Denoising Algorithms for the CUORE Experiment

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CUORE

Project Goals

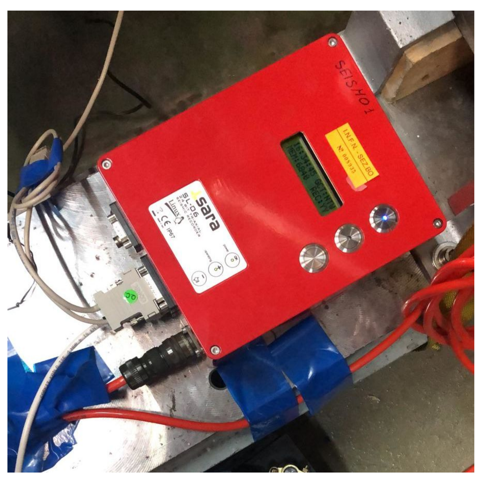
The Cryogenic Underground Observatory for Rare Events (CUORE) experiment is an ongoing search for neutrinoless double beta decay located at the Gran Sasso National Laboratory in Italy. Our previous work has suggested that the quality of CUORE data can be improved by the use of noise decorrelation algorithms using data from auxiliary devices including microphones and accelerometers. Here we discuss the implementation of these algorithms in the CUORE analysis framework and showcase the results of the noise decorrelation including the impact on the energy resolution of the CUORE detector across multiple channels. We also show that these denoising algorithms can be expanded to model non-linear systems and how these expansions improve the performance of the noise decorrelation algorithms for the CUORE detector.

Auxiliary Devices Used in CUORE

To measure vibrational and electrical noise, we install several devices around the CUORE cryostat. All of these devices operate at room temperature and are read out to the CUORE DAQ system. They are digitized simultaneously with the CUORE detector channels at a sampling frequency of 1 kHz.

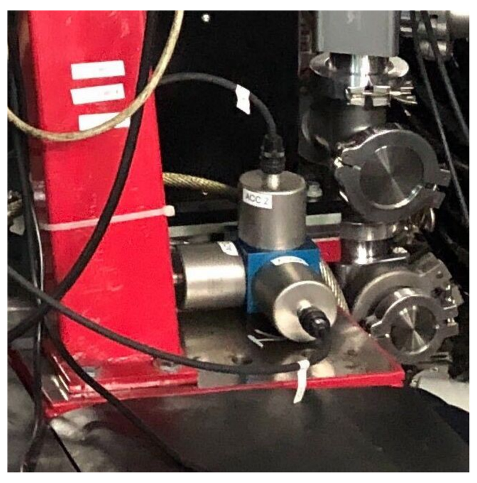
Seismometers:

- Triaxial Sara Electronics SS-01 seismometer mounted to the CUORE suspension system
- 400 V/(m/s) sensitivity
- Sensitive to frequencies between 0.1 and 50 Hz, covering the most important part of the CUORE detector signal band
- Measures signals from structural resonances, microseisms, and sea storm activity in the Tyrrhenian and Adriatic Seas



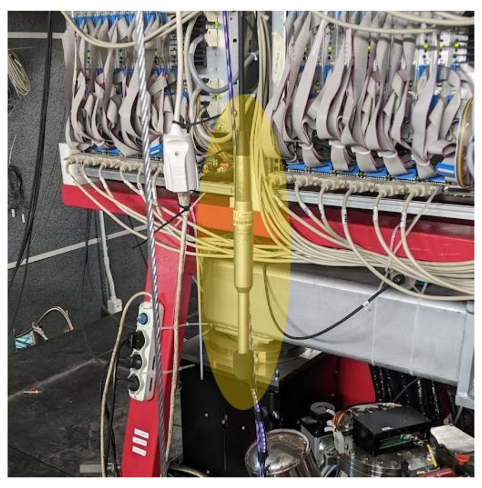
Accelerometers:

- PCB 393B31 accelerometers installed on the main support structure of the CUORE cryostat
- 10 V/(m/s^2) sensitivity
- Sensitive to frequencies between 0.1 and 200 Hz, which covers almost all of the CUORE detector signal band
- Signals are amplified with a PCB 482C15 signal conditioning pre-amplifier



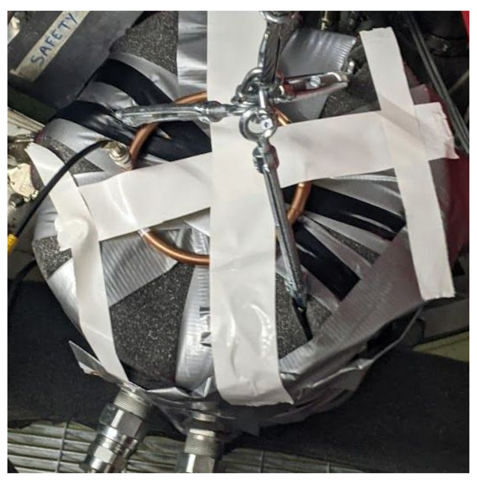
Microphones:

- Four Behringer ECM8000 measurement microphones installed around the CUORE faraday cage
- Sensitive to frequencies from 20 Hz to 2 kHz
- Poor signal quality in the main regions of the CUORE signal band
- Still useful for monitoring noise conditions in the Faraday cage and identifying noise transients



Antennas:

- AH Systems SAS-560 loop antennas placed around each of the four active pulse tubes used in the CUORE experiment
- Two AH Systems SAS-565L loop antennas measure the ambient electrical noise in the CUORE faraday cage
- Measure electrical noise with high sensitivity without needing amplification
- Most prominent electrical noise occurs at 50 Hz and harmonics, falling mostly outside the CUORE signal band



Overview of the Algorithm

1. Create a matrix of spectral densities of the auxiliary devices at each frequency:

$$G_{ij} = \langle X_i^*[f]\, X_j[f] \rangle$$

2. Create a vector of cross-spectral densities between the detector and the auxiliary devices:

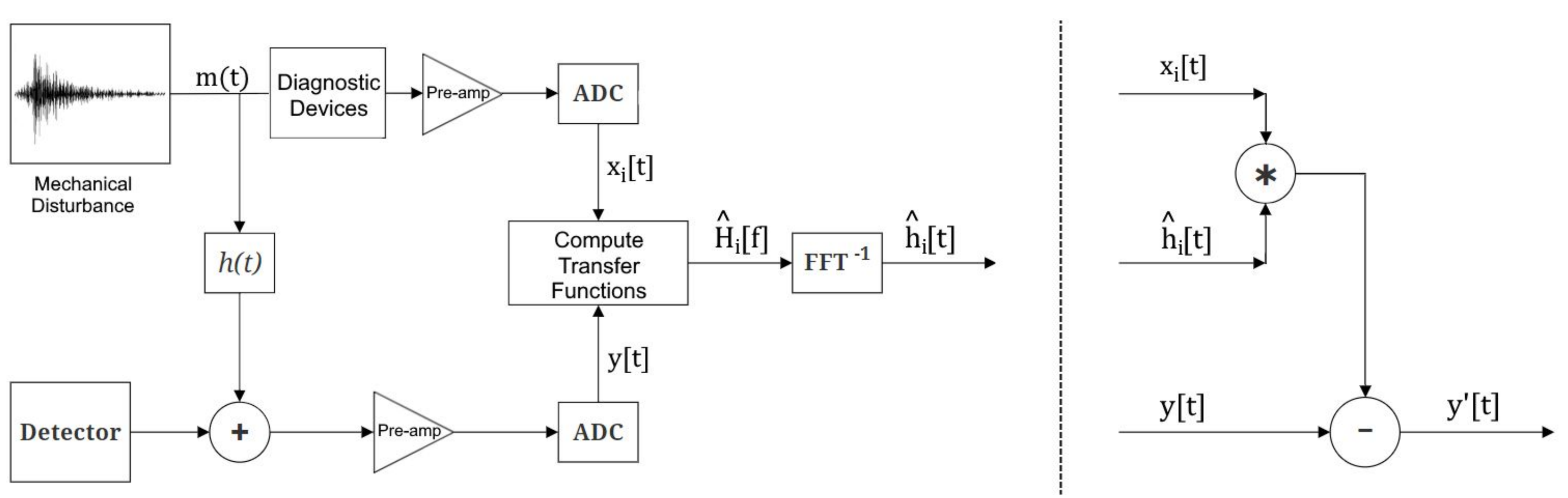
$$G_{iy} = \langle X_i^*[f]\, Y[f] \rangle$$

3. Calculate the transfer function $H_{x_i y}$ by inverting the $G_{x_i x_j}$ matrix:

$$H_{iy} = G_{ij}^{-1} G_{jy}$$

4. Predict the detector noise by filtering the auxiliary device signal with the transfer function:

$$Y_p = H_{iy}^T X_i$$



Acknowledgements

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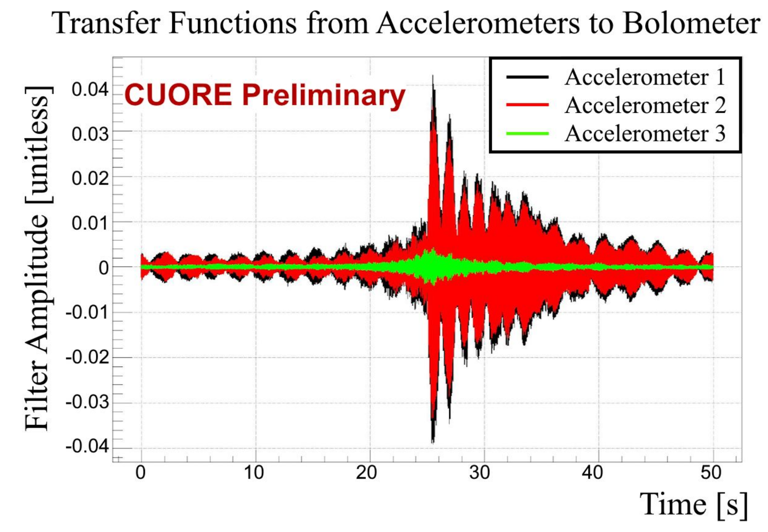
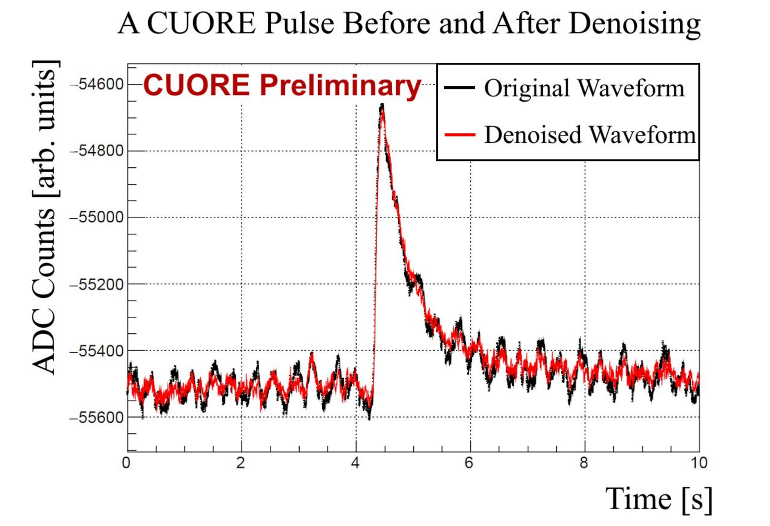
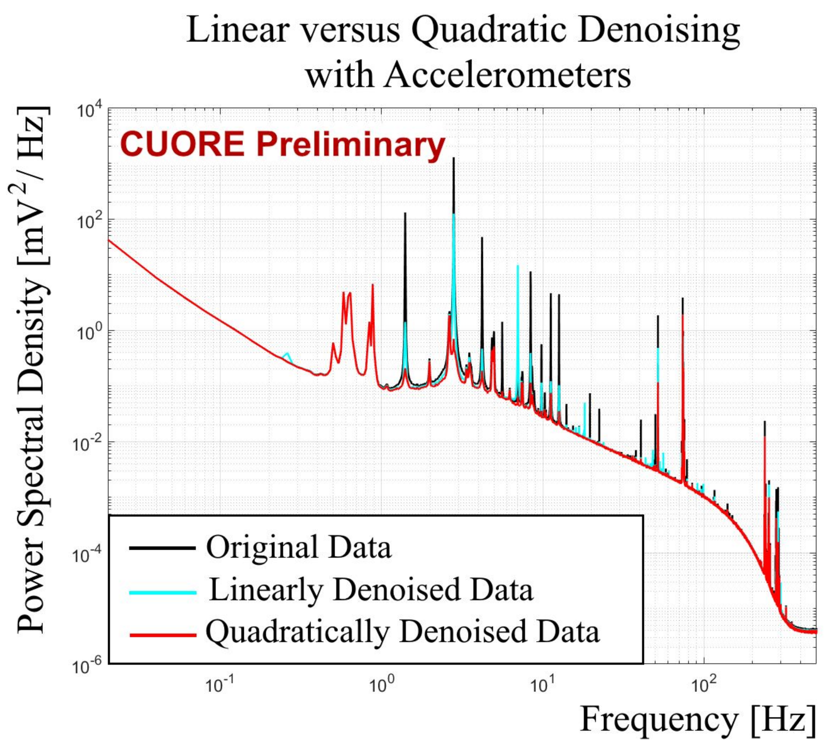
Outputs of the Algorithm

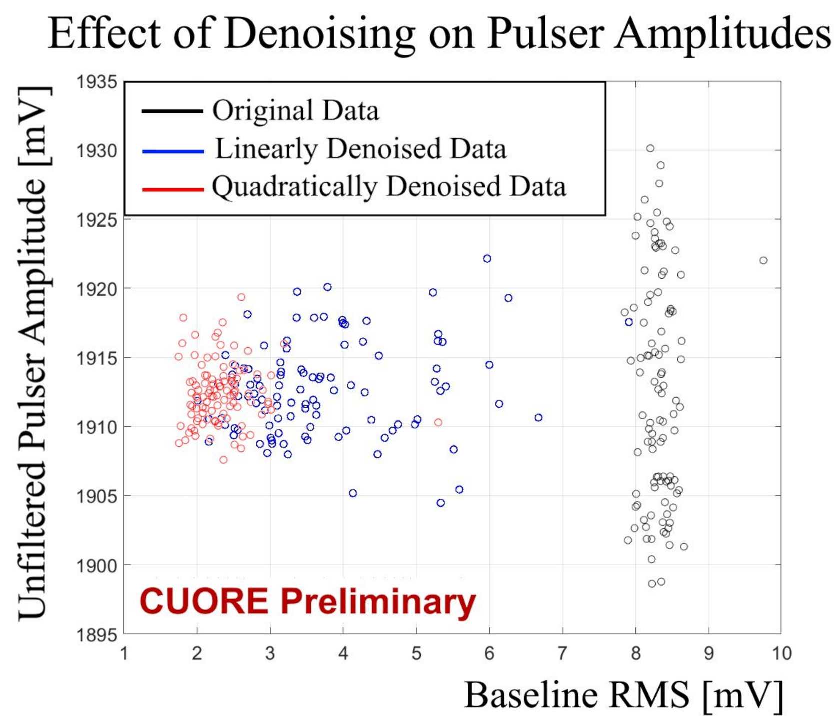




Nonlinear Extension of the Algorithm

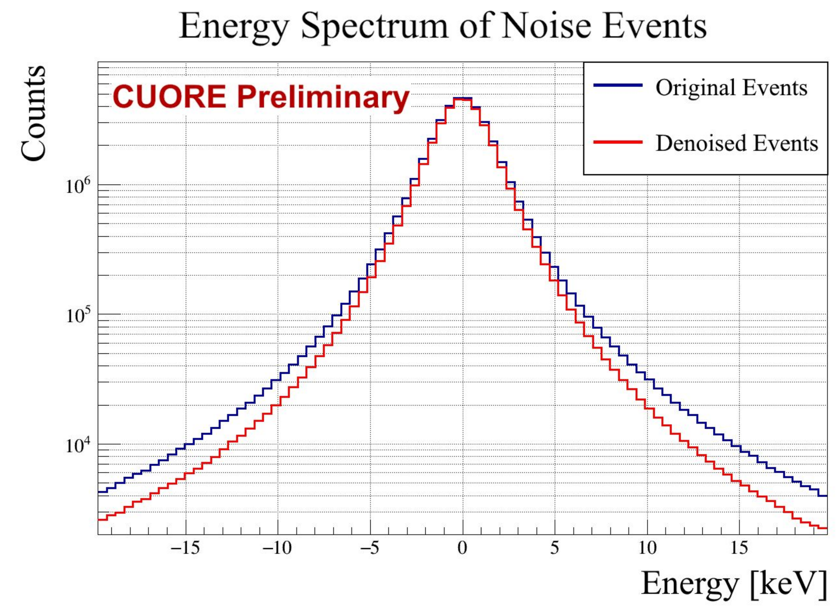
Thermal detectors like those in used CUORE are expected to exhibit a non-linear response to vibrations. The response of a thermal detector should be the same regardless of the directionality of the signal, thus the thermal response to bipolar vibration signals should have a unipolar thermal component along with a potential bipolar capacitive pickup term. This suggests that we can expand the model by including the squares of the auxiliary devices as additional auxiliary signals. This technique further reduces the detector noise, and the denoising is more consistent over time.



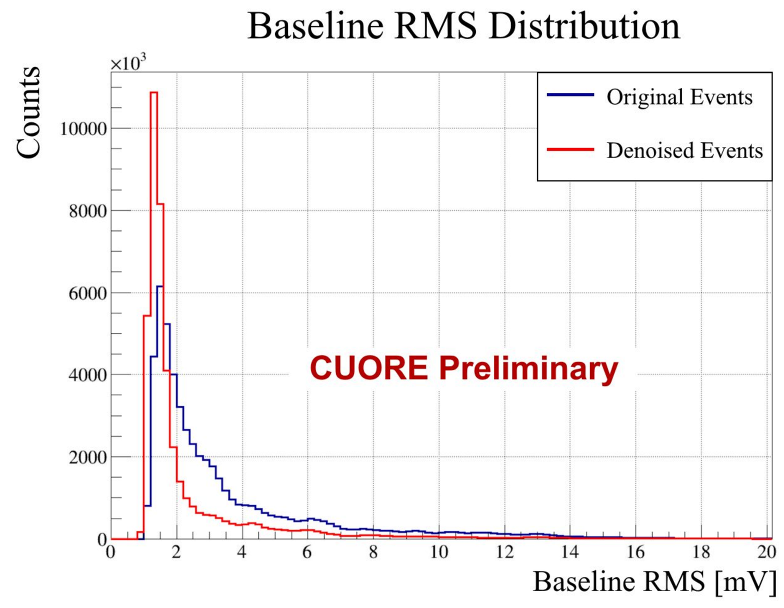


Effects of the Algorithm on the Entire CUORE Detector

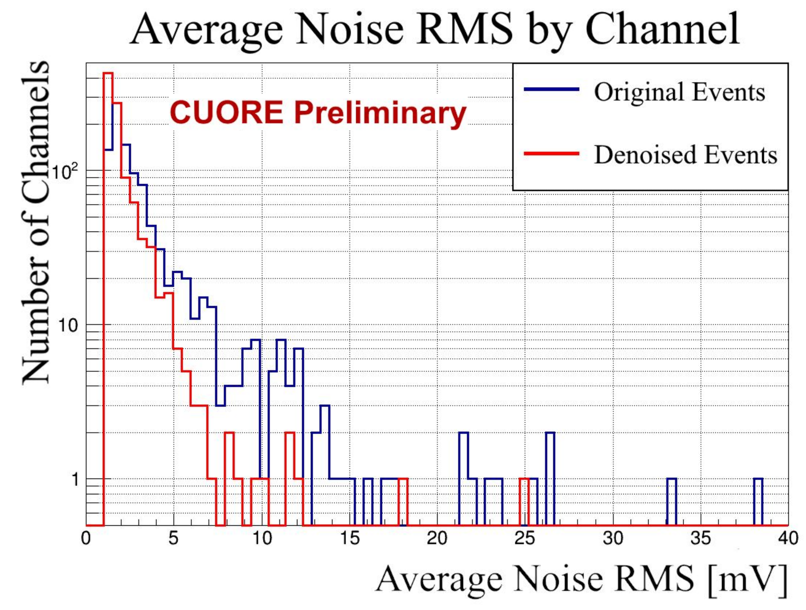
Having validated the algorithm and its nonlinear extension on a single CUORE channel, we implement the algorithm in the CUORE analysis framework, DIANA. Using a single dataset of CUORE data (approximately two months of data-taking), we compare different quantities related to the noise of the detector before and after denoising. For this particular dataset, we decorrelate the noise against the accelerometer signals and their squares.



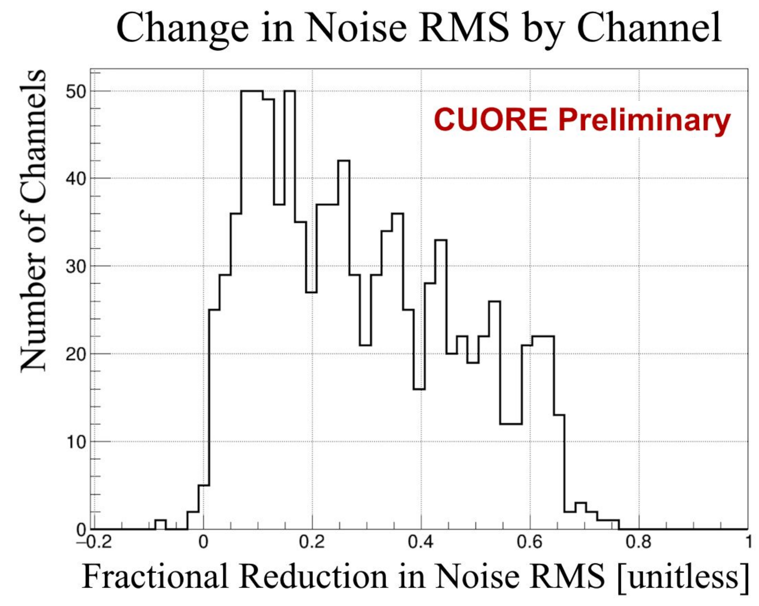
Original Noise RMS: 2.72 keV
Denoised Noise RMS: 2.43 keV



Original Average Baseline RMS: 4.12 mV
Denoised Average Baseline RMS: 2.77 mV



Original Mean Noise RMS: 3.35 mV
Denoised Mean Noise RMS: 2.01 mV



Average Reduction in Noise RMS: 39.6%
Median Reduction in Noise RMS: 25.8%

Future Work

Work is ongoing to analyze the effect of denoising the data from the entire CUORE data-taking campaign using various combinations of microphones, accelerometers, antennas, and seismometers. In the future, we hope to develop a more robust model of the thermal response to vibrations in the CUORE detectors. We are also looking into the use of adaptive algorithms which may further reduce noise due to transient effects such as earthquakes. Noise decorrelation algorithms like the ones illustrated here will be essential to future experiments such as CUPID.

Special Thanks

Thanks to Dr. Steven M. Kay for his guidance and suggestions regarding the spectral analysis of nonlinear systems as well as Dr. Arnaud Allézy for his work on modeling the vibrational modes of the CUORE cryostat.