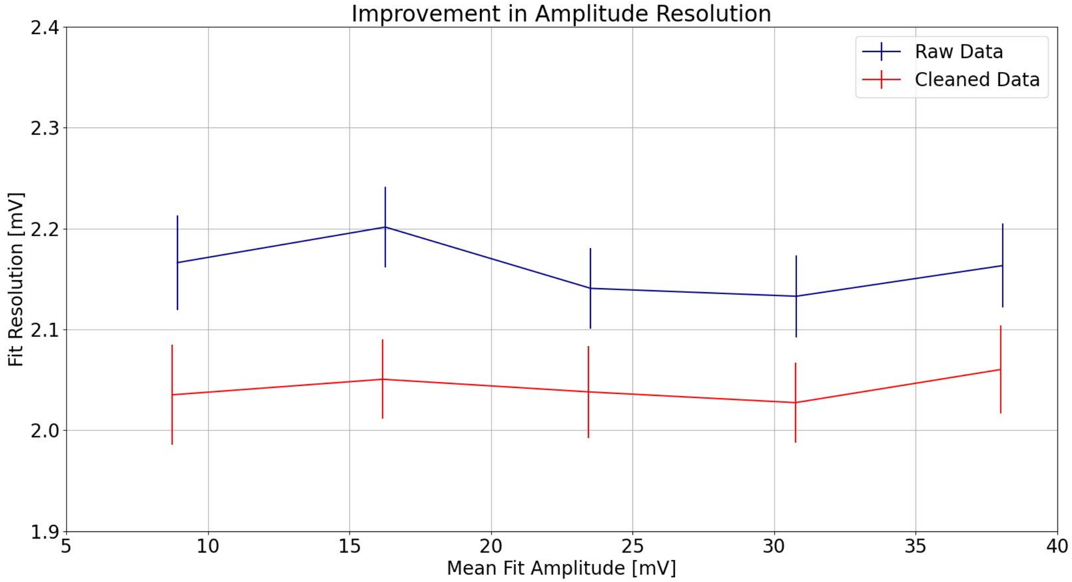
	Raw		Cleaned	
E	μ [mV]	σ^* [mV]	μ [mV]	σ^* [mV]
1	8.92	2.17	8.74	2.04
2	16.27	2.20	16.18	2.05
3	23.52	2.14	23.43	2.04
4	30.78	2.13	30.75	2.03
5	38.07	2.16	38.00	2.06



Note: Each peak contains ~ 2500 events
*uncertainties on σ are roughly 0.05 mV

Comparing Fit Resolutions

E	$\Delta\mu/\mu_{raw}$	$\Delta\sigma/\sigma_{raw}$
1	-2.1%	-6.0%
2	-0.6%	-6.9%
3	-0.4%	-4.8%
4	-0.1%	-4.9%
5	-0.2%	-4.8%



Adaptive Noise Cancellation (ANC)

Towards an Adaptive Noise Cancelling Filter

This algorithm also uses an auxiliary device, e.g. an accelerometer, to predict the timestream of the bolometer noise, which can then be subtracted

Main differences from LNC algorithm:

- ANC assumes the bolometer has a finite impulse response (FIR) given an impulse signal in the accelerometer
- ANC adapts over time rather than averaging over an ensemble of events

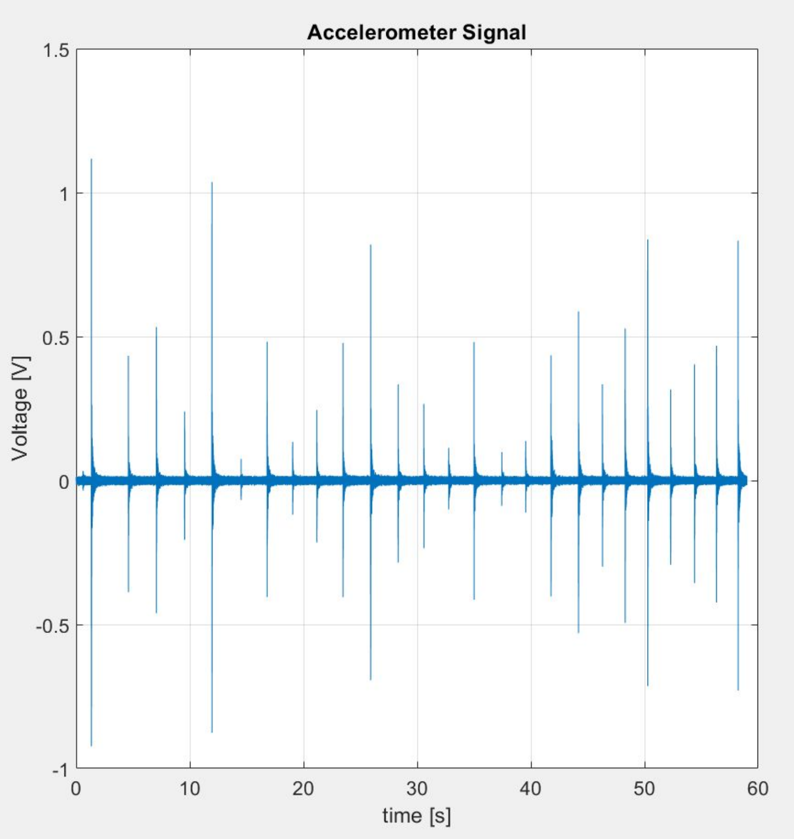
Note: *ANC is still linear in its parameters!*

ANC Tests at Berkeley

I have been developing the algorithm using data from transition edge sensors (TES) here at Berkeley

To get impulse response information, we tap the cryostat several times throughout the run to induce vibrations

Accelerometer timestream is squared and this new signal is the input to the algorithm

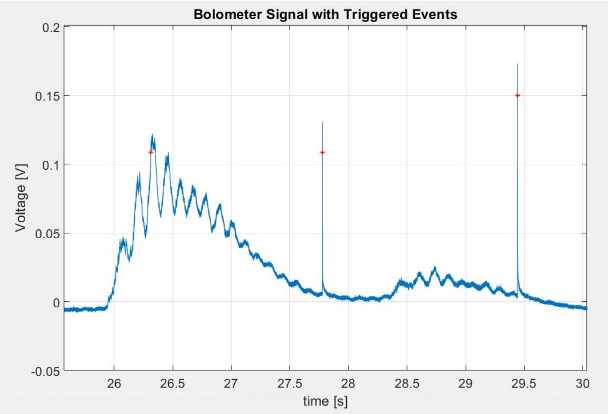


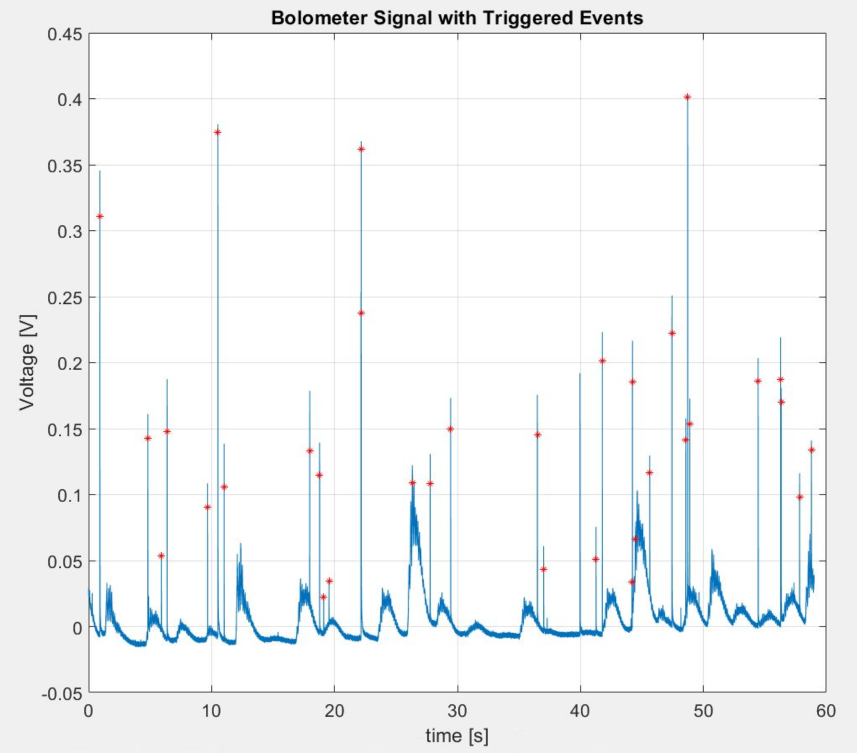
ANC Tests at Berkeley

Bolometer data shows strong oscillations in baseline, clearly due to acoustics

Detector response signal shape is indeed strictly positive, though low-frequency oscillations (~ 8 Hz) appear as well

Triggers are mainly muons





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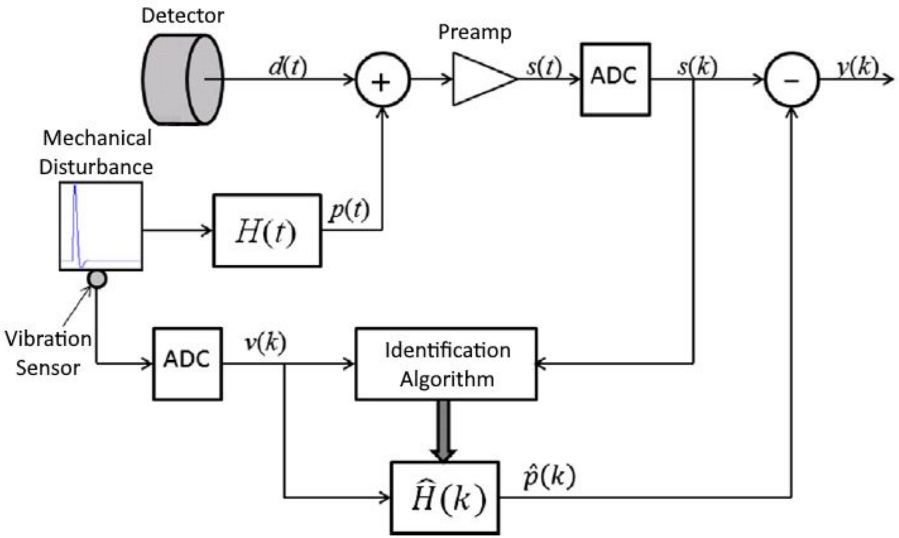
A Linear ANC Algorithm

Thanks to Sergio Zimmerman, whose algorithm provides a starting point for this development and whose guidance has been extremely useful throughout these studies.

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

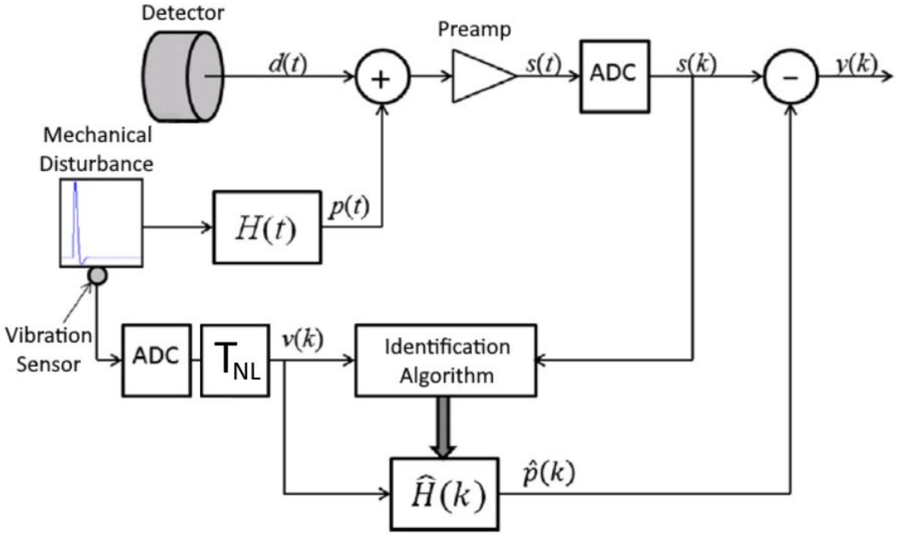


Modifying the Original Algorithm

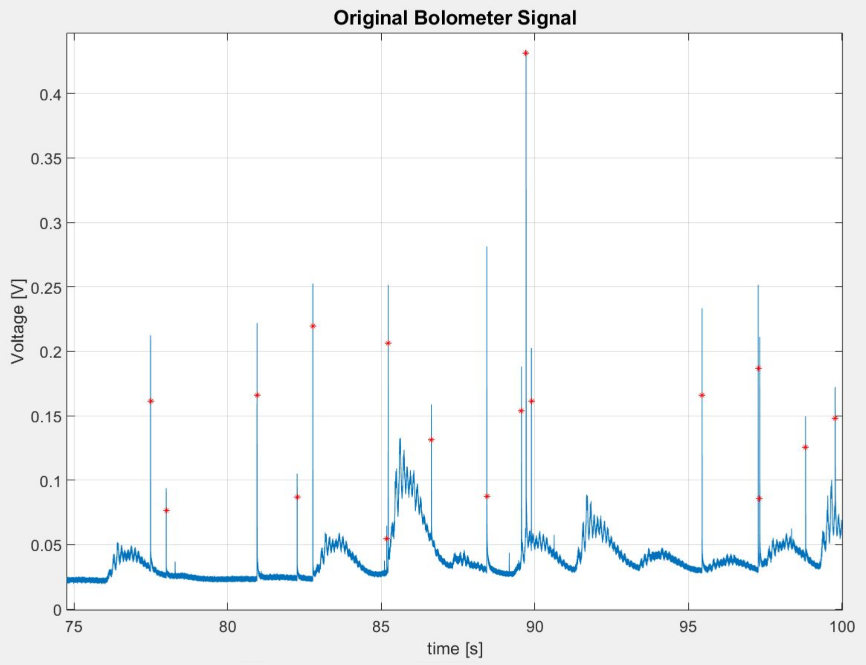
Since bolometer signal due to acoustics is non-negative definite, a linear algorithm requires a strictly positive (unipolar) signal

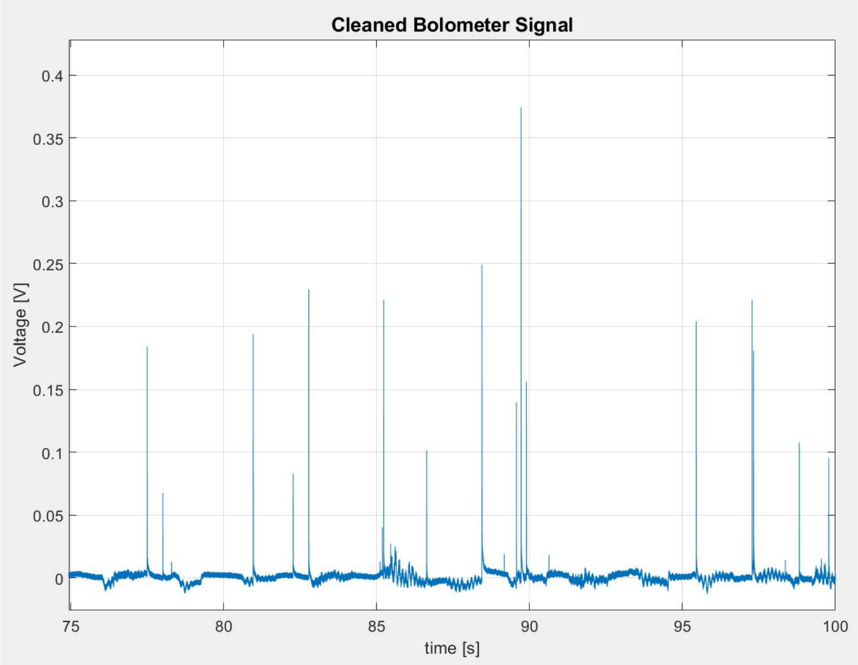
Convergence is otherwise impossible.

This motivates us to square the vibration signal (or apply some other nonlinear transformation to the signal) before continuing



Results of Algorithm (Berkeley TES Muon Data)





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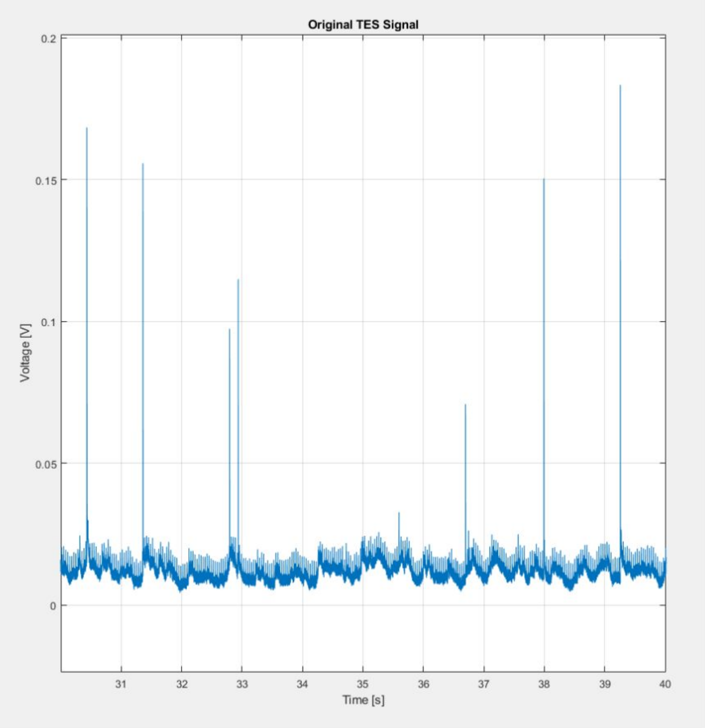
Using ANC with Berkeley LED Data

We employ a fiber-optic cable and an LED to send pulses of varying width as proxies for particle events with varying energies

As an initial test, we conducted an "LED run" with a single pulse width

Initial signal contains muon pulses, LED pulses (smaller), electrical noise, and vibrational noises



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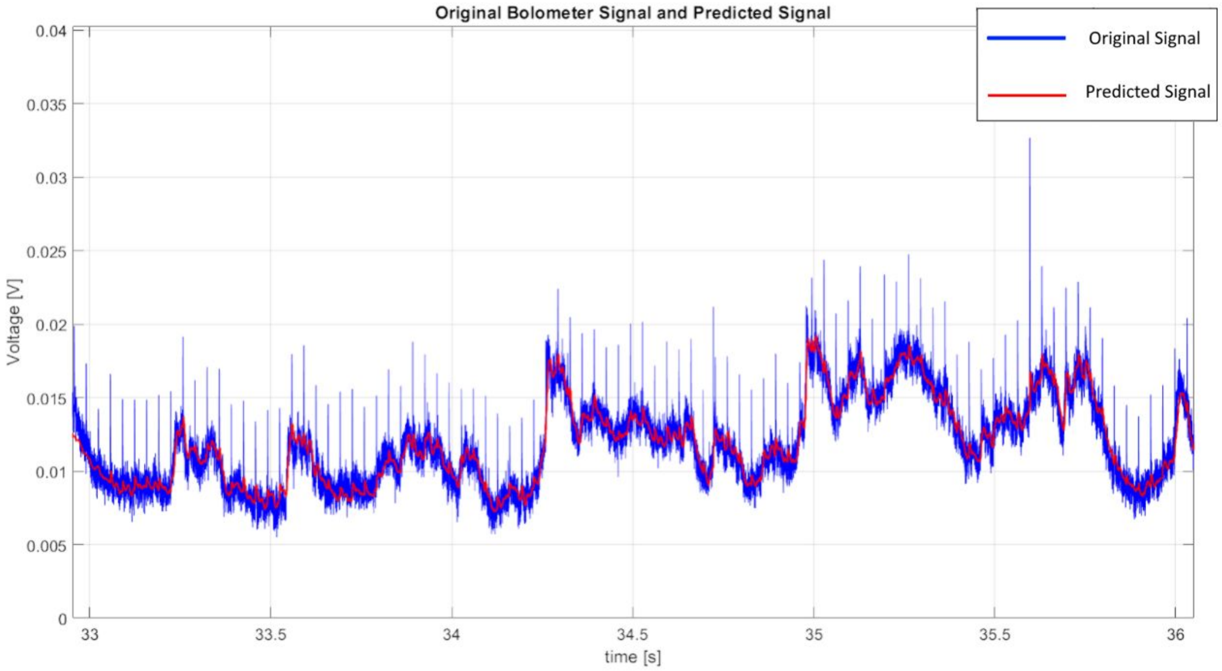
Results of Algorithm (Berkeley TES LED Data)



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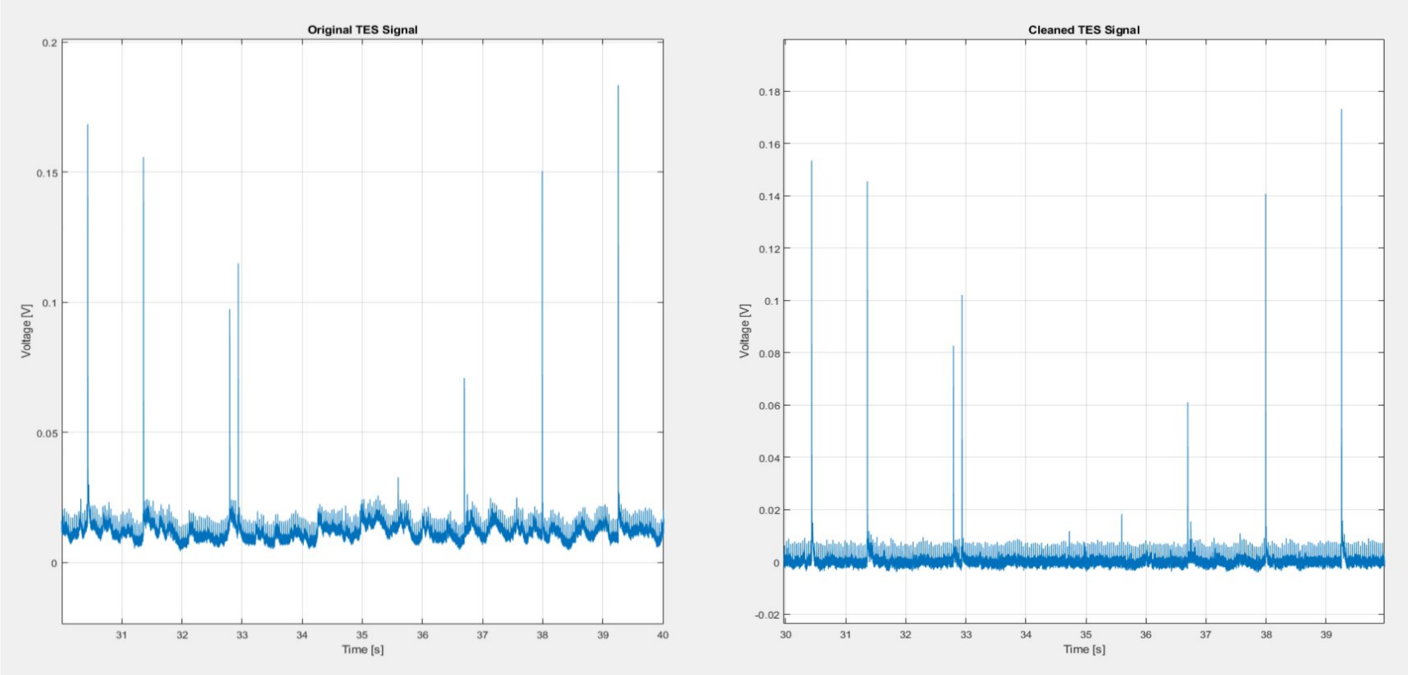
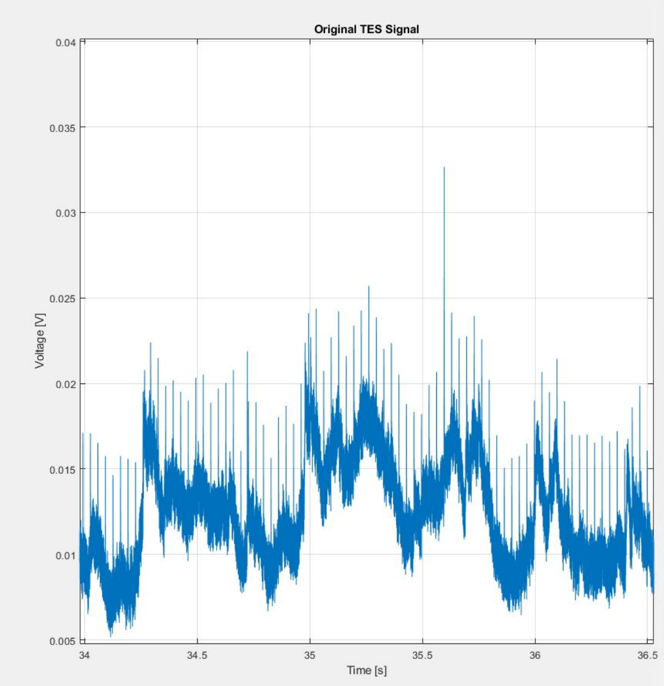
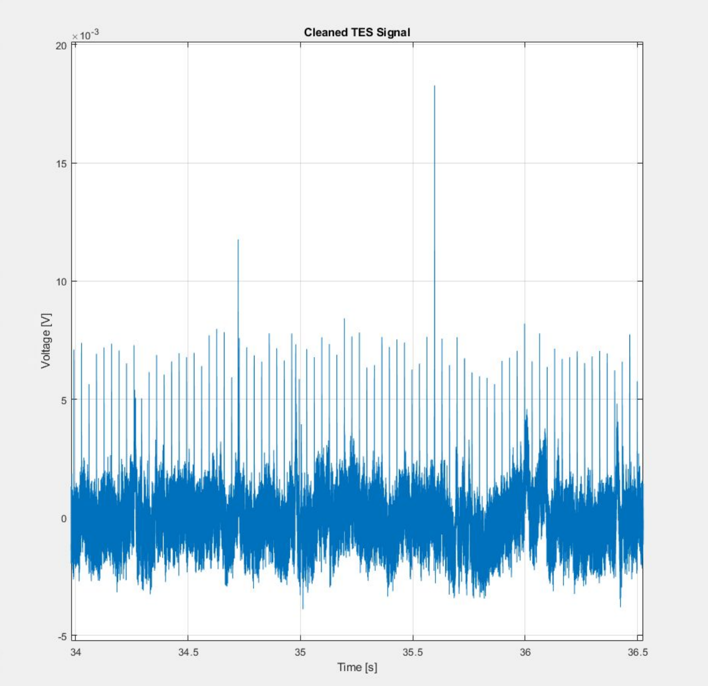
Results of Algorithm (Berkeley TES LED Data)



Results of Algorithm (Berkeley TES LED Data)





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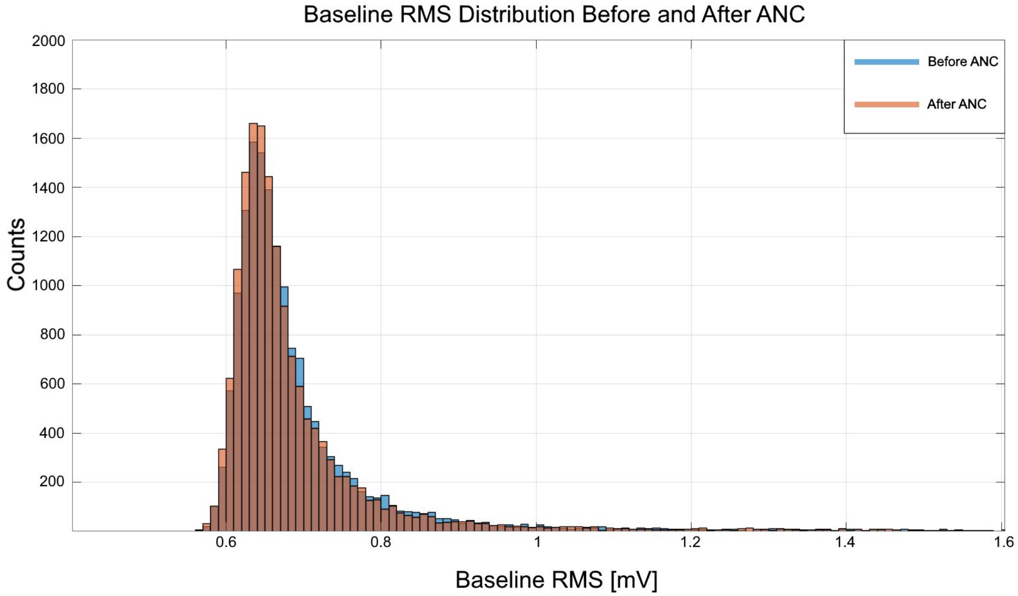
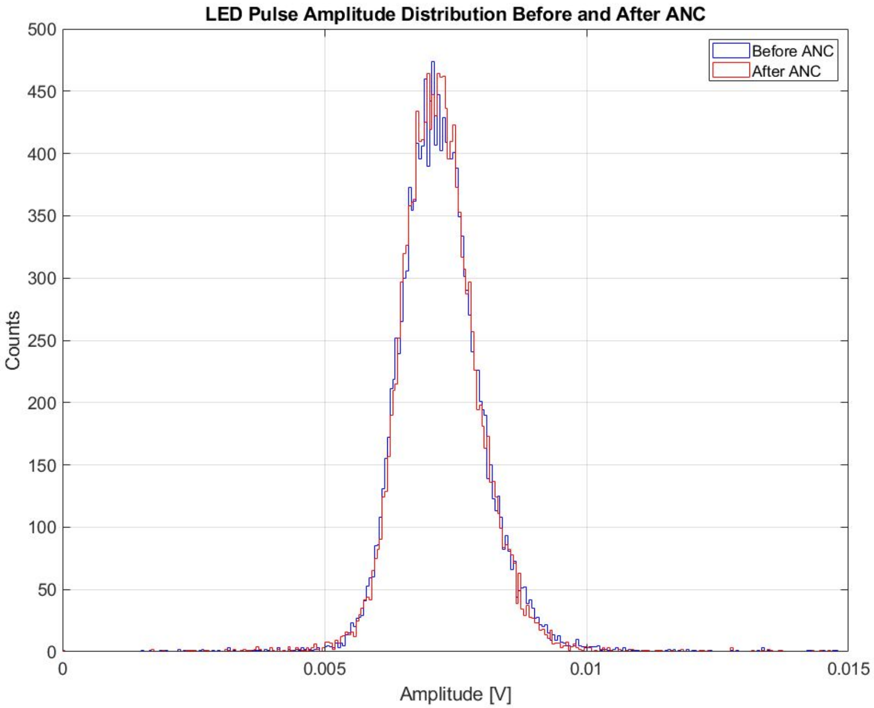
Some Preliminary Findings





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Summary and Future Plans

- Linear Noise Cancellation (LNC) demonstrates a statistically significant improvement in energy resolution of NTD calorimeters
- Adaptive Noise Cancellation (ANC) shows improvement in baseline resolution and significant reduction in low frequency noise in TES data

Future plans:

- Implement LNC algorithm for wider use with all devices including TES, eventually turning to CUORE data for implementation
- Continue to develop ANC algorithm for use with NTDs and comparison with LNC

Thank You!

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Backup

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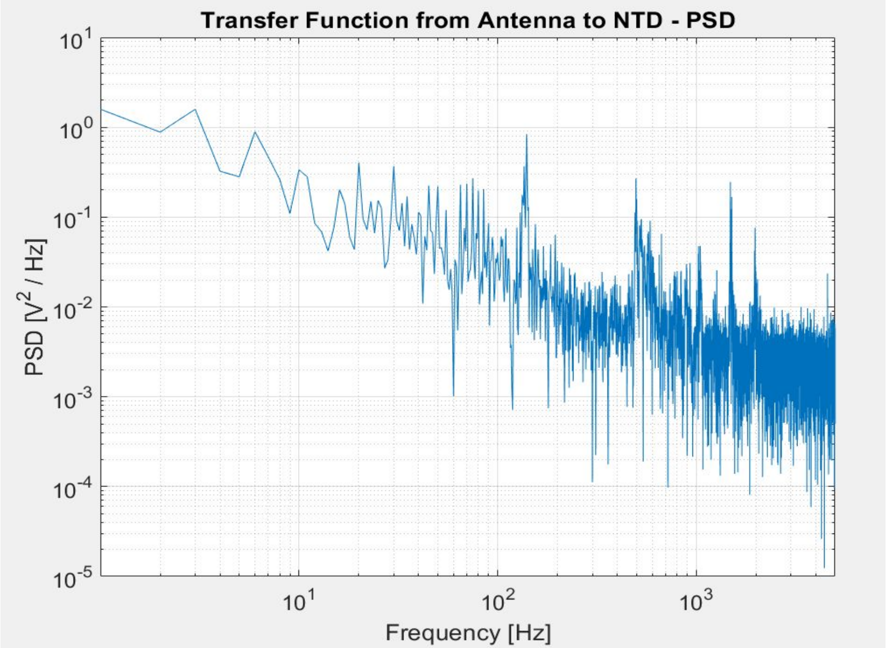
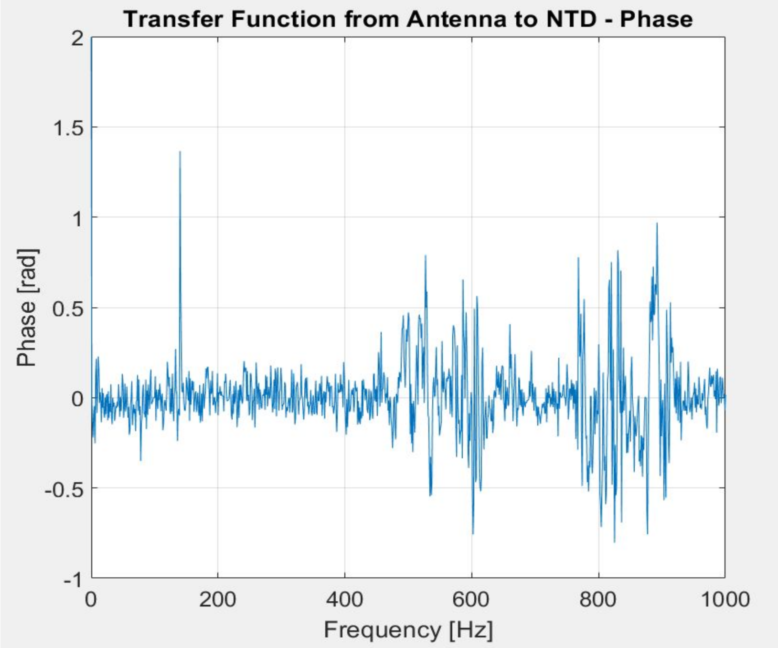
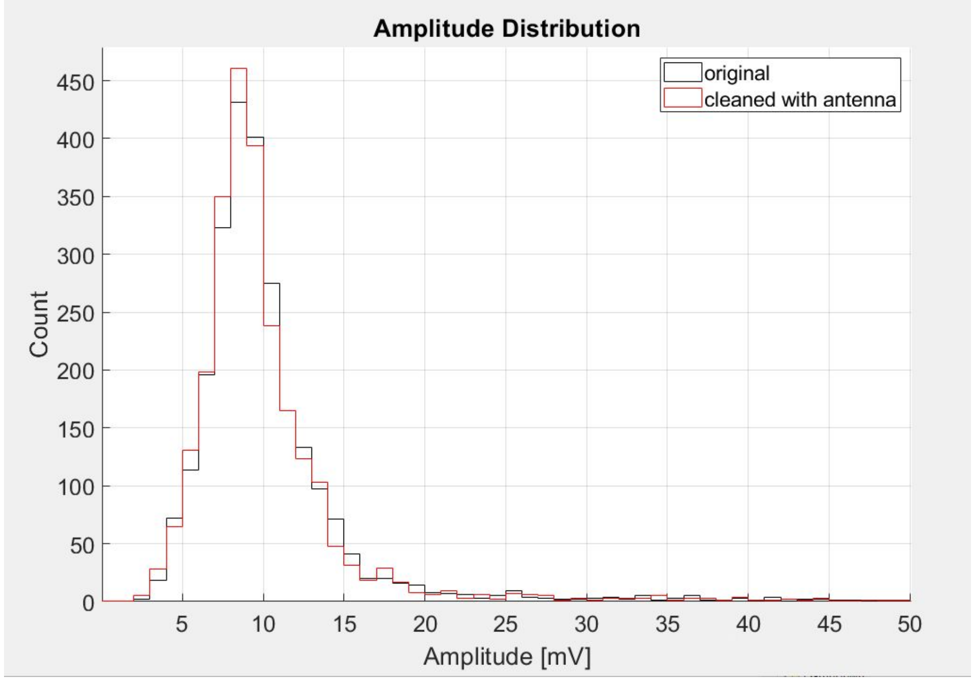
Transfer function from antenna to NTD





Amplitude Spectrum of Single Energy After LNC



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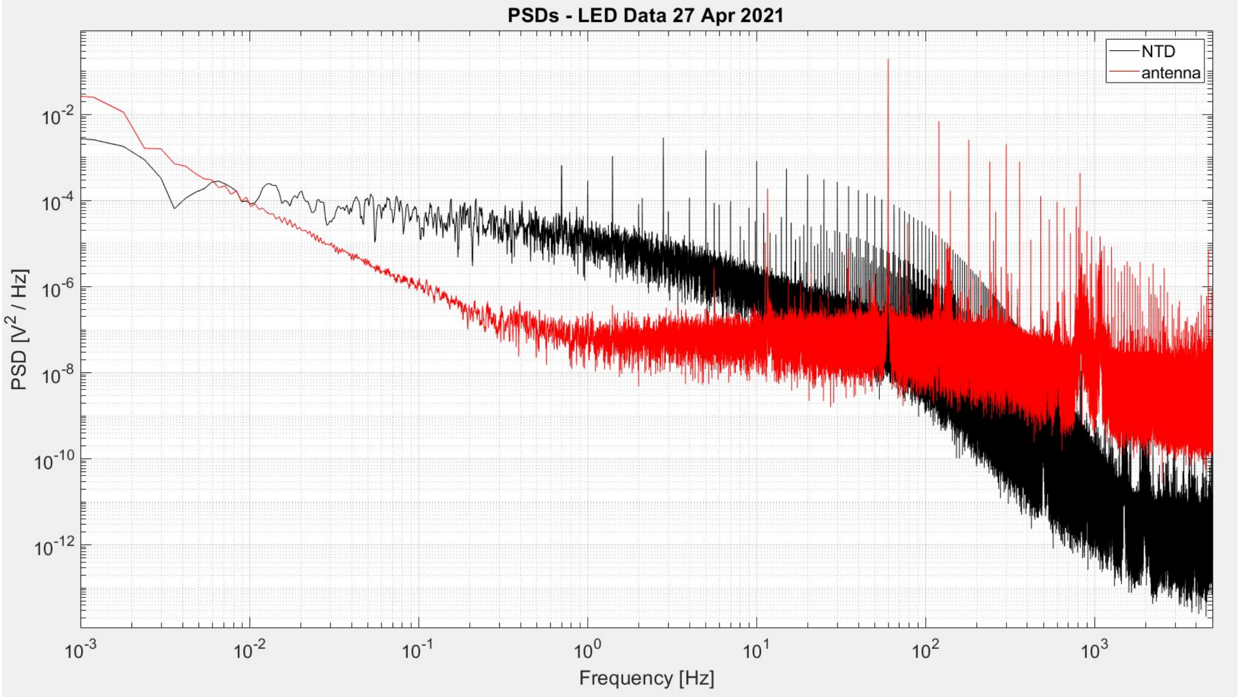
NTD and Antenna Power Spectra



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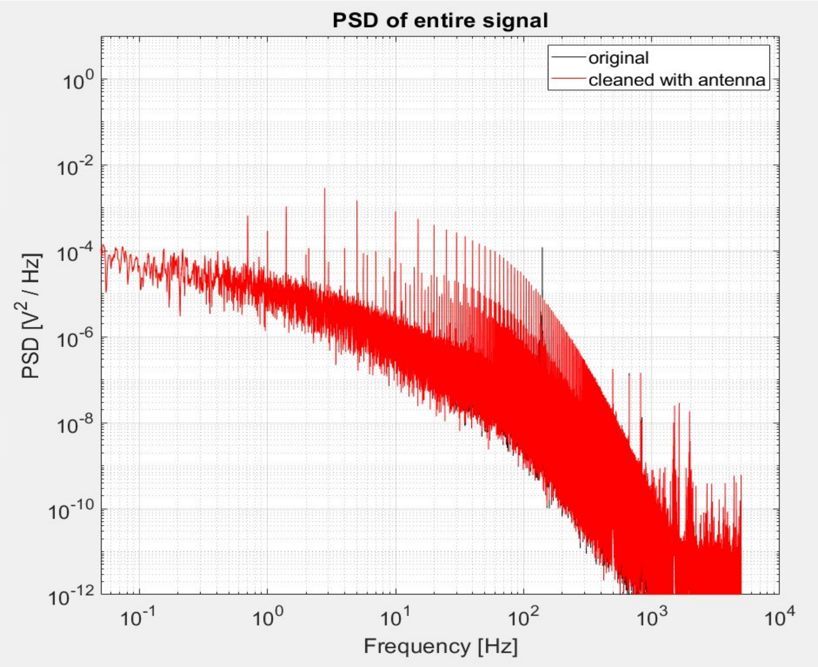
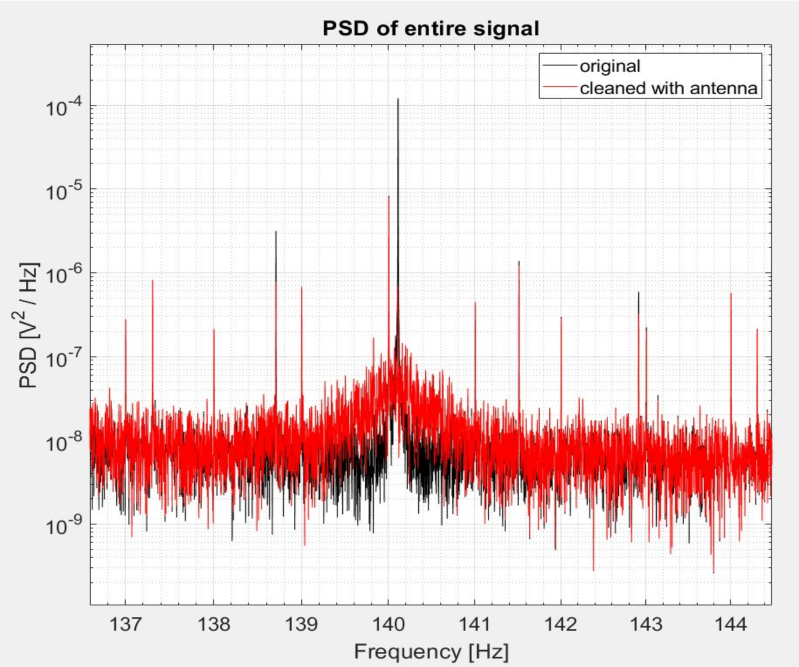
NTD Power Spectrum Before and After LNC

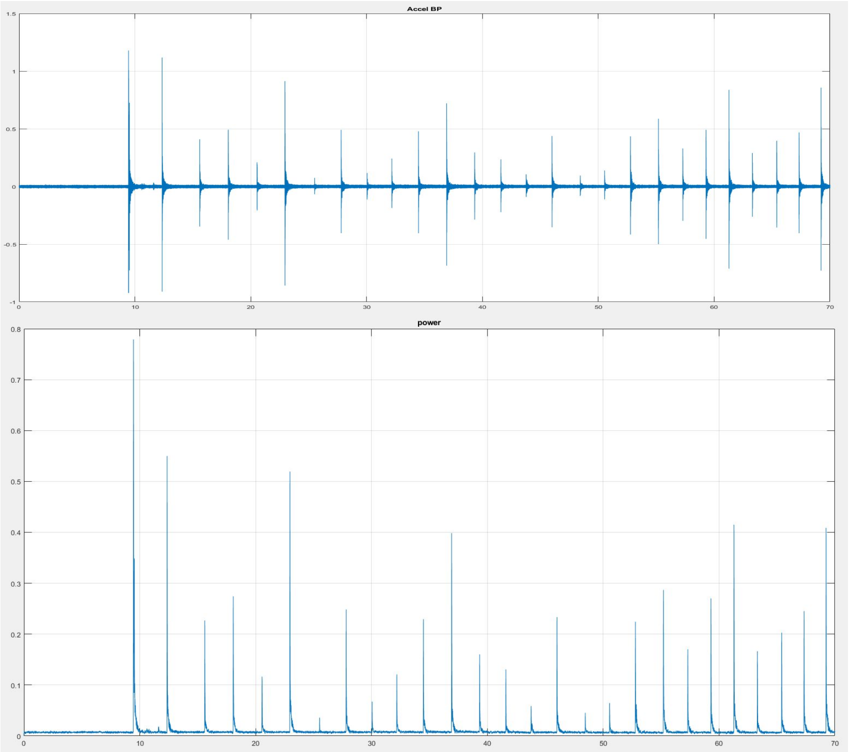




Modifying the Original ANC Algorithm

There exists a better proxy for power transmitted to the bolometer than simply squaring the accelerometer wave function. Instead, we can run it through an *RMS filter.*

Take the accelerometer timestream from t = t′ to t = (t′ - t'_0) and compute the RMS. This is of course a positive definite quantity.



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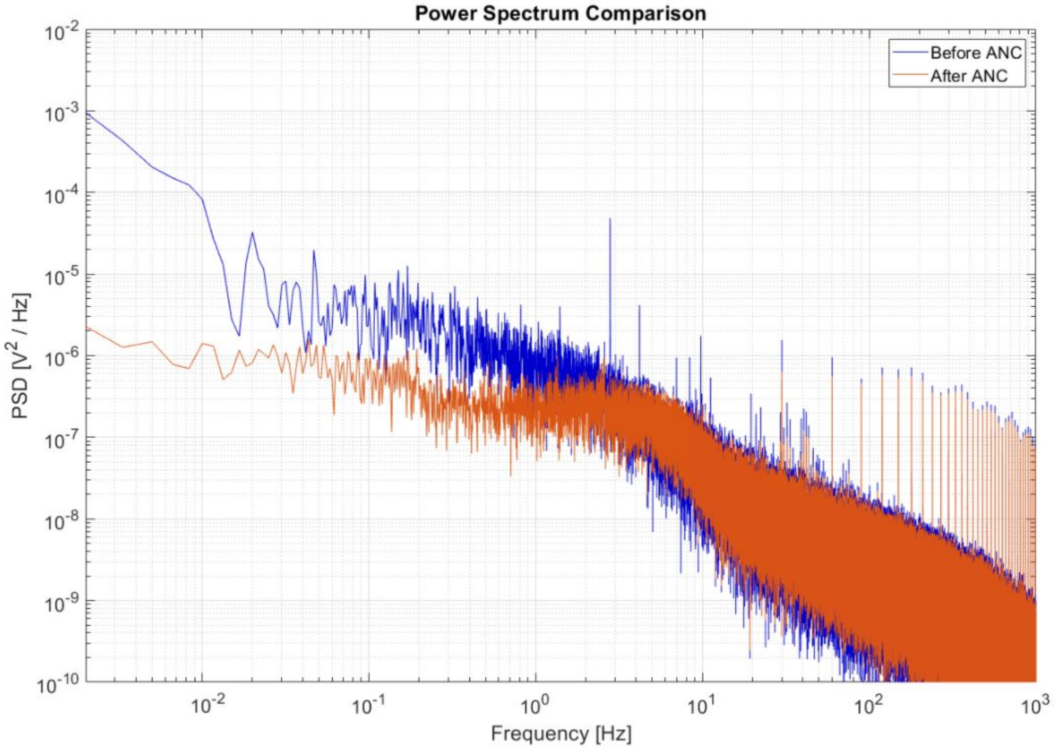
TES Power Spectrum Before and After ANC



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