GQuEST Control System Resolution

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Background

- Developing a quantum description of gravity is a major conundrum in physics, compounded with the challenge of verifying models due to the vastly different measurement scales of gravity and quantum mechanics.
- GQuEST (**G**ravity from **Qu**antum **E**ntanglement of **S**pace-**T**ime) is a collaboration seeking to verify the quantum gravity model proposed by Verlinde & Zurek.
  - From holographic principles, it is predicted that energy fluctuations of vacuum lead to detectable metric fluctuations, which is the pursued measurable [1].
- The apparatus is a highly sensitive Michelson-Morley interferometer with both homodyne readout and superconducting nanowire single-photon detection.

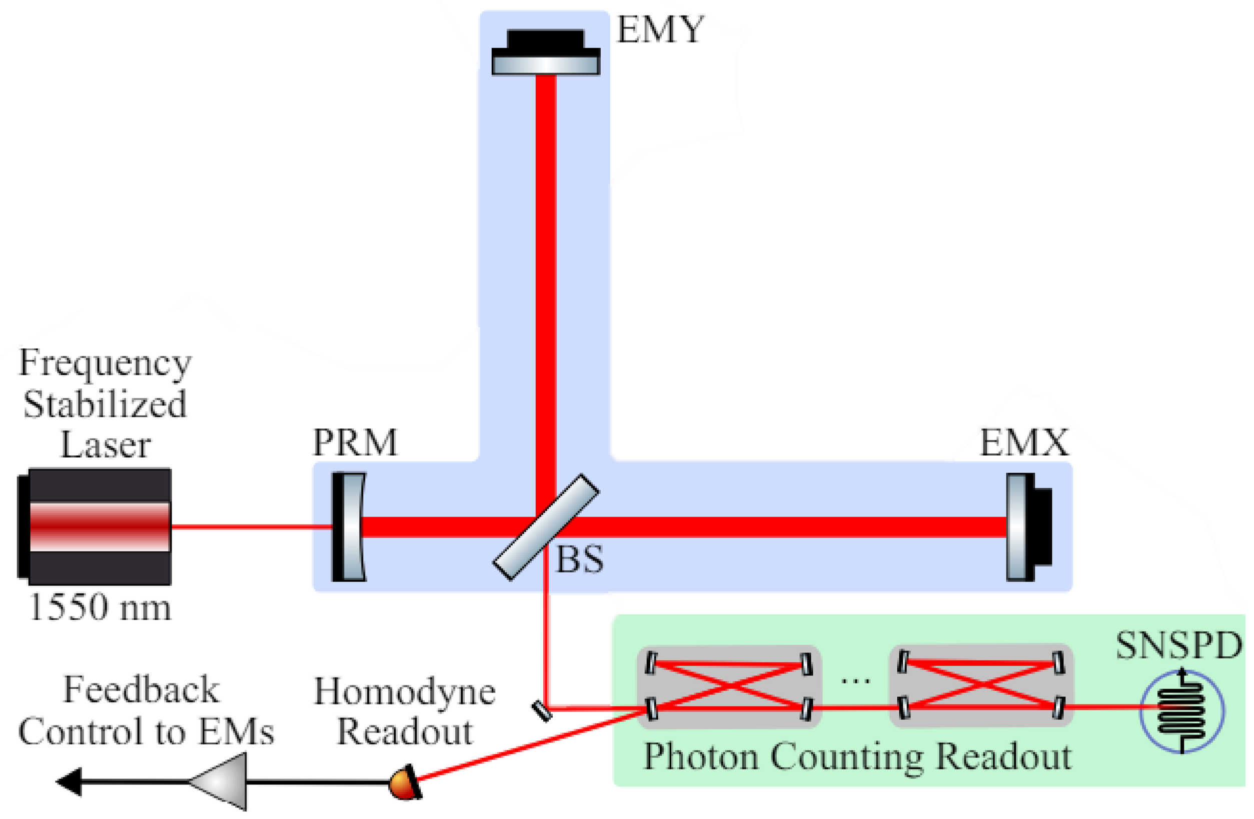

FIG. 1 Simplified experimental design of interferometer (IFO). A 1550 nm laser inputs light into the power-recycling cavity comprised of the power-recycling mirror (PRM), the incidental beamsplitter (BS), and end mirrors (EMX, EMY). The output light is sifted through narrow-band filter-cavities. The superconducting nanowire single-photon detector (SNSPD) detects the filtered photons. The homodyne readout scheme uses the light from the first filter cavity for feedback control of the IFO. [2]

Digital Control System & Goal

- The apparatus uses frequency-dependent filter cavities to block carrier light to allow sensitive detection of light modulated by the Verlinde & Zurek effect.
- My goal from this summer is to develop the software that would be implemented into the FPGAs being used in the control system for the filter cavities.

Digital Signal Processing & Fixed-Point

- A biquadratic filter is a 2nd order iterative filter whose behavior is characterized by five coefficients (b_0, b_1, b_2, a_1, a_2) and the following difference equations:

$$y_n = b_0 w_n + b_1 w_{n-1} + b_2 w_{n-2}$$

$$w_n = x_n - a_1 w_{n-1} - a_2 w_{n-2}$$

- Electronically, these coefficients are represented as fixed-point numbers:

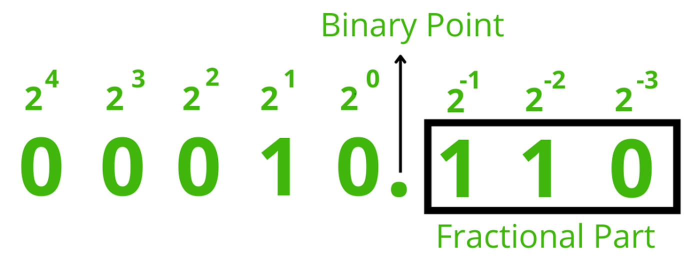

FIG. 2 Example Fixed-Point Representation of 2.75. The number of bits to the left of the binary point determine range and the ones to the right determine precision.

- We choose to stress test the FPGA control system by tuning the fixed-point representation of the five coefficients from a biquadratic low-pass filter.

Threshold Bit Resolution

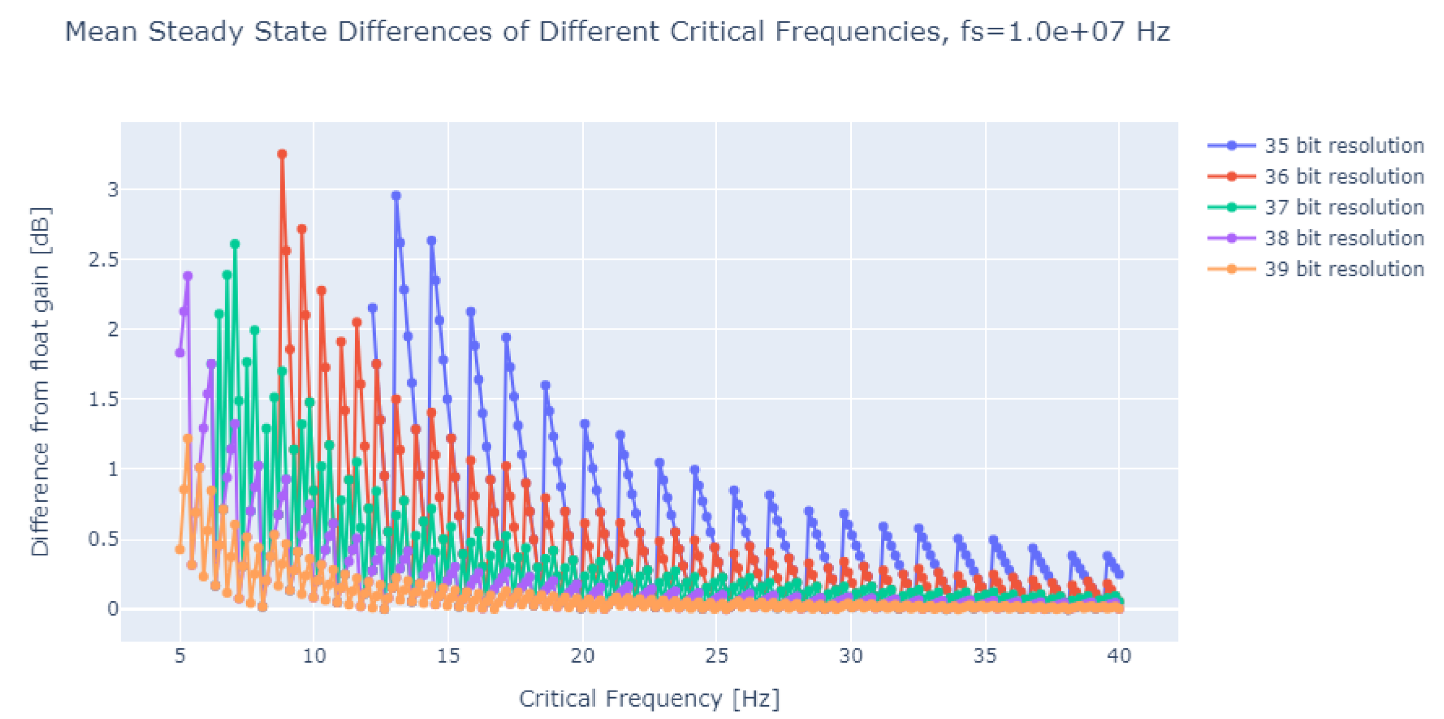

FIG. 3. Mean Steady-State Differences between Floating-Point and Low-Bit-Resolution Coefficients of 2nd order low-pass filter with sampling frequency of 10 MHz.

- We search for the bit resolution that maintains precision while minimizing resources.
- We probed the effects of decreasing bit resolution on the output amplitude, on digitization & readout noise, with various sampling & critical frequencies, and comparing different methods of digital filtering.

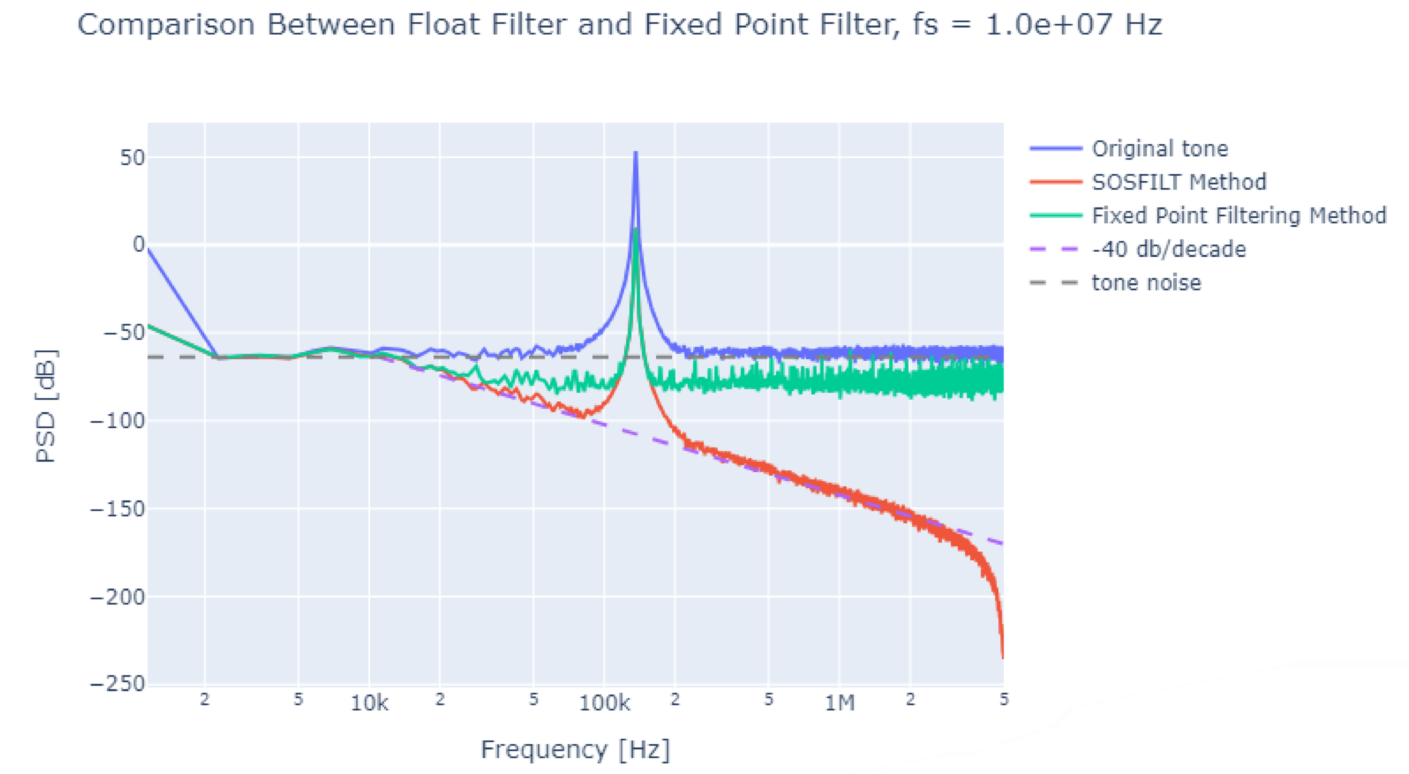

FIG. 4 Power Spectral Density Comparison. The original tone simulates typical read noise and digitization effects. The SOSFILT method is the exact performance calculated in high precision, showing roll off of amplitude by 40 dB per decade. The "Fixed Point Filtering Method" demonstrates similar behavior but limited with higher noise above ~ 30 kHz.

Results & Outlook

- For a critical frequency near 10 Hz, being precise to within 1 dB entails that we need at least 38 bits of resolution on our fixed-point filter.
- 38 bits will not be enough to sufficiently minimize read and digitization noise.
- For future work, we will tune the number of bits further to minimize the effects lower resolution on noise while maintaining precision.

Acknowledgements

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References

[1] K. M. Zurek, "On vacuum fluctuations in quantum gravity and interferometer arm fluctuations," *Physics Letters B*, vol. 826, p. 136910, Mar. 2022, doi: https://doi.org/10.1016/j.physletb.2022.136910.

[2] S. M. Vermeulen et al., "Photon Counting Interferometry to Detect Geontropic Space-Time Fluctuations with GQuEST," arXiv.org, Apr. 11, 2024. https://arxiv.org/abs/2404.07524

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