LIGO SURF Project Plan: Data Acquisition and Signal Processing for the GQuEST Experiment

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1 Introduction

During this summer's LIGO SURF internship, I will be working in Dr. Lee McCuller's group to prepare for GQuEST Gravity from the Quantum Entanglement of Space-Time) experiments. GQuEST uses interferometry and photon-counting to detect geontropic space-time fluctuations, or fluctuations in space-time from entropy. This is a theoretical phenomenon which would indicate the existence of quantum gravity. This experiment uses infrared laser interferometry to detect signal fluctuations hypothesized to exist due to quantum gravity. While earlier experiments have operated in a similar manner, GQuEST also uses superconducting nanowire single-photon detectors (SNSPDs) 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, while photon-counting filters out the local oscillator to measure signal only.

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 aim to isolate this common space-time "shimmer" from the uncorrelated quantum shot noise inherent in individual detectors. The introduction of SNSPDs is a critical advancement; by counting individual photons, the experiment can extract Fisher information regarding the path-length fluctuations much more efficiently than traditional homodyne systems, effectively bypassing the Standard Quantum Limit.

2 Objectives

The primary goal of this project is to complete the hardware-software integration for the GQuEST experiment.

The experiment is designed to detect geontropic space-time fluctuations, providing evidence for quantum gravity, the confirmation of which would extend quantum mechanics further as a theory. Specifically, I will focus on:

- Developing a robust pipeline for high-bandwidth data ingestion.
- Optimizing spectral estimation routines to ensure low-latency processing.

3 Approach

The first step will be to adapt the Holometer data acquisition and signal processing code for GQuEST, based on the differences in technology and experimental design. I will be developing a data analysis system for the homodyne readout, which will operate in parallel to the photon-counting readout.

This program will use Fast Fourier Transform (FFT) to get a cross-spectral density (CSD) for cross-correlation analyis of the interferometer data. By performing these calculations while taking measurements, we can limit the storage space required. The legacy Holometer DAQ system successfully managed data rates of approximately 2.8 Tb/hr by utilizing real-time compression into cross-spectra. My work involves porting these capabilities to the current GQuEST architecture.

Furthermore, I will implement signal-to-noise-weighted averaging as described in the Holometer methodology. This involves dividing the time-stream into frames, applying windowing functions to minimize spectral leakage, and computing the variance of the CSD to establish rigorous error bars for potential signal detection.

Given the high sampling rates required to resolve causal time scales, data management is a primary constraint. The system will ingest raw voltage and pulse data, compute the CSD, and average the results over millions of frames.

I assume a sampling frequency of 100MHz to allow a maximum signal frequency of 50MHz, well above the GQuEST signal bandwidth of 36MHz [5]. This is the same as used in the Holometer[4]. I also assume a 16-bit ADC as used in the Holometer [2]. The Holometer used 4 separate cross-interferometer spectra, so I will assume 4 channels for the GQuEST experiment as well [3].

$$R = 100 \text{ MHz} \quad B = 16 \text{ bits} \quad N = 4 \tag{1}$$

Therefore, we can estimate the approximate amount of data incoming over time:

$$\begin{aligned} \text{rate of data acquisition } &= R \times B \times N && (2)\\ &= 100 \text{ MHz} \times 16 \text{ bits} \times 4 && (3)\\ &= 6.4 \times 10^9 \text{ bits/s} && (4)\\ &\approx 2.8\text{TB/hr} && (5) \end{aligned}$$

The photodetector registers voltages, and the program discretizes the data by creating frequency bins ($\sim$0.655ms integration time for the Holometer gave $N \approx 66,000$) [4]. Each of these bins constitutes one frame. Assuming the signal is stationary, we process the data using these frames and then average to get the final results.

After obtaining the N frames, we apply a Fourier transform. First, we apply the Hanning window function to attenuate the ends of the frame [1]:

$$\omega_n = \frac{1}{2}[1 - \cos(\frac{2\pi n}{N})] \tag{6}$$

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 [4]. 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:

$$N = 100 \text{ MHz} \times 0.655 \text{ ms} \approx 66,000 \tag{7}$$

And therefore the number of frequency bins is:

$$\#\text{ frequency bins} = \frac{N}{2} \approx 33,000 \tag{8}$$

Therefore the amount of data for each frame is:

$$128 \text{ bytes} \times 33,000 \text{ per frame} = 4,224,000 \text{ bytes/frame} \approx 4 \text{ MB/frame} \tag{9}$$

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 ∼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.

If successful, this project will provide the foundational software infrastructure required for GQuEST to achieve its design sensitivity. Detecting geontropic fluctuations would represent a paradigm shift in our understanding of gravity, providing the first experimental evidence that space-time has a quantum-mechanical origin. Even a null result would be significant, as it would place the tightest constraints to date on the scale of holographic noise in the universe.

4 Project Schedule

Weeks 1-2: I will familiarize myself with the program by reading the code and the details of the Holometer experiment.

Week 3: I will test the code using simulated data to better understand how it works.

Weeks 4-6: I will alter the program to adapt it to the hardware used for GQuEST, following the specifications and goals described above.

Weeks 7-10: I will test the setup, which will depend on the state of the system. If everything is going well, I will try to characterize the noise and attempt cross-correlation runs.

References

[1] Michael Cerna and Audrey F. Harvey. *The Fundamentals of FFT-Based Signal Analysis and Measurement*. Application Note 041. National Instruments, July 2000. URL: https://www.ni.com/.

[2] Aaron Chou et al. "The Holometer: an instrument to probe Planckian quantum geometry". In: *Classical and Quantum Gravity* 34.6 (2017), p. 065005. DOI: 10.1088/1361-6382/aa5e5c. URL: https://doi.org/10.1088/1361-6382/aa5e5c.

[3] Jonathan Richardson. *Holometer Data Processing Methodology*. Internal Working Note. The Quantum Exploration of Space Time Holometer project. Fermi National Accelerator Laboratory, Jan. 2015. URL: http://www.holo.fnal.gov/.

[4] Jonathan Richardson. *The Holometer Data Acquisition System*. Technical Document. Details the data processing computation performed by the Julie Stream data acquisition code. Fermi National Accelerator Laboratory, June 2013.

[5] Sander M. Vermeulen et al. "Photon-Counting Interferometry to Detect Geontropic Space-Time Fluctuations with GQUEST". In: *Physical Review X* 15.1 (2025), p. 011034. DOI: 10.1103/PhysRevX.15.011034. URL: https://doi.org/10.1103/PhysRevX.15.011034.

I discussed the project details with Dr. Sander Vermeulen and Alexander Ramirez, who will be overseeing my project. They described the technology and theory of the GQuEST experiment and the role I will be performing in the project.