LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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Data Acquisition and Signal Processing for the GQuEST Experiment

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1 Introduction

1.1 GQuEST

Theoretically, the quantum nature of gravity is expected to stochastically produce "geontropic" space-time fluctuations, or geometric fluctuations in space-time due to entropy [1]. The gravity from the quantum entanglement of space-time (GQuEST) experiment aims to detect these space-time fluctuations as evidence of quantum gravity. GQuEST will use a Michelson interferometer with 7 m long arms and a 1550 nm frequency-stabilized laser with a superconducting nanowire single-photon detector (SNSPD).

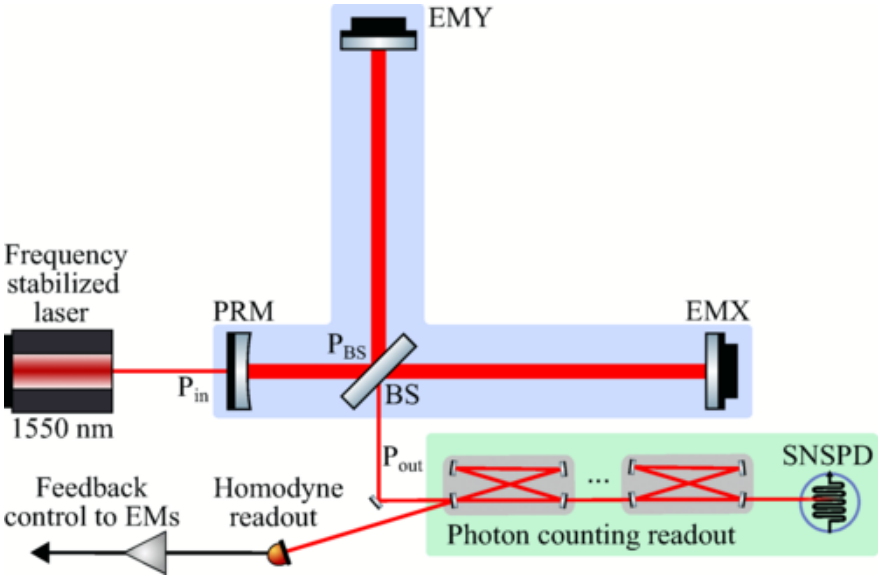


Figure 1: Simplified GQuEST experimental design [2].

The SNSPD will be used in addition to homodyne measurements to get a more precise readout not subject to the limit from photon shot noise. In homodyne, the system measures the signal times the local oscillator and retains phase information, an important metric for LIGO when measuring gravitational waves. Photon-counting filters out the local oscillator and removes phase information. GQuEST will be measuring what is believed to be the stochastic and broadband signal of spacetime fluctuations, meaning phase measurements are no longer necessary. Instead GQuEST will measure an optical power at the IFO output which corresponds to spacetime fluctuation amplitude. These fluctuations are theorized to occur at a specified frequency (roughly 17MHz) where the experimental and background noise is at a minimum [2].

The GQuEST experiment is motivated by recent geontropic quantum gravity models which suggest that space-time is emergent from quantum entanglement. In these models, the volume of space-time is not a smooth continuum but contains a fundamental graininess linked to the information density on its boundary. These fluctuations are predicted to accumulate over macroscopic distances, manifesting as a stochastic "metric noise".

By measuring the cross-correlation between two independent interferometers, we can remove shot noise and examine any classical noise sources and systematic errors. The introduction of SNSPDs is a critical advancement; we will coherently combine light from two interferometers and use an individual photon-counting readout. This way, the experiment can extract Fisher information regarding the path-length fluctuations much more efficiently than traditional homodyne systems, effectively bypassing the Standard Quantum Limit (SQL) [2].

1.2 Cross-Correlation

Cross-correlation allows us to measure two signals and remove uncorrelated signals (e.g., quantum shot noise) while keeping correlated signals (e.g., amplitude fluctuations due to real spacetime fluctuations). GQuEST's homodyne detection system will use two photodetectors routed to two channels in the ADC, where the data is digitized, windowed, and Fast Fourier Transforms (FFTs) are performed. For a continuous function, the cross correlation is found by

$$(f \star g)(\tau) = \int_{-\infty}^{\infty} (f^*(t) g(t+\tau)) dt \tag{1}$$

where τ is the time lag or displacement between the two signals.

GQuEST's signal processing system will use the cross-spectral density (CSD) to get frequency information. This is equivalent to the Fourier transform of the cross-correlation:

$$\begin{aligned}
S_{XY}(f) &= \mathcal{F}(f \star g)(\tau) && (2)\\
&= \int_{-\infty}^{\infty} \left(\int_{-\infty}^{\infty} f^*(t)\, g(t+\tau)\, dt \right) e^{-2i\pi f\tau}\, d\tau && (3)\\
&= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f^*(t)\, g(t+\tau)\, e^{-2i\pi f\tau}\, dt\, d\tau && (4)\\
&= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f^*(t)\, g(u)\, e^{-2i\pi f(u-t)}\, dt\, du \qquad \text{(substitute } u = t+\tau\text{)} && (5)\\
&= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f^*(t)\, g(u)\, e^{-2i\pi fu}\, e^{2i\pi ft}\, dt\, du && (6)\\
&= \left(\int_{-\infty}^{\infty} f^*(t)\, e^{2i\pi ft}\, dt \right) \left(\int_{-\infty}^{\infty} g(u)\, e^{-2i\pi fu}\, du \right) && (7)\\
&= \left(\int_{-\infty}^{\infty} f(t)\, e^{-2i\pi ft}\, dt \right)^* \left(\int_{-\infty}^{\infty} g(u)\, e^{-2i\pi fu}\, du \right) && (8)\\
&= F^*(f)\, G(f) && (9)
\end{aligned}$$

We use $\tau = 0$ because we expect any real signal to be in phase between the two photodetectors. The real data consist of a discrete number of FFTs, and are integrated over a finite number of frames so the CSD is

$$S_{XY} = \frac{1}{N}\sum_{i=1}^{N}(F_i^*(f)G_i(f)) \tag{10}$$

The data acquisition system allows us to choose the FFT window length Δt, and each FFT is saved as a "frame." The data is then accumulated and averaged into "superframes" with a certain overlap (usually 50 % per Welch's Method) between frames.

2 Objectives

The initial goals in the first seven weeks of this project were:

- To test a modified photodiode's frequency response and replicate the modifications on a second photodiode for use in cross-correlation measurements.
- To create data acquisition code based on the code from the Holometer experiment.
- To measure the ADC's cross-correlated noise floor.
- To measure the laser noise at 17 MHz.

3 Approach

3.1 Photodiode modifications

My advisor modified a Thorlabs PDA05CF photodetector to be able to receive higher power by adding an inductor/resistor pair to lower the voltage gain (approximately 0.1 the initial value) at DC, while retaining high gain at RF. I replicated these modifications to a second photodiode to use for cross-correlation measurements.

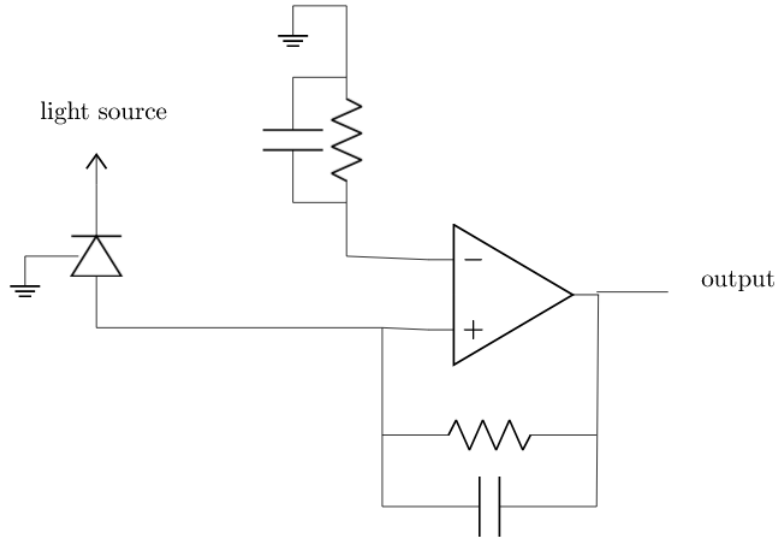


Figure 2: unmodified photodetector board schematic

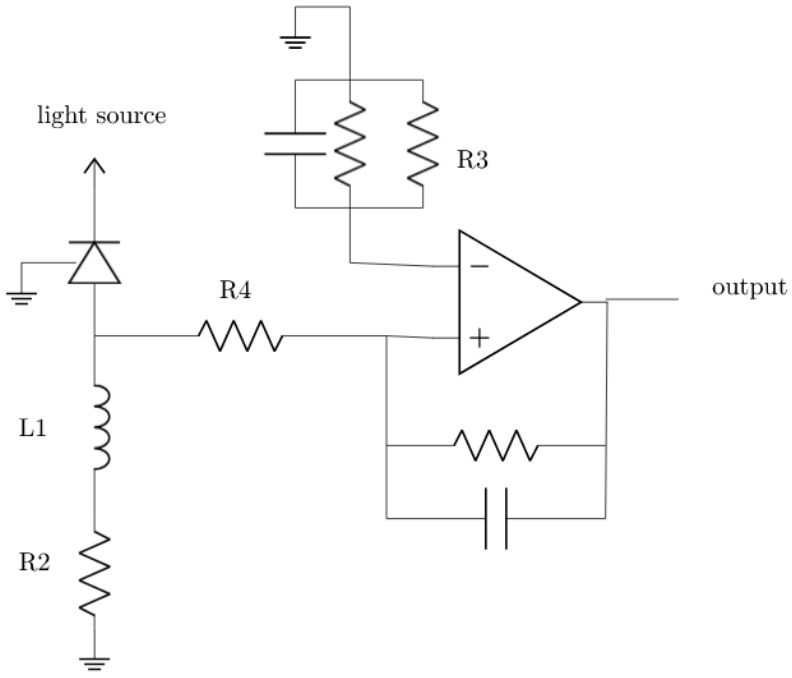


Figure 3: modified photodetector board schematic

I measured the actual inductance and resistance of the added components in both photodetectors:

Based on the alterations, we theoretically expect to see a decrease in voltage gain at DC.

Component	Expected value	Measured value (photodetector A)	Measured value (photodetector B)
L_1	10μH	10.5μH (0.6Ω)	10.7μH (0.8Ω)
R_2	4.7Ω	6.1Ω	6.4Ω
R_3	51Ω	49.7Ω	52.2Ω
R_4	51Ω	50.5Ω	53.8Ω

Table 1: Expected vs measured inductance and resistance of added components

For the expected values, the ratio of the voltage gain of a modified detector at DC to the voltage gain of an unmodified detector at DC is:

$$\frac{V_{mod}}{V_{unmod}} = \frac{R_1 + R_2}{R_4} \tag{11}$$

$$= \frac{4.7}{51} \tag{12}$$

$$= 0.092 \tag{13}$$

For photodetector A, this ratio is actually

$$\frac{R_1 + R_2}{R_4} = \frac{6.1 + 0.6}{50.5} \tag{14}$$

$$= 0.133 \tag{15}$$

For photodetector B, this ratio is actually

$$\frac{R_1 + R_2}{R_4} = \frac{6.4 + 0.8}{53.8} \tag{16}$$

$$= 0.134 \tag{17}$$

3.2 Photodiode Characterization

I built a circuit to use to test the frequency response of the original modified photodiode and compare it to an unmodified model. We need to characterize these photodiodes for future use in quantifying laser and mechanical noise in the interferometer and filter cavities for fine tuning the GQuEST experiment.

I used a bias tee circuit to power an LED. I built the circuit on a breadboard, powered with 6-8 V DC, and initially tested the circuit outputs on various inputs using a Siglent

oscilloscope and a Moku Go. The photodiode showed a peak at the moduilation frequency with 400 mVpp - 1 Vpp. I attempted to use a 1550 nm (Thorlabs LED1550L), 780 nm (Thorlabs LED780L), and 570 nm LED on the photodiode to get the frequency response function, but switched to a 685 nm laser diode (Thorlabs HL6750MG) for a stronger output signal.

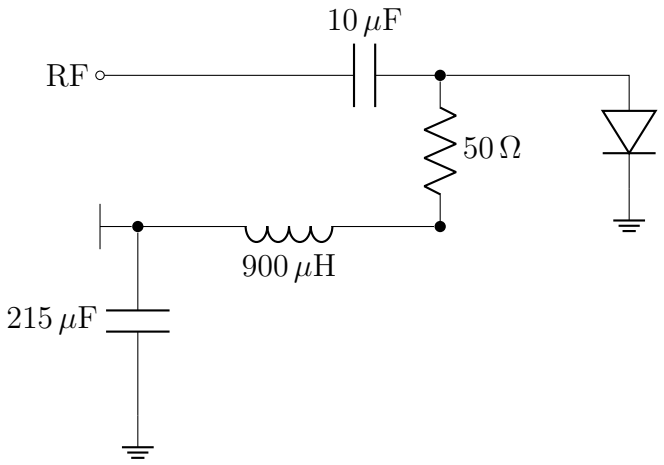


Figure 4: Bias tee circuit used to modulate 685 laser diode

The photodiode used is an Indium Gallium Arsenide (InGaAs) fixed gain amplified detector. The frequency response was tested using the same circuit powered with 8 V DC (with 100 mA current limit) and swept from 1 kHz to 10 MHz with 1 Vpp AC.

The frequency response function of the modified photodiode and an unmodified photodiode confirmed the expected results. At DC, the modified photodiode is theoretically expected to have around 0.1 the amplitude of the unmodified one, while they perform similarly at high frequencies.

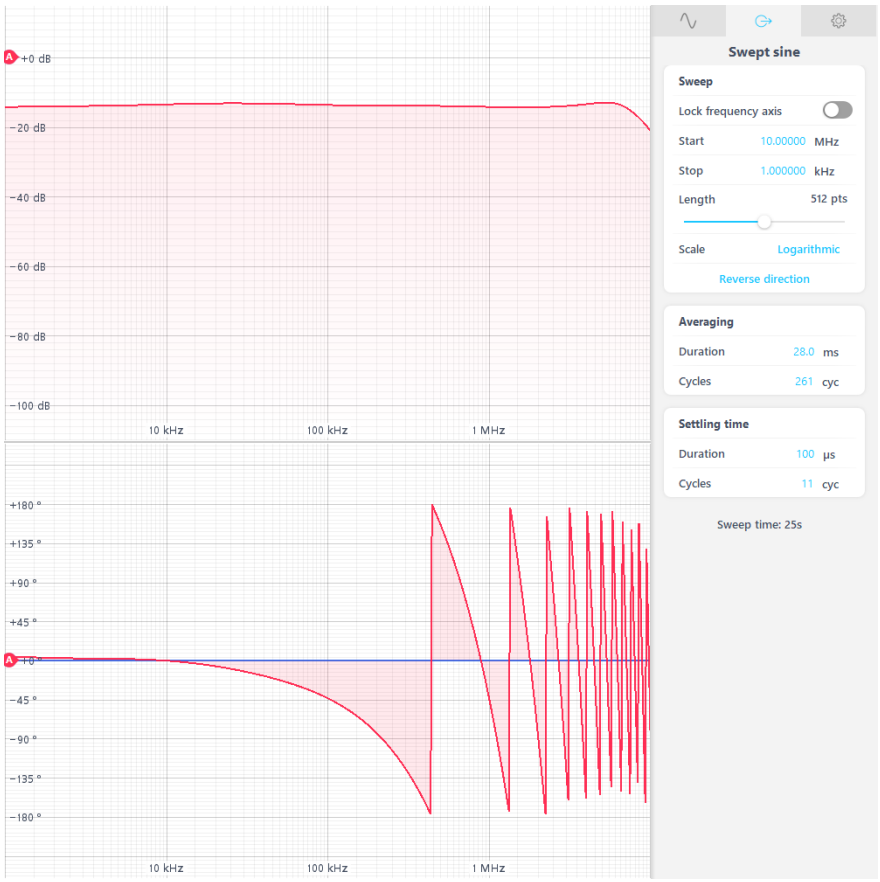


Figure 5: Frequency response of unmodifed photodiode

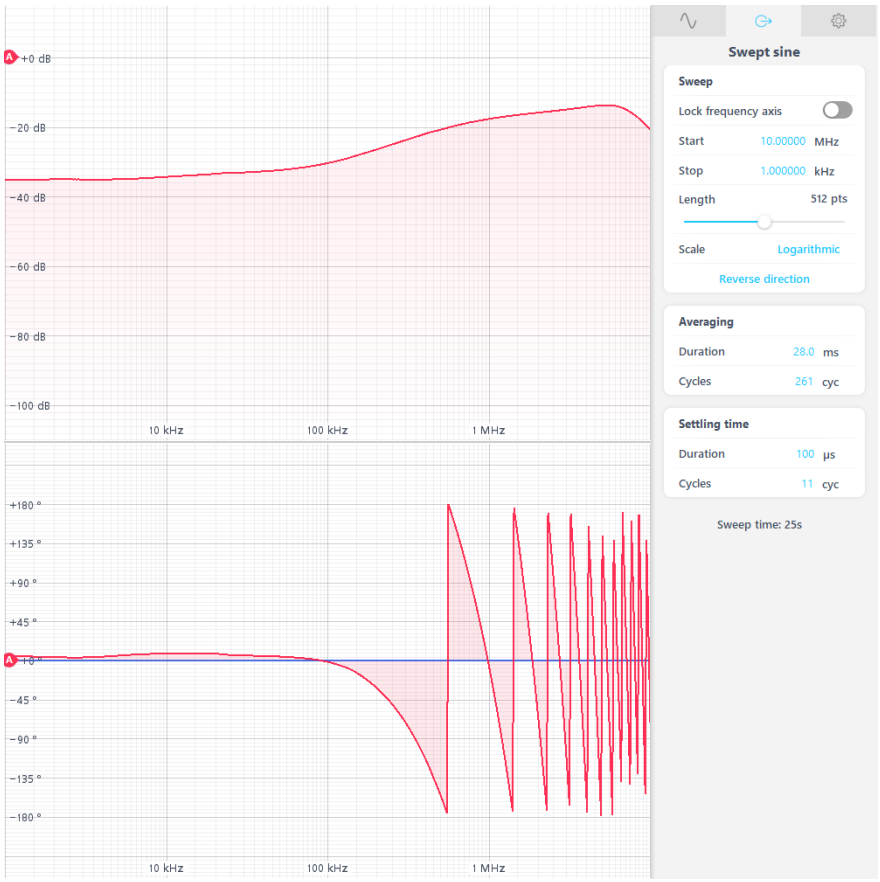


Figure 6: Frequency response of modified photodiode

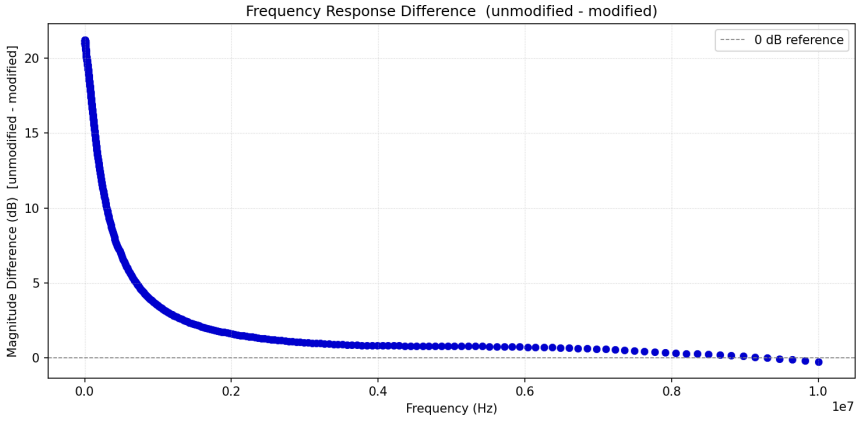


Figure 7: Difference between frequency response of unmodifed and modified photodiode

Figure 6 clearly shows that the modified photodiode has 20 dB lower amplitude (10%) than the unmodified at DC, but the two remain within 1 dB at high frequency.

Furthermore, I compared modified photodetector A with modified photodetector B, which revealed that photodetector B had lower voltage gain across all frequencies. However, the

two were mostly within 2 dB, which is a reasonable difference which we can account for during cross-correlation.

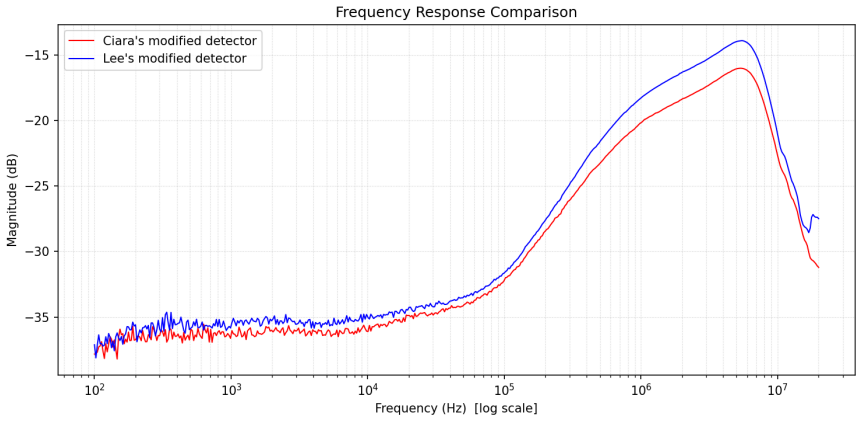


Figure 8: Frequency responses of both modified photodiodes

3.3 Data Acquisition System

GQuEST's data acquisition code is modelled after that of the Holometer experiment [3]. I spent most of Week 3 attempting to modify the existing C++ and Python code from the Holometer experiment to interface with GQuEST's 4-channel, 16Bit, 125 MS/s per channel digitizer from Advantech.

The photodetector measures the incident power of the light as a voltage, and the digitizer discretizes the data by sampling at a given frequency (80 MHz). The program then windows the data to perform Fourier transforms; ∼0.655ms FFT window time for the gives $N \approx 66,000$, as used for the Holometer [3]. This gives a FFT based on N points. Each FFT constitutes one frame. Assuming the signal is stationary, we process the data using these frames and then average to get the final results.

Given that GQuEST is looking for signals on the order of MHz, it needs to have a MHz sampling rate, which results in an enormous rate of data acquisition which is unfeasible to store. As a result, we will store only time-averaged spectra, which are calculated in real time.

After obtaining the N frames, we apply a Fourier transform. First, we apply the Hanning window function to attenuate the ends of the frame in order to reduce spectral leakage[4]:

$$\omega_n = \frac{1}{2}[1 - \cos(\frac{2\pi n}{N})] \tag{18}$$

Next, we perform a Fast Fourier Transform on the data and average over all frames. We can then store the resulting averaged vectors in a covariance matrix, where the diagonal

elements represent the time-averaged power spectrum of each channel and the off-diagonal elements represent the time-averaged cross-correlations between channels [3]. The matrix is symmetric so we can set the lower triangular elements to 0.

Each matrix contains 4 real diagonal elements, each 64 bits or 8 bytes. The 6 complex off-diagonal elements are represented by 2 floating point numbers, so require 16 bytes. This means each matrix requires 128 bytes of storage.

Based on the sampling rate and integration time, the number of samples is:

$$N = 100 \text{ MHz} \times 0.655 \text{ ms} \approx 66,000 \tag{19}$$

And therefore the number of frequency bins is:

$$\#\text{ frequency bins} = \frac{N}{2} \approx 33,000 \tag{20}$$

Therefore the amount of data for each frame is:

$$128 \text{ bytes} \times 33,000 \text{ per frame} = 4,224,000 \text{ bytes/frame} \approx 4 \text{ MB/frame} \tag{21}$$

This is a significant amount of data, so we must determine how often to save a frame in order to preserve storage space. Waiting at least one second between saves to maintain 4 MB/s or lower data rate is a reasonable limitation. The raw data rate of 6.4×10^9 bits/s is roughly equal to 800 MB/s, so this offers roughly 200-fold compression.

This process will reduce the total data footprint substantially, allowing for long-term integration without exceeding storage limits. In order to process the data as fast as it is collected, the program must perform FFTs as fast as each frame takes, which is equal to the integration time of $\sim$0.655ms. Therefore, the program must be optimized, and the limits of the hardware and the program speed (specifically, FFT calculation) must be taken into account when determining the integration time.

I spent most of Week 3 reading the Advantech ADC data acquisition code and the Holometer data acquisition and signal processing code to understand the data flow in each system and how to interface the two.

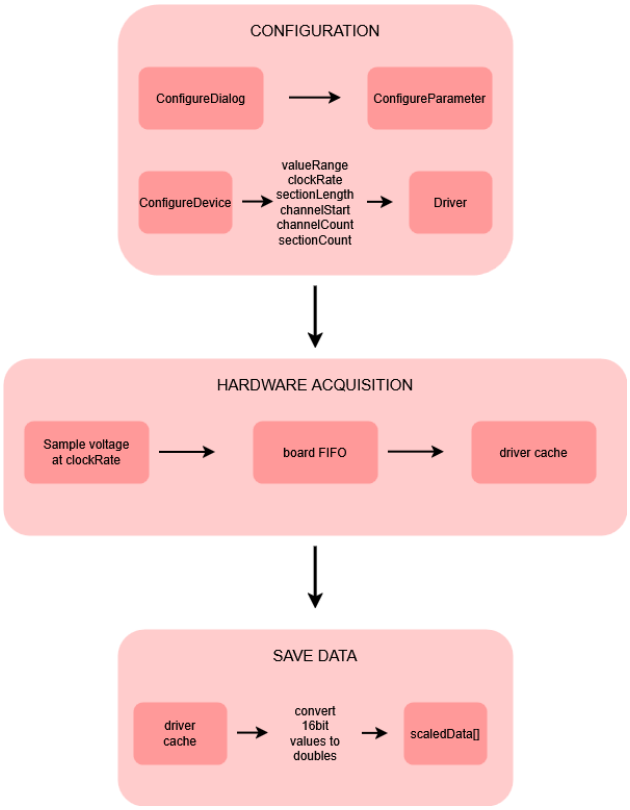


Figure 9: Adventech ADC data acquisition

Essentially, the Advantech code provides a prebuilt system for analog input data acquisition. This allows the user to edit the number of channels and the sampling rate used, which is then sent to the hardware. The voltages are sampled at the chosen clock rate and stored as 16-bit integers on the board, and then send to the computer where it is then converted into doubles and stored in an array. For our purposes, we will actually leave the voltages as 16-bit integers, as the signal processing code takes 16-bit integers as input.

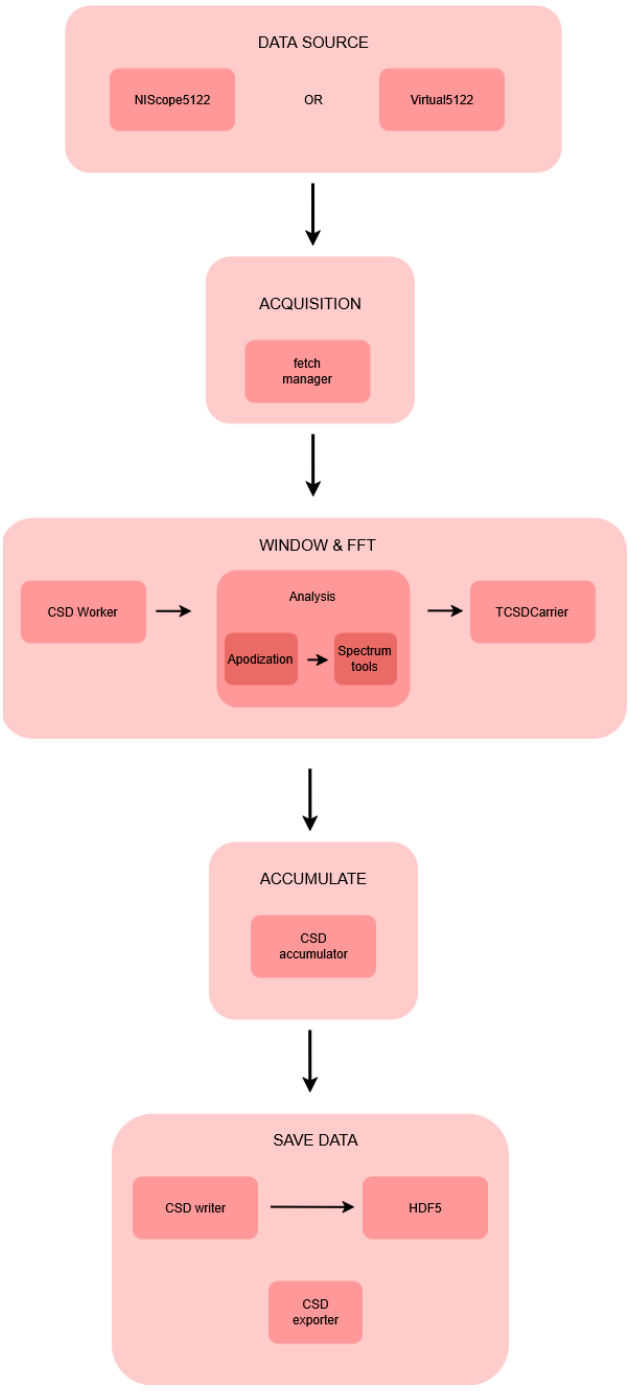


Figure 10: Fermilab Holometer data acquisition and signal processing

The signal processing code takes voltage values (either from a real ADC or simulated source), where it is windowed (apodization) and FFTs are performed (spectrum tools). Then, it is accumulated and saved.

We built a new data source into the Holometer data acquisition code for GQuEST's Advan-

tech ADC. This mimicked the NIScope5122 data source while also implementing all of the necessary hardware configuration from Advantech's existing analog-in code.

Furthermore, we added additional files to the system to adjust configurable settings such as AC/DC coupling, impedance, voltage range, and runtime.

3.4 ADC noise floor characterization

We need to know the cross-correlated electronic noise floor of the ADC before using it for any real measurements. I first calcultated the theoretical noise floor to determine how long we needed to run the system to resolve the noise floor.

3.4.1 Theoretical Noise Floor and Required Runtime

Correlated noise floor as a function of time:

$$\langle S_{CSD} \rangle_{t\to\infty} = S_q^{\text{corr}} \tag{22}$$

$$\langle S_{CSD} \rangle(t) = \frac{\sqrt{S_0 S_1}}{N_{\text{avg}}(t)} + S_q^{\text{corr}} \tag{23}$$

Quantization noise:

$$\sigma_q = \frac{V_{\text{pp}}}{\sqrt{12} \times 2^{N_{\text{bits}}}} \tag{24}$$

with $N_{\text{bits}} = 16$. Theoretical noise floor given quantization noise:

$$\sigma_q^2 = \int_{-\frac{\Delta f}{2}}^{\frac{\Delta f}{2}} S_q(f) df \tag{25}$$

$$= \int_{0\ \text{Hz}}^{40\,\text{MHz}} S_q(f) df \tag{26}$$

$$= S_q \times 40\,\text{MHz} \tag{27}$$

And for $\gamma = (0, 1)$, the cross-correlated noise is:

$$S_q^{\text{corr}} = \gamma\sqrt{S_{q0}S_{q1}} \tag{28}$$
$$= \gamma S_q \tag{29}$$

The theoretical noise floor of each channel is:

$$S_q^{\text{corr}} = \frac{\sigma_q^2}{40\,\text{MHz}} \tag{30}$$
$$= \frac{(\frac{V_{\text{pp}}}{\sqrt{12}\times 2^{N_{\text{bits}}}})^2}{40\,\text{MHz}} \tag{31}$$
$$= \frac{V_{\text{pp}}^2}{12\times 2^{32}\times 40\times 10^6\ \text{Hz}} \tag{32}$$

We are using the ADC with a voltage range of $-1\,\text{V}$ to $1\,\text{V}$, therefore the ADC noise floor is estimated:

$$S_q = \frac{(2\,\text{V})^2}{12\times 2^{32}\times 40\times 10^6\ \text{Hz}} \tag{33}$$
$$= 1.940\times 10^{-18}\ \text{V}^2/\text{Hz} \tag{34}$$

Depending on the factor γ, the correlated value could be much smaller. To properly resolve this, we would like $\frac{\sqrt{S_0S_1}}{N}$ to be an order of magnitude less than S_q. The waveform generators we are using have a minimum possible σ_V of $1\,\text{mV}$.

$$\sqrt{S_0S_1} = S \tag{35}$$
$$= \frac{\sigma_V^2}{20\,\text{MHz}} \tag{36}$$
$$= \frac{(1\times 10^{-3}V)^2}{20\,\text{MHz}} \tag{37}$$
$$= 5\times 10^{-14}\ \text{V}^2/\text{Hz} \tag{38}$$

So to get $N_{\text{avg}} \geq (10)\frac{S}{S_q^{\text{corr}}}$:

$$N_{\text{avg}} \geq (10)\frac{S}{S_q^{\text{corr}}} \tag{39}$$

$$\geq (10)\frac{5 \times 10^{-14}\ \text{V}^2/\text{Hz}}{1.940 \times 10^{-18}\ \text{V}^2/\text{Hz}} \tag{40}$$

$$\geq 10 \times 25773.2 \tag{41}$$

$$\geq 257732 \tag{42}$$

Therefore, we will aim for 260,000 frames. If the FFT window time on the ADC code is set to around 100 ms with 50% overlap, the program collects 20 frames/s. Therefore, we must run the ADC and collect frames for 13,000 seconds, or around **3 hours and 37 minutes**. Then, we must average all 260,000 frames to resolve the true correlated noise floor. We will, however, run for significantly longer to ensure we resolve the noise floor even if the correlation factor γ is under 0.1.

4 17 MHz Laser Noise Measurement

Cross-correlating two interferomters theoretically eliminates all uncorrelated quantum and classical noise sources. However, both single photon counting and cross-correlated homodyne readout should be able to eliminate quantum shot noise even with a single interferometer, so the initial signals we will be reading will be dominated by classical noise sources such as laser noise. Since GQuEST is searching for signals at 17 MHz, we characterized the laser noise at this frequency.

We built a fiber optic Mach-Zehnder interferometer. One arm of the interferometer has a path length 5 m greater than the other. As a result, we will measure any frequency noise in the laser at 17 MHz as a phase difference in the two photodetectors.

It takes light 24.2 ns to travel 5 m in an optical fiber:

$$\tau = \frac{n \cdot \Delta L}{c} \tag{43}$$

$$= \frac{1.45 \cdot 5\text{m}}{3 \times 10^8\text{m/s}} \tag{44}$$

$$= 24.2\ \text{ns} \tag{45}$$

The period of a 17 MHz sine wave is 58.8 ns ($T = \frac{1}{f} = \frac{1}{17\times10^6}$). This is roughly 2 times the travel time of the interferometer arm difference, so it can resolve 17 MHz noise.

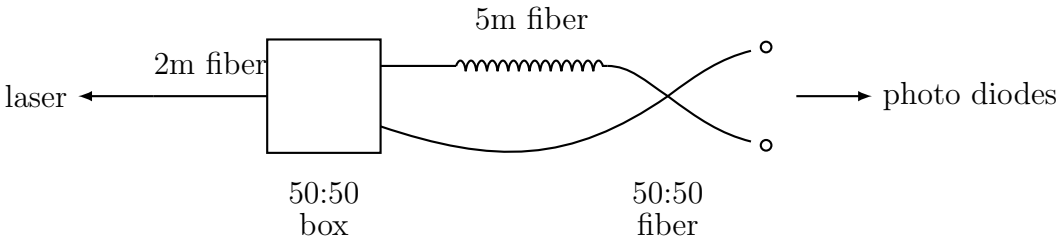


Figure 11: Mach-Zehnder interferometer with two 50:50 fiber couplers

5 Future Plan of Action

In the next few weeks, I plan to finish altering the data acquisition code and use it to help test the photodiode with a laser setup.

Week 8: Take a dark noise measurement of the cross-correlated photodetectors.

Week 9: Use the Mach-Zehnder interferometer to take a laser noise measurement.

Weeks 10: Use the ADC, photodetector, and laser noise measurements to quantify system noise floor. Streamline the data acquisition code.

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