

# **The QUEST Experiment - Laser Interferometry for Fundamental Physics**

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# Summary

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The Quantum Enhanced Space-Time measurement (QUEST) experiment is a modern table-top interferometric setup designed to probe fundamental science signals, such as models of quantum gravity, scalar-field dark matter candidates and high-frequency gravitational waves. The work presented in this thesis has been a contribution to the development and commissioning of the QUEST experiment towards the first science run followed by operating the instrument during the run's data taking. Following that, work has been done towards upgrades and commissioning in preparation for the second science run. The experimental work took the shape of setting up the main power-recycled Michelson interferometers, implementing control loops to lock and operate them and operating, testing and commissioning all the critical apparatus involved such as the ultra-high vacuum systems, high-frequency data acquisition systems etc.

Work has also been done on the data analysis, calibration and processing the data collected during the first science run, which resulted in new limits of correlated length fluctuations of  $4 \times 10^{-20} \text{ m}/\sqrt{\text{Hz}}$  for the frequency band 13 to 80 MHz.



# Statement of work

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## Publications

Part of work presented in this thesis has been published as follows :

- Broadband Limits on Stochastic Length Fluctuations from a Pair of Table-Top Interferometers  
Authors - **Abhinav Patra**, Lorenzo Aiello, Aldo Ejlli, William L. Griffiths, Alasdair L. James, Nikitha Kuntimaddi, Ohkyung Kwon, Eyal Schwartz, Henning Vahlbruch, Sander M. Vermeulen, Keiko Kokeyama, Katherine L. Dooley and Hartmut Grote  
DOI: <https://doi.org/10.1103/61j9-cjkk>

I have performed the experimental commissioning, operation, data-analysis and manuscript preparation of this published work.

- A broadband squeezed light source for table-top interferometry  
Authors - Fabio Bergamin, Nikitha Kuntimaddi, **Abhinav Patra**, Stephanie Montoya, Moritz Mehmet, Katherine Dooley, Hartmut Grote and Henning Vahlbruch  
DOI: <https://doi.org/10.1088/1367-2630/ae2987>

I have contributed to the optical commissioning and the control setup presented in this publication.

## Contributions

My work on the QUEST experiment spans over four years, and a large part of which has been collaborative with other members of the lab, both past and present. As such portions of this thesis are a collective effort of the group. I will try and present an exhaustive list of my contributions to collaborative work done below. If not listed but presented in the thesis, the work is mostly or entirely my own. Whenever used, external sources have been explicitly cited.

- Vacuum systems - Initial commissioning and commissioning and operating for science run 1 and science run 2. Work done alongside Dr. Aldo Ejlli, Dr. Lorenzo Aiello, Dr. Eyal Schwartz, Dr. Will Griffiths, Dr. Satoshi Tanioka and Dr. Fabio Bergamin.
- Squeezing commissioning and balanced homodyne detection - Optical setup, control loops and testing. Work done alongside Dr. Fabio Bergamin, Nikitha Kuntimaddi, Stephanie Montoya.

- High-frequency data acquisition system - Operating as part of science runs, commissioned upgrades to accommodate window functions and further testing. Work done alongside Dr. Sander Vermeulen and Nikitha Kuntimaddi.
- Laser injection commissioning - Mode-matching and operating as part of science runs and power-up tests. Work done alongside Dr. Lorenzo Aiello, Dr. Satoshi Tanioka, Dr. Fabio Bergamin, Dr. William Griffiths, Dr. Ali James and Dr. Eyal Schwartz.
- Photo-detector characterization - Data taking and modeling. Work done alongside Dr. Hartmut Grote and Nikitha Kuntimaddi.
- Output mode-cleaners - Commissioned and setup control loops. Initial design by Dr. Will Griffiths, further collaborative done alongside Asher Tubman and Maxwell Oliveira-Koudry.
- CDS system - Compilation and setup of real-time models and automating with python scripts. Work done alongside Dr. Keiko Kokeyama, Nikitha Kuntimaddi and Dr. Terri Pierce.
- Commissioning viton isolators - Contributed to vacuum systems cycling, alignment and locking of the interferometers and data taking. Work done alongside Dr. Fabio Bergamin and Kushal Jain.
- Contributed to general maintenance of the lab alongside everyone.

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*“To the future”*



# Acknowledgements

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# Chapter 1

## Introduction

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The concept of interferometry has a profound history in probing the fundamental nature of space and time, most notably beginning with the famous Michelson-Morley experiment in 1887 [12]. Originally designed to detect the Earth's motion through the hypothetical luminiferous aether, this foundational experiment utilized a Michelson interferometer to demonstrate the invariance of the speed of light, ultimately paving the way for Einstein's theory of special relativity. Over a century later, this same basic optical topology forms the core of modern gravitational-wave detectors. The critical leap from classical white-light interferometry to these kilometer scale precision instruments was propelled by the invention of the laser in 1960 [13]. The laser provided the highly coherent, intense, and stable light source fundamentally required to measure sub-atomic scale length differences. Building upon this, a four decades-long development period of laser interferometer technologies culminated in the discovery and direct measurement of gravitational waves in 2015 [14], an achievement that has revolutionized astrophysics.

Laser interferometers operate by splitting an incoming laser beam using a half-reflective mirror known as the beam splitter and allowing the two beams to traverse the length of their arms, where they are reflected back using high-reflective mirrors. The reflections combine back on the beam splitter and interfere. This interference encodes the phase difference accumulated between the two beams as they propagate. This difference may be induced by the space-time fluctuation caused by a passing gravitational wave or a local dark matter field or by irreducible length fluctuations of quantum space-time or simply a result of local noise sources such as seismic or thermal noise. Interferometers are instruments that convert these phase fluctuations into measurable fluctuations of laser power exiting their output (anti-symmetric) port.

The Laser Interferometer Gravitational-wave Observatories (LIGO) are probably the most well known modern laser interferometers. Their arms are 4 km long and laser powers of order 100 kW are circulated through them. Following the first measurement of gravitational waves in 2015, which was a result of two binary black-holes merging, LIGO has made repeated measurements of many such mergers. All the signals measured thus

far are transient, only lasting a fraction of a second to a few seconds long. However, gravitational waves are also expected from stationary sources such as rotating neutron stars and stochastic superposition of unresolved astrophysical or cosmological sources [15–20], that are yet to be resolved with direct measurements.

Other stationary space-time fluctuations that are not astrophysical in nature, but rather are a result of local space-time phenomena, are signatures of quantum gravity and scalar field dark matter candidates. LIGO, with its relatively narrow-band sensitivity selectively engineered to make measurements of binary mergers and their sky-localization, lacks substantial sensitivity towards local sources of broadband space-time fluctuations. A powerful measurement technique to search for such stochastic, stationary signals is cross-correlation between two co-located interferometers that share the science signal but are commissioned to be independent in their technical noises. Correlated interferometry was demonstrated at the LIGO Hanford observatory [21] and at Fermilab's Holometer experiment. The Holometer was a prototype scale instrument with two 40 m long interferometers with about 1 kW of circulating power each.

The Quantum-Enhanced Space-time measurement (QUEST) experiment is a successor to the Holometer that is being commissioned at Cardiff University. The QUEST experiment consists of two co-located, table-top power-recycled Michelson interferometers and is dedicated to further developing correlated interferometry to search for fundamental physics signals such as quantum gravity models, scalar field dark matter candidates and high-frequency gravitational waves [7]. Figure 1.1 presents a schematic layout of the experiment and presents the core components such as the laser sources, photo-detectors and core optics of the interferometers.

The work presented in this thesis is a culmination of commissioning and instrument development, as a result of the QUEST experiment's first science run. This thesis is structured as follows:

1. Chapter 2 presents a review of the coupling of quantum space-time fluctuations, scalar-field dark matter and high-frequency stochastic gravitational waves to laser interferometers, with a discussion on the expected signal in the QUEST interferometers.
2. Chapter 3 presents a review of the homodyne readout scheme used by the QUEST interferometers and the shot-noise-limited sensitivity. It also presents a derivation of the main data analysis routines used by the QUEST experiment.
3. Chapter 4 describes the experimental apparatus in detail. Various sub-systems that constitute the QUEST experiment are introduced and described.
4. Chapter 5 presents the experimental commissioning work that was done in preparation for the first science run of the QUEST experiment.

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5. Chapter 6 details the data-analysis and science output of the science run as well as the operation of the interferometers during the data run.
  6. Chapter 7 presents the ongoing work of commissioning the QUEST experiment for a second science run and the sensitivity projections and future prospects of the experiment.
  7. Chapter 8 concludes the thesis with a review of the work done and the future prospects of the experiment.

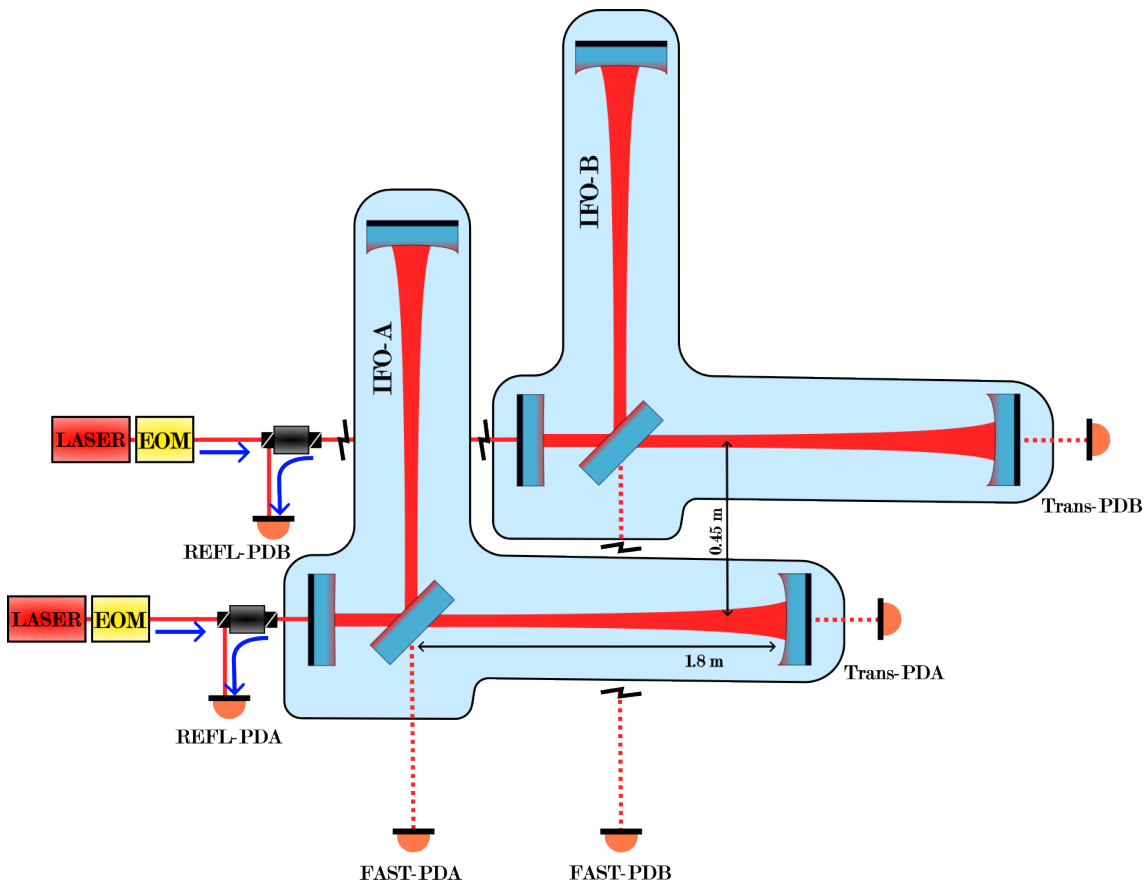


**Figure 1.1.** The general layout of the QUEST experiment. QUEST consists of two power recycled Michelson interferometers each housed in its own vacuum envelope and is commissioned with independent laser injection and control systems. The interferometers have arm lengths of 1.83 m and are 0.45 m apart.

## Chapter 2

# Fundamental Science with Laser Interferometers

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The QUEST experiment aims to study the signatures of quantum gravity, dark matter candidates and stochastic and stationary gravitational waves. QUEST is uniquely suited to study these fundamental science signals with its ability to perform cross-correlation between the outputs of two interferometers. This chapter presents a review of these three science targets and the expected signals in an experiment like QUEST.

### 2.1 Gravitational waves

In the framework of general relativity, gravitational waves (GWs) are fluctuations of spacetime curvature which can be represented as transverse and traceless perturbations ( $h_{\mu\nu}$ ) over a flat Minkowski background metric ( $\eta_{\mu\nu} = \text{diag}[-1, 1, 1, 1]$ ) that propagate at the speed of light [22].

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}; |h_{\mu\nu}| \ll 1 \quad (2.1)$$

These waves are generated as a result of time-dependent change of non-axisymmetric mass-energy distributions with a non-zero quadrupole moment, such as the inspiral and merger of binary black holes or neutron stars, where the radiative component of these metric perturbations satisfies the linearized Einstein field equations in the Lorenz gauge:

$$\square \bar{h}_{\mu\nu} = -\frac{16\pi G T_{\mu\nu}}{c^4} \quad (2.2)$$

where  $\square = \eta^{\mu\nu} \partial_\mu \partial_\nu = -\frac{1}{c^2} \frac{\partial^2}{\partial t^2} + \nabla^2$  is the D'Alembert operator and  $T_{\mu\nu}$  is the stress-energy tensor. These tensor perturbations can be represented with two distinct polarization states, plus ( $h_+$ ) and cross ( $h_\times$ ), which physically manifest as differential strains that orthogonally compress and expand spacetime. This infinitesimal stretching and squeezing alters the proper distance between free-falling test masses, whose relative positions can be measured as a phase change in a probe laser field using a laser interferometer. Without

loss of generality by choosing the direction of propagation of a GW along the  $z$ -axis, the resulting spatial metric fluctuations will be of the form:

$$h_{ij}(t, z) = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}_{ij} \cos \left[ \omega \left( t - \frac{z}{c} \right) \right], \quad (2.3)$$

where  $\omega$  is the angular frequency of the GW. The corresponding change in proper distance is given by:

$$\begin{aligned} ds^2 = -c^2 dt^2 + dz^2 + & \left\{ 1 + h_+ \cos \left[ \omega \left( t - \frac{z}{c} \right) \right] \right\} dx^2 \\ & + \left\{ 1 - h_+ \cos \left[ \omega \left( t - \frac{z}{c} \right) \right] \right\} dy^2 \\ & + 2h_\times \cos \left[ \omega \left( t - \frac{z}{c} \right) \right] dx dy. \end{aligned} \quad (2.4)$$

As a result of this passing GW, a Michelson interferometer with its arms parallel to the  $x$  and  $y$  directions will experience this simultaneous stretching and squeezing of arm lengths, resulting in a measurable differential arm (DARM) length change signal from the interferometer.

### 2.1.1 Stochastic gravitational wave background

The direct measurements of GWs so far have been the result of astrophysical sources, specifically from compact-body coalescence, where the signal's source parameters—such as the masses, sky location, and astrophysical distances—can be modeled and estimated from the measurements. GWs are also expected from unresolved sources, which are an incoherent superposition of various astrophysical and cosmological sources where the resulting signal is expected to be stationary in both time and amplitude. This signal is typically referred to as the gravitational wave stochastic background.

The absolute displacement sensitivity observed in interferometers such as QUEST can also be used to search for the GW stochastic background. The sensitivity in QUEST is a result of the cross-correlation and averaging of the signals between two interferometers at radio frequencies. Because this technique requires the probed signals to be stationary in nature, QUEST is an excellent instrument to measure or constrain the amplitude of the ultra-high-frequency ( $\geq 1$  MHz) GW stochastic background.

The signal from the GW stochastic background is assumed to be isotropic in sky location and unpolarized. To calculate the appropriate calibration factor that translates a QUEST interferometer's absolute displacement sensitivity ( $\sqrt{S(f)}$ ) to the strain ( $\sqrt{h(f)}$ ) of the arm length change, a sky-position and polarization-averaged conversion factor is derived. A GW with unity amplitude is considered from every sky position and polarization,

and a quadratic mean is calculated for every frequency. Because the spatial response of the detector is strongly coupled to the signal frequency in the high-frequency regime, this integration must be evaluated across the sky at each individual frequency bin. This approach is similar to the antenna pattern calculation of the LIGO detectors [2, 3].

$$\sqrt{h(f)} = \left[ L_{\text{arm}} \cdot \sqrt{I(f)} \right]^{-1} \cdot \sqrt{S(f)} \quad (2.5)$$

$$I(f) = \frac{1}{4\pi} \int_0^{2\pi} \int_0^\pi \left( |h_x^+(\theta, \phi, f) - h_y^+(\theta, \phi, f)|^2 + |h_x^\times(\theta, \phi, f) - h_y^\times(\theta, \phi, f)|^2 \right) \sin \theta d\theta d\phi \quad (2.6)$$

Typically, the antenna pattern for LIGO detectors is calculated at DC ( $f = 0$ ); as a result, this conversion factor simplifies to  $\sqrt{h(f=0)} = [1/L_{\text{arm}}] \cdot \sqrt{S(f=0)}$ , resulting in a strain amplitude spectral density  $\sqrt{h(f)}$  with units of  $1/\sqrt{\text{Hz}}$ . Similarly, the term in the square brackets in Eq. 2.5 is the frequency-dependent conversion factor (whose spectrum is shown in Fig. 2.1) that translates absolute displacement sensitivity to strain and carries the units m. Here,  $L_{\text{arm}}$  is the arm length of the QUEST interferometers (1.83 m). The terms  $h_{x,y}^{+,\times}(\theta, \phi, f)$  represent the frequency-dependent effective strain response in the x and y arms of the interferometers caused by GWs in the plus and cross polarizations, which intrinsically capture the free-spectral-range resonance behavior of the arms.

In the general case of using a network of two detectors to search for a GW stochastic background, an overlap-reduction function ( $Q(f)$ ) is used to optimally combine the strain signals observed by the two detectors to obtain the final cross-correlated strain sensitivity, such as  $h_{ab}(f) = \sqrt{h_a^\dagger(f) \cdot h_b(f) \cdot Q(f)}$ . The overlap-reduction function is a result of the physical distance and inclination difference between the two detectors. In the case of QUEST, the detectors are co-aligned and co-located with an intra-arm distance of 0.45 m, which results in all signals below the frequency of 330 MHz being coherent and in-phase between the detectors. This frequency corresponds to the inverse light-crossing time ( $c/(2 \cdot 0.45 \text{ m})$ ) due to the intra-arm distance; as a result,  $Q(f)$  can be taken to be unity in QUEST's science frequency band of 1 to 200 MHz.

### 2.1.2 Gravitational wave energy density

To compare the experimental bounds set by various instruments, the measured strain sensitivity is cast into a dimensionless scalar called the gravitational wave energy density,  $\Omega_{\text{GW}}(f)$ , as defined in [23] and [6]. The explicit relationship defining this density is given by:

$$\Omega_{\text{GW}} = \frac{1}{\rho_c} \frac{d\rho}{d \ln f} \quad (2.7)$$

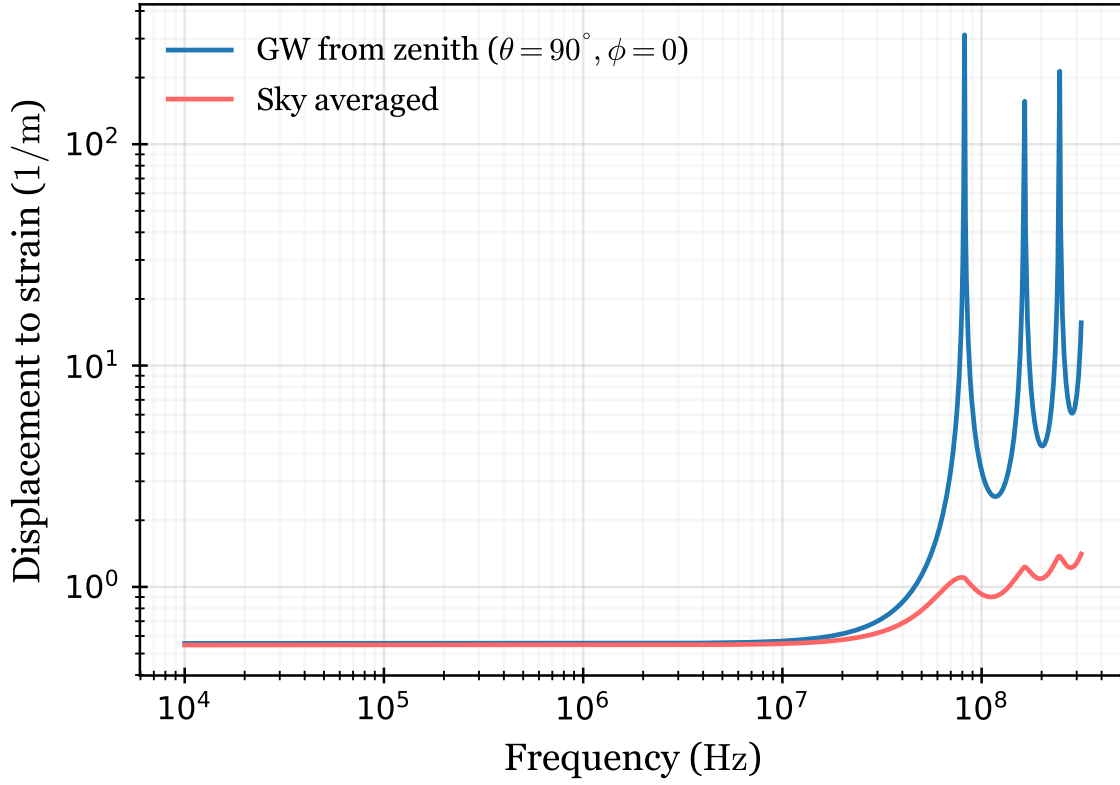


**Figure 2.1.** The frequency-dependent calibration factor to translate from absolute displacement to sky-averaged strain sensitivity of the QUEST interferometers is estimated numerically. The zeros in the strain sensitivity, which occur as a result of the free spectral range of the interferometer arm lengths (1.83 m), can be seen at the GW sky position corresponding to the zenith ( $\theta = 90^\circ, \phi = 0^\circ$ ). The sky-position averaging approach has been adopted from [2, 3].

where  $\rho_c = \frac{3c^2 H_0^2}{8\pi G}$  is the critical energy density of the Universe. Here,  $H_0$  is the Hubble constant, and  $d\rho$  is the gravitational wave energy density within the frequency range  $f$  to  $f + df$ . The gravitational energy density as a function of the cross-correlated strain power spectral density,  $\Re[h_{ab}(f)]$ , is given by [6]:

$$\Omega_{\text{GW}}(f) = \frac{\Re[h_{ab}(f)]}{K(f)} \quad (2.8)$$

where the conversion factor  $K(f)$  is defined as:

$$K(f) = \frac{3H_0^2}{10\pi^2} \frac{1}{f^3} \quad (2.9)$$

The Hubble constant  $H_0$  is parameterized as  $H_0 = h_{100} \times 100 \text{ km/s/Mpc}$ . The dimensionless parameter  $h_{100}$  accounts for variations in the measured value of the

Hubble constant:

$$\begin{aligned} H_0 &= h_{100} \times 100 \text{ km/s/Mpc} \\ &\approx 3.24 \times 10^{-18} \cdot h_{100} \text{ s}^{-1} \end{aligned} \quad (2.10)$$

Consequently, the parameterized gravitational wave energy density,  $h_{100}^2 \Omega_{\text{GW}}(f)$ , is calculated from the strain sensitivity to characterize the stochastic GW background independently of the exact Hubble constant value. Due to the cubic scaling of  $\Omega_{\text{GW}}$  with respect to the measurement frequency  $f$  derived from Eq. 2.8 and Eq. 2.9, high-frequency experiments such as QUEST face a severe penalty when constraining the energy density compared to audio-band instruments like LIGO. Nevertheless, searching this high-frequency region remains critical for constraining exotic sources of GWs such as primordial black hole superradiance, cosmic strings, etc. [19], which explicitly predict spectral peaks at megahertz to gigahertz frequencies.

Evaluating the numerical factors yields:

$$\begin{aligned} h_{100}^2 \Omega_{\text{GW}}(f) &= \frac{10\pi^2 f^3 \cdot \Re[h_{\text{ab}}(f)]}{3 \cdot (3.24 \times 10^{-18} \text{ s}^{-1})^2} \\ &\approx 3.13 \times 10^{14} \cdot \left( \frac{\sqrt{\Re[h_{\text{ab}}(f)]}}{1 \times 10^{-20} \text{ Hz}^{-1/2}} \right)^2 \cdot \left( \frac{f}{1 \text{ MHz}} \right)^3 \end{aligned} \quad (2.11)$$

The Holometer has set an upperbound of about  $10^{12}$  for this dimensionless gravitational energy density metric at 1 MHz [6]. The explicit constraint of  $h_{100}^2 \Omega_{\text{GW}}(f)$  as a result of LIGO, Holometer and QUEST's observed strain sensitivities are presented in the results chapter.

## 2.2 Dark Matter

Modern theories of cosmology introduce the presence of a non-baryonic, non-luminous matter, known as dark matter (DM), which constitutes approximately 27% of the universe's total energy. This correction was introduced as a result of decades of astrophysical and cosmological observations spanning from galactic rotational curves and weak and strong gravitational lensing [24–26], to measurements of precise temperature anisotropies of the cosmic microwave background. These unambiguously indicate the presence of matter that is not observable via electromagnetic measurements but interacts gravitationally with observable matter. These observations have led to the conclusion that the Standard Model (SM) of particle physics is incomplete, making the direct measurement of fundamental physical properties of DM, such as mass, spin, and non-gravitational coupling constants, which currently remain unmeasured, a critical open problem in modern physics.

A general relativistic description of the gravitational dynamics of the universe is given by the Einstein field equation:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = T_{\mu\nu} \quad (2.12)$$

where the Einstein tensor  $G_{\mu\nu}$  describes the spacetime that is influenced by the gravity induced by the energy-momentum tensor  $T_{\mu\nu}$ . While the observed gravitational anomalies could be reconciled by modifying the left-hand side of Eq. 2.12, known as “modified gravity” frameworks, increasingly precise tests of general relativity have not yet yielded any deviations from the theory. This has led to DM being generally modeled as additional quantum fields that can be integrated into the SM, and as such modify  $T_{\mu\nu}$ .

Weakly Interacting Massive Particles (WIMPs), with particle masses between 10 GeV and 1 TeV, have been the first DM candidates to receive experimental scrutiny. High-energy particle collider-based experiments were performed to generate and detect interactions of these particles and have thus far not yielded a positive detection. This null result has motivated a vast experimental parameter-space search for DM candidates across a broad range of particle masses, which has shifted the focus towards the search for weakly interacting, low-mass ( $\ll 1$  eV) fields that manifest as classical, coherently oscillating wave-like fields rather than discrete particles [27, 28].

Laser interferometers developed primarily for detecting gravitational waves provide exceptional sensitivity to the differential phase of the laser fields that traverse their arms. This sensitivity can be used as a tool to search for low-mass dark matter candidates. This approach leverages a novel mechanism proposed by Grote and Stadnik in 2019 [29] and has been tested with the GEO600 [9], Holometer [8], and LIGO-VIRGO [30, 31] detectors. The detection mechanism relies on non-gravitational, linear couplings between the local scalar field of dark matter  $\phi$  and SM fields. This interaction is parameterized by adding a linear term to the SM Lagrangian of the form [29, 8]:

$$\mathcal{L}_{\text{int}} = \frac{\phi}{\Lambda_\gamma} \frac{F_{\mu\nu} F^{\mu\nu}}{4} - \frac{\phi}{\Lambda_e} m_e \bar{\psi}_e \psi_e \quad (2.13)$$

where  $F_{\mu\nu} F^{\mu\nu}$  is the electromagnetic field tensor,  $m_e$  is the electron rest mass, and  $\bar{\psi}_e, \psi_e$  are the SM electron field and its conjugate. The parameters  $\Lambda_\gamma$  and  $\Lambda_e$  parameterize the strength of the DM field’s coupling to photons and electrons, respectively.

### 2.2.1 Virialized Field Dynamics and Fundamental Constants

In standard galactic models, a local dark matter scalar field is virialized via self-gravitation within the Milky Way’s gravitational potential well. This results in the field of particles taking up a Maxwell-Boltzmann-like velocity distribution rather than behaving as a perfectly monochromatic wave. This non-relativistic velocity dispersion ( $v_{\text{obs}} \approx 10^{-3}c$ )

introduces a small Doppler shift to the observed field oscillations. The consequence of this virialization is that the DM field possesses a finite coherence time and a characteristic spread in observed frequency (linewidth) given by  $\Delta\omega_{\text{obs}}/\omega_\phi \approx v_{\text{obs}}^2/c^2 \approx 10^{-6}$ . For a nominal field frequency of  $\omega_\phi = 1$  MHz, this velocity dispersion yields a finite signal linewidth of exactly  $\Delta\omega_{\text{obs}} = 1$  Hz, which imposes unique constraints on data analysis and signal-integration timelines [32]. The resulting scalar field manifests as a coherently oscillating wave:

$$\phi(t, \vec{r}) = \phi_o \cos(\omega_{\text{obs}}t - \vec{k} \cdot \vec{r}) \quad (2.14)$$

where the baseline angular Compton frequency  $\omega_\phi = m_\phi c^2/\hbar$ , which represents the natural frequency associated with the particle's rest mass, is shifted due to kinetic energy into an observed frequency  $\omega_{\text{obs}} \approx \omega_\phi + m_\phi v_{\text{obs}}^2/(2\hbar)$ , and  $\vec{k} = (m_\phi \vec{v}_{\text{obs}})/\hbar$  is the wave vector, with  $m_\phi$  being the mass of the field and  $\vec{v}_{\text{obs}}$  the velocity relative to the observer. The field amplitude is given by:

$$\phi_o = \frac{\hbar \sqrt{2\rho_{\text{local}}}}{m_\phi c} \quad (2.15)$$

where  $\rho_{\text{local}} = 0.4 \text{ GeV/cm}^3$  [33] is the local galactic dark matter density.

The coupling of the oscillating dark matter field to the SM Lagrangian induces a direct, periodic modulation of fundamental constants at the characteristic frequency of the DM field. Specifically, the electron rest mass  $m_e$  and the fine-structure constant  $\alpha$  vary as [8]:

$$m_e \rightarrow m_e \left(1 + \frac{\phi}{\Lambda_e}\right), \quad \alpha \rightarrow \alpha \left(1 + \frac{\phi}{\Lambda_\gamma}\right) \quad (2.16)$$

Because the physical dimensions  $l$  and refractive index  $n$  of a solid are functions of  $m_e$  and  $\alpha$  ( $l \propto 1/(m_e \alpha)$ ;  $1/n \propto m_e \alpha^2$ ), these variations drive macroscopic changes in the optical elements of the interferometers. The resulting variations in the physical length ( $\delta l$ ) and refractive index ( $\delta n$ ) of the beam splitter substrate are given by:

$$\frac{\delta l}{l} = \left(-\frac{\delta \alpha}{\alpha} - \frac{\delta m_e}{m_e}\right) \left(\left|1 - \frac{\omega^2}{\omega_o^2}\right|\right)^{-1} \quad (2.17)$$

$$\frac{\delta n}{n} = C_{\text{disp}} \left(2\frac{\delta \alpha}{\alpha} + \frac{\delta m_e}{m_e}\right) \quad (2.18)$$

where  $\omega_o$  is the fundamental mechanical resonance frequency of the beam splitter and  $C_{\text{disp}}$  is the chromatic dispersion constant of the material. For the specific case of the QUEST experiment, these parameters for the fused silica beam splitters are  $l = 6$  mm,  $\omega_o \approx 2\pi \times 470$  kHz,  $n = 1.45$ , and  $C_{\text{disp}} \approx -5 \times 10^3$  [29].

Consequently, the differential optical path length between the arms of an interferometer,  $\delta(L_x - L_y)$ , generated as a result of the changes  $\delta l$  and  $\delta n$ , is given by the relation:

$$\delta(L_x - L_y) \approx \sqrt{2} \left[ \left( n - \frac{1}{2} \right) \delta l + l \delta n \right] \quad (2.19)$$

By substituting the field-dependent corrections into this equation, the complete expected differential path length signal induced by a DM field is given by [8]:

$$\begin{aligned} \delta(L_x - L_y) \approx & \left( \frac{2cl\sqrt{\rho_{\text{local}}}}{\omega_\phi} \right) \cdot \text{sinc}^{-1} \left( \frac{\omega_\phi L}{c} \right) \\ & \cdot \left\{ (n - 1/2) \left( \left| 1 - \frac{\omega^2}{\omega_o^2} \right| \right)^{-1} \left( \frac{1}{\Lambda_\gamma} + \frac{1}{\Lambda_e} \right) + n \left( \frac{10^{-2}}{\Lambda_\gamma} + \frac{5 \times 10^{-3}}{\Lambda_e} \right) \right\} \end{aligned} \quad (2.20)$$

Here, the  $\text{sinc}(\omega_\phi L/c)$  term accounts for the modulation of the phase sensitivity of the interferometer caused by the finite transit time of light within its arms of length  $L$ .

Crucially, because the dark matter field is virialized, its de Broglie wavelength (defined as  $\lambda_\phi = 2\pi/|\vec{k}|$ ) is roughly three orders of magnitude larger than its Compton wavelength [34]. For a field frequency of 1 MHz, this translates to a macroscopic spatial coherence length of approximately 300 m. In QUEST, the separation distance between the beam splitters of the two instruments is about 0.45 m. Because this physical separation is far smaller than  $\lambda_\phi$ , the DM field is completely coherent between the two detectors, causing identical, in-phase fluctuations in both interferometers.

Similar to the data analysis methodologies implemented for the Holometer [8], QUEST's sensitivity to these signals will improve with cross-correlation and averaging. While in the case of single detectors, special care must be taken to account for the time coherence of the virialized DM field [31], in cross-correlation measurements of co-located detectors, such as QUEST, the dark matter signal is coherent between the two detectors, amortizing the field's amplitude at the time of measurement. The nature of cross-correlated measurements allows for upper limits to be set on the inverse coupling constants  $1/\Lambda_\gamma$  and  $1/\Lambda_e$  across the sensitive frequency bands of QUEST. A comparison of these constraints between LIGO, GEO600, the Holometer, and QUEST is presented in Chapter 6.

## 2.3 Signatures of quantum gravity

The pursuit of a complete theory of quantum gravity seeks to resolve the fundamental incompatibility between GR's continuous manifold description of space-time and the probabilistic mass-energy distribution of quantum mechanics. In a purely quantum mechanical framework, mass-energy can be expressed as a superposition of states, which

fundamentally breaks the description of the curvature of space-time associated with it, in the GR picture. Because the Einstein equations lack a consistent mechanism to account for such superposition states, a definitive description of the resulting dynamics remains out-of-scope for current theoretical frameworks. To overcome this mathematical limitation, physicists have proposed empirical searches for signatures of quantum gravity phenomena and one such mechanism is to look for irreducible quantum fluctuations in the geometry of space-time itself.

The magnitude of these quantum space-time fluctuations can be estimated through a heuristic thought experiment in which a distance  $L$  is measured by timing a photon's round trip between a clock of mass  $M$  and a distant mirror [35]. According to the Heisenberg uncertainty principle ( $\Delta x \Delta p \geq \hbar/2$ ), the clock cannot be absolutely stationary. Minimizing its position and momentum uncertainties yields the Standard Quantum Limit (SQL) relation for length measurements,  $\delta L_{QM} \geq \sqrt{\frac{\hbar L}{Mc}}$  [36]. In GW detectors like LIGO, this fundamental uncertainty of the position of masses manifests as so-called radiation-pressure noise, which captures the position uncertainty of the interferometer's mirrors. This is one of the fundamental limiting noises at low frequencies.

While quantum mechanics suggests this uncertainty could be minimized by arbitrarily increasing the clock's mass, general relativity imposes a strict upper limit. A massive clock would perturb the space-time curvature, requiring that the measurement uncertainty be strictly greater than the clock's Schwarzschild radius,  $\delta L_{GR} > \frac{GM}{c^2}$  [35, 37, 38]. By substituting the resulting gravitational mass limit,  $M < \frac{\delta L c^2}{G}$ , into the quantum uncertainty relation, a fundamental length measurement uncertainty is derived:

$$\delta L \geq (l_P)^{2/3} (L)^{1/3} \quad (2.21)$$

where  $l_P = \sqrt{\hbar G/c^3} \approx 1.6 \times 10^{-35}$  m is the Planck length. As a heuristic this irreducible variance scaling with the measured length  $L$  can be generalized to characterize different theoretical models of quantum space-time fluctuations and can be written in a parametrized relation:

$$\delta L \propto (l_P)^\alpha (L)^{1-\alpha} \quad (2.22)$$

where  $\alpha$  is a constant determined by the specific model of quantum gravity. Old theories of quantum gravity, such as the heuristic presented above, predict  $\alpha = 2/3$  [39] and models based on the holographic principle [40, 41] or in general "random-walk-like" [42] models predict  $\alpha = 1/2$ . Fundamental, bottom-up, mathematical frameworks of quantum space-time, like string theory and loop quantum gravity, predict  $\alpha = 1$  [43, 44], decoupling the irreducible uncertainty scaling from the measured length.

### 2.3.1 The Holographic Principle

The holographic principle postulates a fundamental relationship between the geometry of space-time and the entropy it contains. It proposes that the information capacity within a given volume of space-time is strictly bounded by the area of an appropriate bounding surface [45]. Formally known as the covariant entropy bound [46], this limit specifies that the entropy  $S_C$  within a hypersurface bounded by a spatial surface of area  $A_H$  is constrained as follows:

$$S_C \leq \frac{A_H}{4G} \quad (2.23)$$

Because entropy is directly proportional to the number of fundamental degrees of freedom,  $S \propto N_{\text{d.o.f.}}$ , this principle suggests that conventional volumetric field theories systematically overcount a system's true degrees of freedom, which instead scale intrinsically with the boundary area.

To heuristically derive the resulting quantum space-time fluctuations for an measurement of length  $L$ , a causally connected space-time volume, or causal diamond, is considered which is defined by the measurement's converging light cones. Assuming this causal diamond saturates the covariant entropy bound, its entropy is determined by the area of a sphere of radius  $L$ :

$$S_C = \frac{A_H}{4G} = \frac{8\pi L^2}{(l_P)^2} \quad (2.24)$$

Consequently, the number of internal quantum degrees of freedom scales proportionately:

$$N_{\text{d.o.f.}} \propto \frac{L^2}{(l_P)^2} \quad (2.25)$$

If one postulates that the total energy  $E$  of these degrees of freedom is subject to quantum fluctuations governed by Poisson statistics, similar to quantum shot noise of photons, the fractional energy fluctuation scales inversely with the square root of the number of degrees of freedom:

$$\frac{\delta E}{E} \propto \frac{1}{\sqrt{N_{\text{d.o.f.}}}} \quad (2.26)$$

Finally, GR dictates that energy fluctuations induce geometric strain fluctuations [22]:

$$\left(\frac{\delta L}{L}\right)^2 \propto \frac{\delta E}{E} \quad (2.27)$$

Combining these relations ultimately reveals that the predicted macroscopic length uncertainty scales as:

$$\delta L \propto \sqrt{l_P L} \quad (2.28)$$

Interferometers, which measure lengths by comparing the phase fronts of light beams across separated optical paths, are uniquely suited to detect these irreducible fluctuations.

### 2.3.2 Modeling response in interferometers

Two models of quantum space-time (QST) that rely on the holographic principle explicitly postulate quantum correlations and fluctuations in space-time and present calculated signals and spectral responses in laser interferometers: The geontropic fluctuations induced by a fluctuating “pixellon” field by Zurek [47] and the coherent, non-local space-time quantum states picture by Kwon [41].

Verlinde and Zurek formulate the phenomenology of holographic QST fluctuations by applying the covariant entropy bound directly to the causal diamond delineated by an interferometric measurement [40, 4]. They describe the quantum state inside this causal diamond using a density matrix defined by a modular Hamiltonian  $K$ , expressed as  $\rho = \frac{e^{-K}}{Z}$ . By enforcing that the entropy associated with this density matrix saturates the covariant entropy bound,

$$S_{ent} = \frac{A_H}{4G}, \quad (2.29)$$

they find that the variance of the modular Hamiltonian,  $\Delta K = K - \langle K \rangle$ , scales linearly with the boundary area:

$$\langle \Delta K^2 \rangle = \frac{A_H}{4G}. \quad (2.30)$$

To provide a more explicit mechanism, Zurek introduces “pixellons” as the fundamental quantum excitations of these holographic degrees of freedom, governed by a thermal density matrix and exhibiting specific thermodynamic energy fluctuations. The gravitational impact of these energy fluctuations on an interferometric measurement is then computed using formalisms of direct metric-induced time delays [4]. Their model predicts that these space-time fluctuations possess macroscopic angular correlations bounded by the horizon, resulting in the perturbations being coherent across points transverse to the propagation direction of light in an interferometer. This spatial coherence is quantified using an angular two-point correlation function  $g(\gamma)$ , expanded into spherical harmonics [4]:

$$g(\gamma) = \langle \delta L(\vartheta) \delta L(\vartheta + \gamma) \rangle = \frac{l_P L}{(4\pi)^2} \sum_{l,m} \frac{Y_{l,m}(\vartheta) Y_{l,m}(\vartheta + \gamma)}{l^2 + l + 1} \quad (2.31)$$

To explicitly derive the expected spectral signatures of these fluctuations within this framework, Zurek et al. extended the model by describing the holographic degrees of freedom using a massless scalar field,  $\phi$ , known as the pixellon field, which couples directly to the space-time metric. By treating these metric perturbation as a breathing mode

of a spherical entangling surface, the local space-time geometry that the interferometer occupies is parametrized as  $ds^2 = -dt^2 + (1 - \phi)(dr^2 + r^2 d\Omega^2)$ . The interferometer response is calculated by integrating the time delay for a photon round trip, yielding a fluctuation  $\delta T(t, n)$  for an arm oriented in direction  $n$ . Taking the Fourier transform of the time-delay correlation functions provides the two-sided power spectral density for the arms,  $\tilde{C}(\omega, \theta)$ , evaluated over the spatial separation  $\mathcal{D}(r_1, r_2, \theta)$  [4]:

$$\tilde{C}(\omega, \theta) = \frac{al_p}{8\pi c_s^2 L^2} \int_0^L dr_1 \int_0^L dr_2 \frac{\sin[\omega \mathcal{D}/c_s]}{\omega \mathcal{D}} \cos[\omega(L - r_1)] \cos[\omega(L - r_2)] \quad (2.32)$$

where  $a$  is a dimensionless scaling parameter and  $c_s = 1/\sqrt{3}$  is the sound speed of the scalar mode. Because an interferometer fundamentally measures the differential phase between two arms, the true physical observable is the differential time delay,  $\mathcal{T}(t, \theta) = \delta T(t, n_2) - \delta T(t, n_1)$ . The measurable strain power spectral density is thus given by:

$$\tilde{C}_{\mathcal{T}}(\omega, \theta) = 2[\tilde{C}(\omega, 0) - \tilde{C}(\omega, \theta)] \quad (2.33)$$

While the length fluctuations  $\tilde{C}(\omega, \theta)$  has a flat, white-noise-like spectral shape at low frequencies, the angle-independent leading-order terms cancel out in the differential measurement  $\tilde{C}_{\mathcal{T}}$ . Consequently, the resulting interferometric strain spectrum is quadratically suppressed at low frequencies and peaks primarily near the inverse light-crossing time ( $\omega \sim c/L$ ) [4].

Current experimental constraints on holographic QST fluctuations are set by LIGO and the Holometer. The anticipated signal strain is theoretically parameterized by a dimensionless constant  $\alpha$  (different from  $\alpha$  in Eq. 2.22, but the notation is kept the same to match broader literature), where  $\alpha \sim 1$  represents the natural benchmark for the predicted macroscopic effect. At a  $3\sigma$  significance level, LIGO constraints  $\alpha \leq 3$  assuming a theoretical infrared cutoff and  $\alpha \leq 0.1$  without a cutoff. The Holometer provides similarly competitive bounds with  $\alpha \leq 0.7$  and  $\alpha \leq 0.6$  for with and without IR cutoff cases [4]. Similar to the Holometer, QUEST aims to set limits on  $\alpha$  by performing cross-correlation measurements between two interferometers that are bounded by a common causal boundary, resulting in the irreducible metric-fluctuations being coherent between the instruments. The expected strain amplitude spectra in QUEST is presented in Figure 2.2

The primary difference between Kwon's model [41] of QST fluctuations and the framework established by Zurek et al. centers on how the underlying quantum geometry interacts with a macroscopic measurement apparatus. While Zurek's approach effectively maps the holographic fluctuations to local scalar metric perturbations, Kwon argues that this local field-theoretic treatment fundamentally strips the fluctuations of their inherent quantum properties like, non-locality and observer-dependence. Starting directly from 't

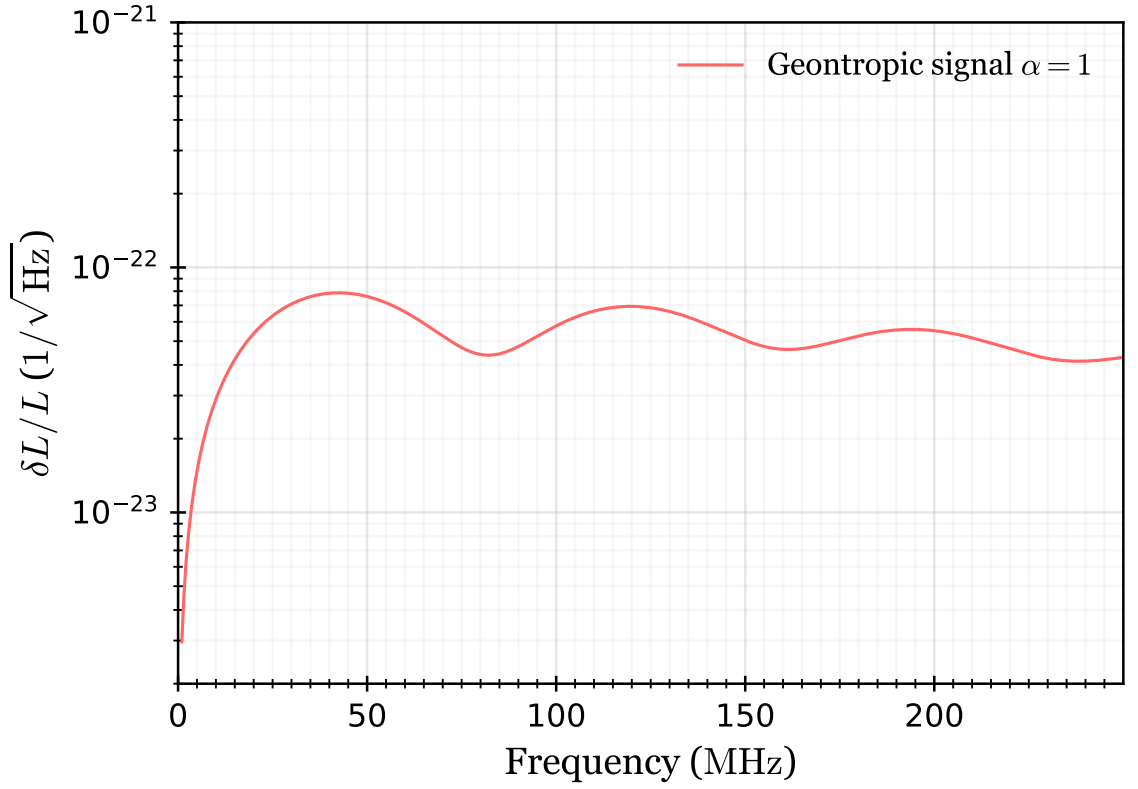


**Figure 2.2.** The expected strain signal amplitude spectral density in a QUEST interferometer is presented. This signal is a theoretical prediction of the irreducible length uncertainty proposed by Zurek’s geontropic fluctuations model [4]. The characteristic strain amplitude and the peak frequency are a result of QUEST’s 1.83 m long arms.

Hooft’s algebra for black hole horizons, Kwon postulates that the coherent states of space-time must span the entire boundary of a causal diamond in flat space. In this picture, the fluctuations are not definite perturbations resting on a background metric, but rather relational uncertainties that only “decohere” or collapse relative to a specific observer’s measurement. Because these spherical harmonic states naturally accept rotational solutions, Kwon concludes that a simple radial measurement in a standard, straight-arm Michelson interferometer fails to capture the true quantum irreducible uncertainty of these length measurements. He instead suggests, measuring these irreducible fluctuations requires coupling the instrument to incompatible rotational degrees of freedom. Kwon proposes using interferometers with orthogonal, bent arms [41], allowing the propagating light fields in the arms to sample and differentially measure the macroscopic transverse correlations of the causal boundary. No experimental constraints have been set yet for this model of holographic QST fluctuations, and QUEST, with its planned 3D design [7], will be the first experimental verification of this model.



## Chapter 3

# Laser Interferometry

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The QUEST experiment is an interferometric system consisting of two co-located, table-top laser interferometers that incorporates technical design details from the Fermilab Holometer and gravitational-wave detectors such as LIGO. This chapter presents a review of two important aspects of the experiment: a review of the homodyne readout scheme for Michelson interferometers and the fundamental sensitivity limit imposed by quantum shot noise. A detailed description of QUEST's primary data-analysis routines of cross-correlation and averaging the signals between the two interferometers is also presented.

### 3.1 Interferometric readout and displacement sensitivity

*Homodyne readout:* The homodyne readout scheme, also known as DC-offset readout, is an operational mode of the Michelson interferometer that was utilized by the Holometer and is currently being used by LIGO and the QUEST experiments to extract the phase fluctuation signals from the instruments. This operation mode allows the arms length fluctuation signals from the interferometers to be read out as power modulations of light exiting the anti-symmetric ports of the instruments.

As part of a homodyne readout scheme the interferometers are intentionally de-tuned from the dark-fringe condition (which corresponds to perfect destructive interference of the two beams traversing the arms) by maintaining a small macroscopic phase difference (a DC-offset) between the two arms' optical path-lengths. Let this phase de-tuning be denoted as  $\phi_{\text{DC}}$  and the fundamental laser power circulating within each arm be  $P_{\text{arm}}$ .

As a result of this DC offset, the total phase difference between the recombining laser fields on the beam splitter is expected to be  $\Delta\phi = \phi_{\text{DC}} + \delta\phi(t)$ , where  $\delta\phi(t)$  represents the time-dependent phase fluctuation induced by a signal of interest. The macroscopic DC-offset phase is much larger than the signal and satisfies the condition  $\phi_{\text{DC}} \gg \delta\phi(t)$ . The total laser power that exits the anti-symmetric port of the interferometer ( $P_{\text{AS}}$ ) is given by:

$$P_{\text{AS}} = 2P_{\text{arm}} \sin^2 \left( \frac{\phi_{\text{DC}} + \delta\phi(t)}{2} \right) \quad (3.1)$$

Given that this phase difference is small and the instrument is near the dark-fringe condition, the response of the interferometer can be considered to be linear and the small-angle approximation ( $\sin \theta \approx \theta$ ) can be applied:

$$P_{AS} \approx 2P_{\text{arm}} \left( \frac{\phi_{\text{DC}} + \delta\phi(t)}{2} \right)^2 \quad (3.2)$$

$$= \frac{1}{2}P_{\text{arm}}(\phi_{\text{DC}}^2 + 2\phi_{\text{DC}}\delta\phi(t) + \delta\phi(t)^2) \quad (3.3)$$

By neglecting the infinitesimally small second-order term ( $\delta\phi^2$ ), the power exiting the anti-symmetric port can be decomposed into two parts: a DC (static) component,  $P_{\text{DC}}$ , and a fluctuating component,  $\delta P_{\text{sig}}$ , which are defined as:

$$P_{\text{DC}} = \frac{1}{2}P_{\text{arm}}\phi_{\text{DC}}^2 \quad (3.4)$$

$$\delta P_{\text{sig}} = P_{\text{arm}}\phi_{\text{DC}}\delta\phi \quad (3.5)$$

It is important to note that the fluctuations in power exiting the anti-symmetric port are only a result of the time-dependent phase fluctuations  $\delta\phi(t)$ , but the magnitude of  $\delta P_{\text{sig}}$  is directly proportional to both the power in the arms ( $P_{\text{arm}}$ ) and the DC-offset ( $\phi_{\text{DC}}$ ).

## 3.2 Quantum shot noise

### 3.2.1 Quantization and the Coherent State

To model the fundamental noise floor of a laser field, we must treat the electromagnetic field quantum mechanically. A stable, continuous-wave laser field can be represented by a coherent state  $|\alpha\rangle$ .

Let  $\hat{a}$  and  $\hat{a}^\dagger$  be the photon annihilation and creation operators for a single mode of the laser field at angular frequency  $\omega$ . The number operator, which represents the number of photons in the field, is defined as  $\hat{n} = \hat{a}^\dagger\hat{a}$ . By definition, the coherent state is an eigenstate of the annihilation operator:

$$\hat{a}|\alpha\rangle = \alpha|\alpha\rangle \quad (3.6)$$

The expected (mean) number of photons,  $\bar{n}$ , measured over a time interval  $\tau$  is the expectation value of the number operator:

$$\bar{n} = \langle\alpha|\hat{n}|\alpha\rangle = \langle\alpha|\hat{a}^\dagger\hat{a}|\alpha\rangle = |\alpha|^2 \quad (3.7)$$

### 3.2.2 Photon Counting Statistics

Quantum shot noise physically manifests due to the fundamental uncertainty [48, 36] in the arrival time of individual photons, which translates to a variance in the photon number. The variance is given by:

$$\Delta n^2 = \langle \hat{n}^2 \rangle - \langle \hat{n} \rangle^2 \quad (3.8)$$

To evaluate  $\langle \hat{n}^2 \rangle$ , we use the canonical commutation relation  $[\hat{a}, \hat{a}^\dagger] = 1$  to place the operators in normal order (creation operators to the left of annihilation operators):

$$\hat{n}^2 = (\hat{a}^\dagger \hat{a})(\hat{a}^\dagger \hat{a}) = \hat{a}^\dagger (\hat{a} \hat{a}^\dagger) \hat{a} = \hat{a}^\dagger (\hat{a}^\dagger \hat{a} + 1) \hat{a} = \hat{a}^{\dagger 2} \hat{a}^2 + \hat{a}^\dagger \hat{a} \quad (3.9)$$

Taking the expectation value for the coherent state  $|\alpha\rangle$  yields:

$$\langle \hat{n}^2 \rangle = |\alpha|^4 + |\alpha|^2 = \bar{n}^2 + \bar{n} \quad (3.10)$$

Substituting this back into the variance equation:

$$\Delta n^2 = (\bar{n}^2 + \bar{n}) - \bar{n}^2 = \bar{n} \quad (3.11)$$

This result ( $\Delta n^2 = \bar{n}$ ) demonstrates that the photon counting statistics of a coherent laser field follow a Poisson distribution, where the variance is equal to the mean.

### 3.2.3 Power Fluctuations and Spectral Density

In a homodyne detection scheme, we measure optical power rather than discrete photon number. The total energy of  $\bar{n}$  photons is  $E = \bar{n} \hbar \omega$ . When detected over an integration time  $\tau$ , the continuous average (DC) power is:

$$P_{\text{DC}} = \frac{\bar{n} \hbar \omega}{\tau} \implies \bar{n} = \frac{P_{\text{DC}} \tau}{\hbar \omega} \quad (3.12)$$

The variance in the measured power,  $\Delta P^2$ , scales directly with the variance in the photon number:

$$\Delta P^2 = \left( \frac{\hbar \omega}{\tau} \right)^2 \Delta n^2 = \left( \frac{\hbar \omega}{\tau} \right)^2 \bar{n} \quad (3.13)$$

Substituting the expression for  $\bar{n}$  in terms of  $P_{\text{DC}}$  gives:

$$\Delta P^2 = \left( \frac{\hbar \omega}{\tau} \right)^2 \left( \frac{P_{\text{DC}} \tau}{\hbar \omega} \right) = \frac{P_{\text{DC}} \hbar \omega}{\tau} \quad (3.14)$$

To express this noise as a single-sided power spectral density (PSD),  $S_{P, \text{shot}}$  (with units of  $\text{W}^2/\text{Hz}$ ), we relate the time-domain variance to the frequency-domain bandwidth.

According to the Nyquist-Shannon sampling theorem, an integration time  $\tau$  corresponds to an effective measurement bandwidth of  $\Delta f = 1/(2\tau)$ .

For a frequency-independent (white) noise source, the variance in power is the product of the PSD and the measurement bandwidth, yielding  $\Delta P^2 = S_{P,\text{shot}}/(2\tau)$ . Equating this with our derived variance yields a single-sided power spectral density of  $S_{P,\text{shot}} = 2\hbar\omega P_{\text{DC}}$ . Taking the square root gives the amplitude spectral density:

$$S_{P,\text{shot}}^{1/2} = \sqrt{2\hbar\omega P_{\text{DC}}} \quad (3.15)$$

This quantity,  $S_{P,\text{shot}}^{1/2}$ , represents the fundamental shot noise equivalent power fluctuation at the anti-symmetric port as a result of operating the interferometer with a homodyne readout. Because this irreducible quantum noise masks arbitrary power modulations, it dictates the absolute minimum detectable signal. With this fundamental noise floor established, we can now evaluate the ultimate shot-noise-limit of the interferometer's sensitivity by comparing this noise to the expected homodyne signal.

### 3.3 Shot-Noise-Limited sensitivity

To determine the shot-noise-limited sensitivity of an interferometer, the signal-to-noise ratio ( $\text{SNR}_{\text{shot}}$ ) is evaluated by taking a ratio between the signal equivalent power and the root-mean-square (RMS) shot noise power fluctuations. To explicitly track the integration of photon statistics, we first define this ratio in the time domain over an observation time  $\tau$ :

$$\text{SNR}_{\text{shot}} = \frac{\delta P_{\text{sig}}}{\Delta P_{\text{shot}}} \quad (3.16)$$

From Eq 3.14, the RMS power fluctuation over the interval  $\tau$  is  $\Delta P_{\text{shot}} = \sqrt{P_{\text{DC}}\hbar\omega/\tau}$ . Substituting the expanded expressions for both the signal power ( $\delta P_{\text{sig}} = P_{\text{arm}}\phi_{\text{DC}}\delta\phi$ ) and the DC port power ( $P_{\text{DC}} = P_{\text{arm}}\phi_{\text{DC}}^2$ ) results in:

$$\text{SNR}_{\text{shot}} = \frac{P_{\text{arm}}\phi_{\text{DC}}\delta\phi}{\phi_{\text{DC}}\sqrt{\frac{P_{\text{arm}}\hbar\omega}{\tau}}} \quad (3.17)$$

Critically, in this expression the static phase offset  $\phi_{\text{DC}}$  algebraically cancels out, demonstrating that the shot-noise-limited SNR is independent of the homodyne offset phase. Simplifying the expression yields:

$$\text{SNR}_{\text{shot}} = \delta\phi\sqrt{\frac{P_{\text{arm}}\tau}{\hbar\omega}} \quad (3.18)$$

By setting  $\text{SNR}_{\text{shot}} = 1$ , the minimum detectable phase shift ( $\delta\phi_{\text{min}}$ ) for a given observation time is derived as:

$$\delta\phi_{\text{min}} = \sqrt{\frac{\hbar\omega}{P_{\text{arm}}\tau}} \quad (3.19)$$

In the context of interferometric gravitational wave detectors like LIGO and high-frequency experiments like QUEST, measurements are typically characterized in the frequency domain. Applying the Nyquist-Shannon relationship again, the observation time and the effective measurement bandwidth follow:  $\Delta f = 1/(2\tau)$  and we can substitute  $\tau = 1/(2\Delta f)$  into our minimum phase expression:

$$\delta\phi_{\text{min}} = \sqrt{\frac{2\hbar\omega\Delta f}{P_{\text{arm}}}} \quad (3.20)$$

Factoring out the bandwidth yields the fundamental shot noise amplitude spectral density (in  $\text{rad}/\sqrt{\text{Hz}}$ ):

$$S_{\phi,\text{shot}}^{1/2} = \sqrt{\frac{2\hbar\omega}{P_{\text{arm}}}} \quad (3.21)$$

This final expression setting the fundamental sensitivity of an interferometer utilizing a homodyne (DC-offset) readout scheme is determined only by the power circulating in the arms ( $P_{\text{arm}}$ ). As such, interferometric experiments like QUEST are engineered to achieve as high of a circulating laser power as possible to minimize this fundamental quantum noise floor.

### 3.4 Statistics of cross-correlation and averaging

The primary data processing step that the QUEST experiment performs is cross-correlation between the displacement signals generated by the two interferometers operating with a DC-offset readout scheme. This is achieved by performing a Hadamard product (element-wise product) between the discrete complex frequency spectra of the two signals:

$$S_{AB} = F_A^\dagger \odot F_B \quad (3.22)$$

Here  $\odot$  is the Hadamard product and  $F_A$ ,  $F_B$  are the complex frequency spectra output from the interferometers. The result of the Hadamard product is a complex frequency spectrum that has units of power spectral density (PSD) but also preserves the phase information between the two signals. We will refer to this frequency spectrum as cross spectral density (CSD) from now on.

Multiple CSD measurements are averaged to improve the signal-to-noise ratio (SNR) of correlated signals between the two interferometers, against any uncorrelated noise resulting from environmental, thermal, or photon shot noise that is encoded in an

interferometer's output:

$$S_{AB}^N = \frac{1}{N} \sum_{n=1}^N F_{A,n}^\dagger \odot F_{B,n} \quad (3.23)$$

### 3.4.1 SNR Improvement

The complex frequency spectra components  $F_A$  and  $F_B$  are derived by performing a Fast-Fourier transform (FFT) of stochastic time-domain noise, dominated by photon shot noise in the case of QUEST. The Fourier coefficients follow a complex Gaussian distribution where the real and imaginary parts are independent and identically distributed normal variables:

$$\text{Re}(F), \text{Im}(F) \sim \mathcal{N}(0, \sigma^2) \quad (3.24)$$

The mean statistic  $S_{AB}^N$  follows a  $\chi^2$  distribution because it is a linear combination of the product of two Gaussian variables ( $F_A$  and  $F_B$ .) For auto-correlation ( $A = B$ ), the term  $|F|^2 = \text{Re}(F)^2 + \text{Im}(F)^2$  is the sum of two squared normal distributions, which defines a  $\chi^2$  distribution with 2 degrees of freedom. For large  $N$  of averaged CSD spectra, the distribution approaches a Gaussian shape.

For uncorrelated noise sources, the phase relationship between  $F_A$  and  $F_B$  is random, ensuring that the expectation value of the CSD is zero:

$$\langle S_{AB}^N \rangle = 0 \quad (3.25)$$

While the mean is zero, the variance of the estimator decreases as the number of averages  $N$  increases. The standard deviation of the noise  $\sigma_N$  scales as:

$$\sigma_N = \frac{\sigma_A \sigma_B}{\sqrt{N}} \quad (3.26)$$

If a common signal power  $S_{\text{sig}}$  is present in both channels, the signal-to-noise ratio for the *power* improves proportionally to the square root of the number of measurements:

$$\text{SNR}_{\text{power}} = \frac{S_{\text{sig}}}{\sigma_N} = \frac{S_{\text{sig}}}{\sigma_A \sigma_B} \sqrt{N} \quad (3.27)$$

However, the physical field we seek to detect is a displacement amplitude  $h_{\text{sig}}$  (measured in meters), where the signal power is proportional to the square of this amplitude ( $S_{\text{sig}} = |h_{\text{sig}}|^2$ ). Because the minimum detectable power scales as  $N^{-1/2}$ , the minimum detectable physical amplitude that is used to set limits and constraint the presence of detectable signals, scales as  $N^{-1/4}$ . Therefore, the SNR of the physical *amplitude* scales with the 4th root of the number of averages:

$$\text{SNR}_{\text{amp}} = \sqrt{\text{SNR}_{\text{power}}} = \frac{|h_{\text{sig}}|}{\sqrt{\sigma_A \sigma_B}} N^{1/4} \quad (3.28)$$

This  $N^{1/4}$  scaling reflects the incoherent averaging of independent time chunks. It allows us to resolve correlated signals and build statistical power for physical displacements that are significantly weaker than what could be resolved in an individual PSD of a single interferometer, which is dominated by stochastic noise sources such as the photon shot noise.

It is crucial to emphasize that in Eq. 3.27, while the mean of the uncorrelated noise (such as the steady-state shot noise) is incoherently subtracted and approaches zero in the cross-spectral density ( $\langle S_{AB}^N \rangle = 0$ ), the random fluctuations of this noise cannot be subtracted. As seen in the expression for power SNR, these random fluctuations remain in the denominator, represented by  $\sigma_A \sigma_B$ , setting the sensitivity limit. Because the number of averages  $N$  is directly proportional to the total integration time  $T_{\text{obs}}$ , the resulting  $N^{-1/4}$  scaling for the minimum detectable physical amplitude also represents an equivalent  $T^{-1/4}$  measurement sensitivity scaling, for time-varying signals, for integration times longer than their coherence time [49].

### 3.4.2 Detection thresholds and signal amplitude constraints

The threshold to claim a detection of a physical signal, or to set upper limits on its amplitude if no signal is present, is generally parameterized by a statistical significance level  $k\sigma$ . To claim a confident detection, we evaluate the signal power and typically require a  $3\sigma$  excess in the power signal-to-noise ratio ( $\text{SNR}_{\text{power}} \geq 3$ , or  $k = 3$ ). Conversely, if no detection is claimed, the same number of averages  $N$  is used to set an upper limit constraint on the physical displacement amplitude  $h_{\text{sig}}$ .

The number of CSD measurements  $N$  required to reach a  $k\sigma$  power detection threshold, and the resulting constraints on the physical amplitude, depend on the strength and morphology of the correlated signal. The cases for three different signal morphologies are derived here:

#### 1. Monochromatic and narrowband signals

For a signal concentrated within a single discrete FFT frequency bin  $f_i$ , the statistical power is derived solely from temporal averaging. To claim a detection at a  $k\sigma$  threshold, we require the signal power SNR to satisfy  $\text{SNR}_{\text{power}} \geq k$ :

$$\text{SNR}_{\text{power}} = \frac{S_{\text{sig}}}{\sigma_A \sigma_B} \sqrt{N} \geq k \quad (3.29)$$

Solving for  $N$ , the required number of averages to claim a detection is:

$$N_{\text{mono}} \geq k^2 \left( \frac{\sigma_A \sigma_B}{S_{\text{sig}}} \right)^2 \quad (3.30)$$

If no signal is detected after  $N$  averages, the upper limit constraint on the physical displacement amplitude (where  $S_{\text{sig}} = |h_{\text{sig}}|^2$ ) is established by rearranging the same

relationship:

$$|h_{\text{sig}}| \leq \left( k \frac{\sigma_A \sigma_B}{\sqrt{N}} \right)^{1/2} = k^{1/2} \sqrt{\sigma_A \sigma_B} N^{-1/4} \quad (3.31)$$

In this regime, sensitivity is limited strictly by the total integration time  $T_{\text{obs}} = N \cdot \Delta t$ , where  $\Delta t$  is set by the FFT bin width.

## 2. Broadband signals and frequency integration

For a physical signal  $h_{\text{sig}}$  that spans a broad frequency band  $\Delta f$ , across  $M$  independent FFT bins and has a flat spectral shape (the signal power is same in all  $M$  frequency bins), the total SNR improvement is a result of both temporal and spectral averaging. Treating the discrete FFT bins as statistically independent measurements gives a total power SNR of:

$$\text{SNR}_{\text{power, total}} = \frac{S_{\text{sig}}}{\sigma_A \sigma_B} \sqrt{N \cdot M} \geq k \quad (3.32)$$

To achieve a  $k\sigma$  power detection for a flat broadband signal, the required number of temporal averages is reduced by the factor  $M$ :

$$N_{\text{flat}} \geq \frac{k^2}{M} \left( \frac{\sigma_A \sigma_B}{S_{\text{sig}}} \right)^2 \quad (3.33)$$

Conversely, if no detection is made after  $N$  averages, the upper limit constraint placed on the broadband physical amplitude  $h_{\text{sig}}$  is:

$$|h_{\text{sig}}| \leq k^{1/2} \sqrt{\sigma_A \sigma_B} (N \cdot M)^{-1/4} \quad (3.34)$$

This allows us to place constraints on a broadband  $h_{\text{sig}}$  that is significantly weaker than what could be resolved in any individual frequency bin, for a given observation time  $T_{\text{obs}}$ .

## 3. Optimal filtering for shaped spectra

For correlated physical signals with a known non-flat spectral shape  $h_{\text{sig}}(f_j)$ , the sensitivity is maximized using a weighted optimal filter. The total discrete optimal power SNR adds in quadrature across bins:

$$\text{SNR}_{\text{power, opt}} = \sqrt{N} \left[ \sum_{j=1}^M \frac{|h_{\text{sig}}(f_j)|^4}{P_A(f_j) P_B(f_j)} \right]^{1/2} \geq k \quad (3.35)$$

where  $P_A$  and  $P_B$  are the shot-noise-limited PSDs of the two interferometers respectively. Setting  $\text{SNR}_{\text{power, opt}} = k$ , the required number of averages  $N_{\text{opt}}$  for a shaped spectrum to claim a detection must satisfy:

$$N_{\text{opt}} \geq k^2 \left[ \sum_{j=1}^M \frac{|h_{\text{sig}}(f_j)|^4}{P_A(f_j) P_B(f_j)} \right]^{-1} \quad (3.36)$$

If no detection is made, we can constrain the overall physical amplitude scale of the spectrum. By parameterizing the signal as  $|h_{\text{sig}}(f_j)|^2 = h_0^2 \bar{S}(f_j)$ , where  $h_0$  is the amplitude scale and  $\bar{S}(f_j)$  is the normalized spectral shape, the constraint on  $h_0$  for a given number of averages  $N$  is:

$$h_0 \leq k^{1/2} N^{-1/4} \left[ \sum_{j=1}^M \frac{\bar{S}(f_j)^2}{P_A(f_j)P_B(f_j)} \right]^{-1/4} \quad (3.37)$$

In QUEST, the signals from stochastic gravitational waves and dark matter candidates are treated independently for each FFT bin, while in the case of quantum gravity signatures a spectra-averaged metric is used to claim detection or set limits. Further details on these signal sources is presented in Chapter 2.



## Chapter 4

# The QUEST Experiment

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The interferometers in QUEST are designed to be sensitive to a broad frequency band (1 - 250 MHz) [7]. To achieve this, QUEST consists of two power-recycled Michelson interferometers (PRMI) that are co-located and co-aligned. The signal coherence between the interferometers is characterized by their inter-arm separation of 0.45 m in the realized experiment [50], leading to signals between the instruments being in-phase for frequencies up to 330 MHz (section 2.1.1). This allows for full-bandwidth and real-time cross-correlation calculation to be performed between the two interferometer outputs without the use of computationally expensive optimal filters.

The optical configuration of LIGO detectors is known as dual-recycled Fabry-Perot Michelson interferometry. In LIGO, resonant Fabry-Perot cavities are used in the arms to achieve a high circulating power, but this comes at the direct expense of bandwidth. An arm cavity acts as a single-pole low-pass filter [48] for the gravitational wave signal, with a frequency response characterized by the cavity pole frequency,  $f_{\text{pole}}$ , given by:

$$f_{\text{pole}} = \frac{c}{4L\mathcal{F}} \quad (4.1)$$

where  $c$  is the speed of light,  $L$  is the length of the arm cavity, and  $\mathcal{F}$  is the cavity finesse. Because circulating power enhancement is directly proportional to  $\mathcal{F}$ , achieving high power fundamentally lowers the cutoff frequency, restricting the detector's sensitivity bandwidth. As LIGO targets audio band sources of gravitational waves, this design choice is favored over achieving a broadband detector.

The broadband sensitivity requirement of QUEST restricts the use of optical designs that selectively improve sensitivity in a narrow part of the spectrum, such as arm cavities and signal recycling. Similar to the Holometer, the interferometers in QUEST achieves the resonant enhancement of the circulating power, with the use of just a power recycling cavity (PRC). This provides a mechanism to increase the effective laser power directly on the beam splitter, by which the sensitivity of the interferometer can be improved uniformly over a broad frequency range without introducing a low-pass filtering effect as seen in the LIGO detectors.

The design of the QUEST experiment [7] targets a circulating power of 5 kW in the arms of each interferometer, corresponding to 10 kW on the beam splitters. As QUEST aims to make measurements of irreducible quantum uncertainties in measurements of space-time, with the goal to test and discriminate between various models, it has been designed to allow various interferometer geometries. Specifically, Kwon's model of quantum gravity (see section 2.3) dictates the need for an interferometer configuration that can capture out-of-plane (3D) space-time fluctuations. As such, QUEST's final interferometer design targets a configurable setup, where parameters such as the angle of the arms at the beam splitter, 3D-bent-arms etc. can be varied.

Thus far, the QUEST interferometers have been commissioned with 1.83 m long straight arms with an intra-arm angle of  $90^\circ$  at the beam splitters. A staggered upgrade cycle has been planned; the first commissioning cycle and the details of its corresponding science run are presented in chapters 5 and 6, respectively. Further commissioning of the instrument with a target science run is underway, with details presented in chapter 7. Comparison between instrument's various parameters such as the arm lengths, circulating powers, expected displacement sensitivities and other technical details that are different across these stages are shown in Table 4.1.

## 4.1 QUEST systems design

### 4.1.1 Interferometer configuration

The schematic for a single power-recycled Michelson interferometer (PRMI) in QUEST is shown in Figure 4.1. The interferometer consists of four core optics: the beam splitter (BS), two end mirrors (EX, EY), and a power recycling mirror (PRM).

The BS, EX, and EY form a simple Michelson interferometer. The critical longitudinal degree of freedom for this system is the differential arm (DARM) length, defined as  $\Delta L = l_X - l_Y$ . The response of a simple Michelson follows:

$$P_{\text{ASymm}} = P_{\text{BS}} \sin^2 \left( \frac{2\pi \Delta L}{\lambda} \right) \quad (4.2)$$

$$P_{\text{Symm}} = P_{\text{BS}} \cos^2 \left( \frac{2\pi \Delta L}{\lambda} \right) \quad (4.3)$$

where  $P_{\text{ASymm}}$  (not to be confused with the photodetector label  $\text{PD}_{\text{AS}}$ ),  $P_{\text{Symm}}$ , and  $P_{\text{BS}}$  are the laser power exiting the anti-symmetric (AS) port, the power reflected back to the symmetric port, and the power injected onto the beam splitter, respectively. The AS-port is where the main signal output of the interferometer is measured.

**Table 4.1.** Comparison of QUEST optical configurations between the design and the science runs.

|                              | 3D Configuration [7]              | SR1 [50]                | SR2                               |
|------------------------------|-----------------------------------|-------------------------|-----------------------------------|
| Arm length                   | 3 m                               | 1.83 m                  | 1.83 m                            |
| Arm configuration            | Folded out of plane               | Straight                | Straight                          |
| Angle at the BS              | 45° (designed for various angles) | 45°                     | 45°                               |
| PRM reflectivity             | 99.9 %                            | 99.5 %                  | 99.5 %                            |
| End mirror transmissivity    | 13 ppm                            | 13 ppm                  | 13 ppm                            |
| Core optic substrate         | –                                 | Suprasil 3001           | Suprasil 3001                     |
| Power on the BS              | 10 kW                             | 100 W                   | 1 kW                              |
| IFO displacement sensitivity | $\approx 10^{-19}$ m              | $5.5 \times 10^{-18}$ m | $1.0 \times 10^{-18}$ m           |
| Integration time             | $10^6$ s                          | $10^4$ s                | $\geq 10^6$ s (planned)           |
| Vibration isolation          | Optical table                     | Optical table           | Optical table and viton isolation |
| Contrast defect (CD)         | 1 ppm                             | 32 ppm                  | 32 ppm                            |
| Output Mode-cleaner (OMC)    | Yes                               | Tested but not used     | Tested but not used               |
| Squeezing                    | 10 dB                             | Tested but not used     | Tested but not used               |
| Detection bandwidth          | 250 MHz                           | 80 MHz                  | $\geq 100$ MHz                    |
| Angular Dofs stabilization   | –                                 | –                       | Yes (automatic script)            |
| Auto-relock                  | –                                 | –                       | Yes                               |

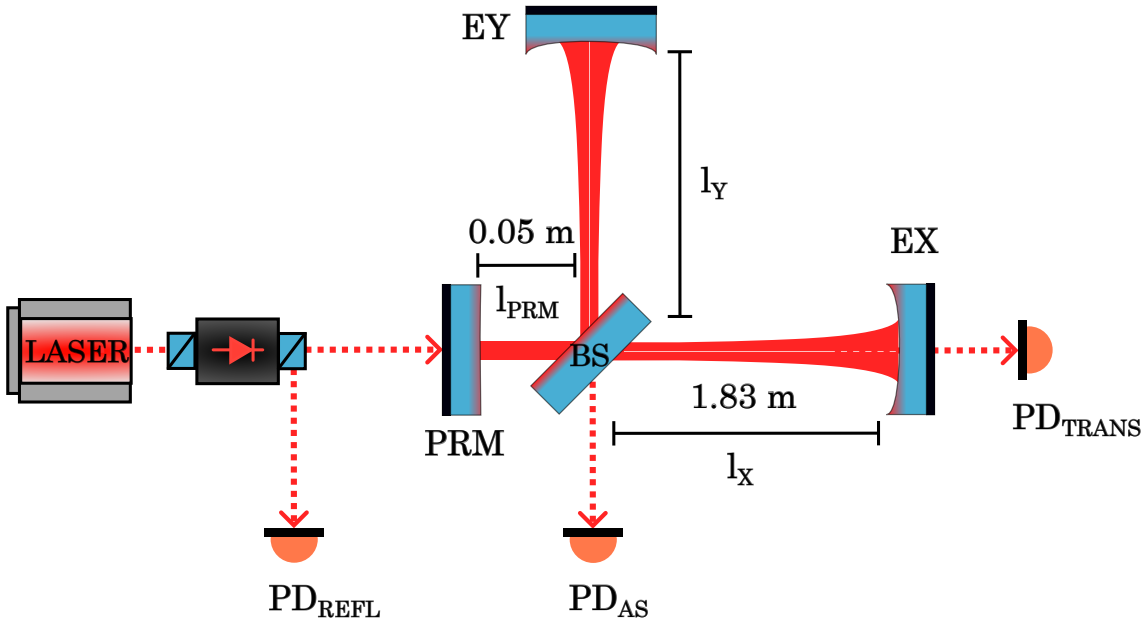


**Figure 4.1.** The optical layout of QUEST's power-recycled Michelson interferometer is shown. The core optics are housed in vacuum chambers, while the main photo-detectors, laser source are in air. Auxiliary optics such as lens, half and quarter waveplates, beamdumps etc. has not been shown.

The simple Michelson interferometer can be treated as a mirror whose effective power reflectivity,  $R_{\text{MI}}$ , can be controlled using the DARM length ( $\Delta L$ ):

$$R_{\text{MI}} = \frac{P_{\text{Symm}}}{P_{\text{BS}}} = \cos^2 \left( \frac{2\pi \Delta L}{\lambda} \right) \quad (4.4)$$

*Power Recycling Cavity response:* The PRM and the compound mirror of the simple Michelson comprise the power recycling cavity (PRC). The role of the PRC is to resonantly enhance the power circulating in the interferometer arms. To observe this resonant enhancement, the length of the cavity must be maintained as an integer multiple of half the laser wavelength ( $2L_{\text{PRC}} = n\lambda$ ) or equivalently, its frequency. The power circulating in the PRC follows the relation:

$$P_{\text{circ}} = P_{\text{in}} \left| \frac{t_{\text{PRM}}}{1 - r_{\text{PRM}} \cdot r_{\text{MI}} \cdot e^{-i \frac{4\pi L_{\text{PRC}}}{\lambda}}} \right|^2 \quad (4.5)$$

$$\equiv P_{\text{in}} \frac{T_{\text{PRM}}}{\left| 1 - \sqrt{R_{\text{PRM}} \cdot R_{\text{MI}}} \cdot e^{-i \frac{4\pi L_{\text{PRC}}}{\lambda}} \right|^2} \quad (4.6)$$

Here,  $P_{\text{in}}$  and  $P_{\text{circ}}$  denote the input and circulating powers of the cavity, respectively. The parameters  $R_{\text{PRM}}$  and  $T_{\text{PRM}}$  are the power reflectivity and transmissivity of the power recycling mirror, which, alongside intracavity losses, satisfy  $R_{\text{PRM}} + T_{\text{PRM}} + \text{loss} = 1$ . The corresponding amplitude reflectivity and transmissivity for this mirror are given

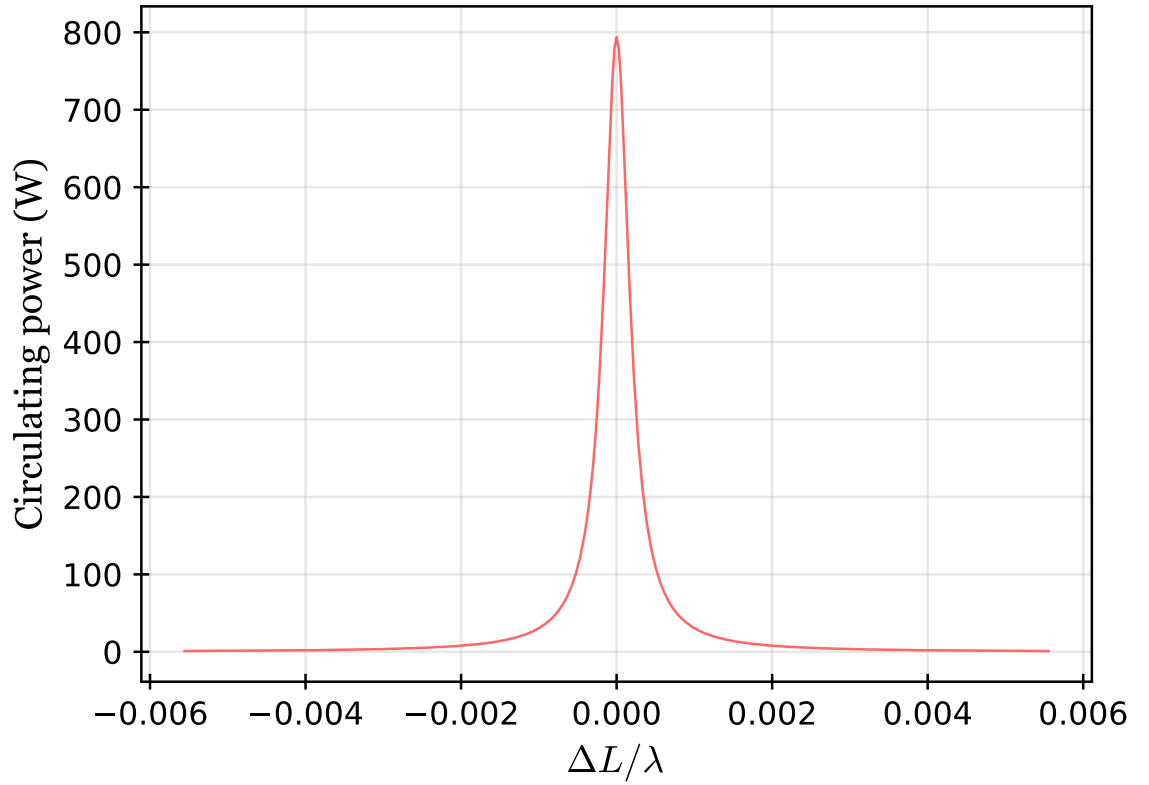


**Figure 4.2.** The power of the circulating laser field inside a cavity, simulated using Eq 4.6, is shown. Resonance enhancement occurs when  $2L_{\text{PRC}} = n\lambda$  for integer  $n$ . Parameters of core optics such as: reflectivities and transmissivities of the power recycling mirror and end mirror, corresponding to the lossless case of QUEST's power recycling cavity (see Section 4.1.2), were chosen for this simulation.

by  $r_{\text{PRM}} = \sqrt{R_{\text{PRM}}}$  and  $t_{\text{PRM}} = \sqrt{T_{\text{PRM}}}$ . Additionally,  $r_{\text{MI}} = \sqrt{R_{\text{MI}}}$  represents the amplitude reflectivity of the compound mirror formed by the Michelson interferometer. Finally,  $L_{\text{PRC}}$  defines the effective length of the recycling cavity, expressed as:

$$L_{\text{PRC}} = l_{\text{PRC}} + \frac{l_X + l_Y}{2} \quad (4.7)$$

The AS-port response of a full power-recycled Michelson interferometer (PRMI) as a function of DARM ( $\Delta L$ ) is a consequence of both Eq 4.2 and Eq 4.6. Although an analytical expression can be derived, it is more convenient to solve for the response numerically. Figure 4.3 shows the simulation of the normalized power exiting the AS-port.

#### 4.1.2 Core optics

The core optics for the QUEST experiment were a custom purchase from Laseroptik, where the optics were both polished and coated. The substrate material chosen for all the optics is Heraeus Suprasil 3001 [51]. The quoted absorption coefficient for the

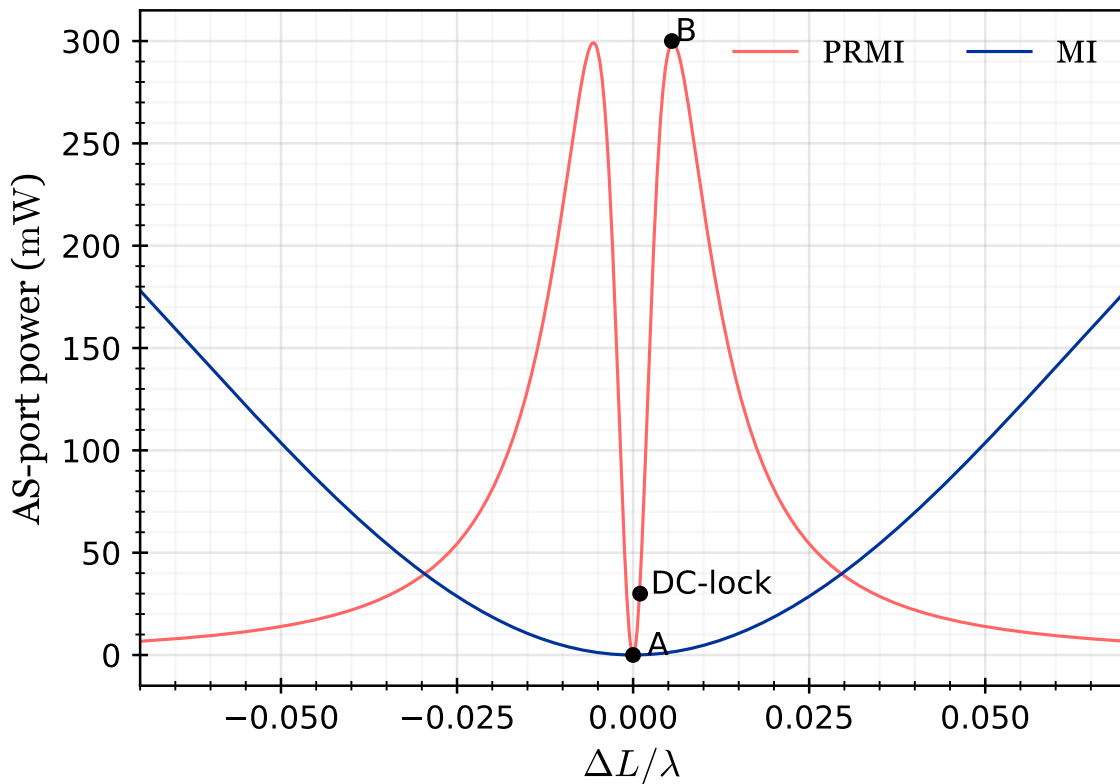


**Figure 4.3.** Simulated power exiting the anti-symmetric port of a PRMI and a simple Michelson interferometer (MI) as a function of  $\Delta L/\lambda$ . The simulation parameters are chosen to represent the lossless case of the fiducial QUEST interferometers during Science Run 1. Point A is the dark-fringe condition, and point B is the maximum transmitted power through the AS-port, corresponding to about 5.5 nm away from the dark-fringe. The “DC-lock” is the typical operating point for science data taking, corresponding to 30 mW or about 1 nm of offset from the dark-fringe. The numerical simulation needed to generate this data was performed using Finesse [5].

substrate is 0.25 ppm/cm. A low absorption coefficient is essential for the beam splitters to accommodate the high circulating laser powers of the QUEST design.

**End mirrors:** The end mirrors are 25 mm in diameter and 6 mm thick. The front surface of the mirrors is curved with a radius of curvature of 6 m. This same surface is coated with a high-reflective coating throughout to the edge of the optic. The coating’s transmissivity was measured to be 13 ppm.

**Beam splitters:** The beam splitters are also circular optics with a 25 mm diameter and 6 mm thickness. The front surface is coated with a 50:50 reflective coating, and the back surface is coated with an anti-reflective coating. The beam splitters are wedged to prevent parasitic interference caused by internal reflections within the optic. The wedge angle is  $0.6^\circ$  (about 0.01 rad). This wedge angle allowed for the measurement of the anti-reflective coating’s reflectivity, which was found to be about 178 ppm. Further characterization of the beam splitter is presented in section 7.1.2.

**Power recycling mirrors:** The power recycling mirrors used are flat and are also 25 mm in diameter with a 6 mm thickness. Various reflectivities for the PRM were purchased: 99.5 %, 99.9 %, and HR (13 ppm transmission). The 99.5 % reflective PRMs were used for the commissioning and operation of the interferometers during Science Run 1.

### 4.1.3 Laser injection system

Two identical copies of the laser injection system (LIS) were commissioned, one for each PRM in QUEST. The LIS provides a carefully engineered input laser beam that meets the necessary beam geometry requirements of the interferometers. These systems also provide the seed beam necessary to generate the bright squeezed beam required by the QUEST design.

The main laser source for each LIS is a Coherent Mephisto non-planar ring oscillator (NPRO) continuous-wave laser that outputs up to 0.5 W of power at an infrared (IR) wavelength of 1064 nm. To meet the necessary power requirements, a free-space amplifier stage is used (neoLASE neoVAN). These setups were tested up to a maximum continuous operating laser power of 24 W. Complete polarization control stages (half and quarter waveplates) and Faraday isolators are installed immediately after the laser and the amplifier stages to prevent back-reflections and parasitic interference.

Each LIS is always operated with a steady-state output power of 15 W, with most of the power being dumped using a power control stage consisting of a half-wave plate and a polarizing beam splitter that is part of a Faraday isolator. This allows for the commissioning of optimal beam-shaping telescopes to meet the seed beam geometry requirements of the amplifier stages, which is a function of the thermal lens formed by the high laser power in the solid-state amplification medium. To achieve this, a 100 mW seed beam from the NPRO laser is fed into the amplification stage, which is operated with 10 A of diode current.

The final components of the LIS are the electro-optic modulators (EOMs), used to induce phase modulation sidebands onto the IR carrier wave. These sidebands are used as references in the Pound-Drever-Hall sensing scheme for laser frequency stabilization (see Section 4.2). The laser frequency actuators are the NPRO cavity PZT and the cavity temperature, both of which are used for frequency stabilization. The amplitude noise of the laser is not actively suppressed; the PRC provides passive isolation against amplitude noise in the science frequency band.

The interferometers in QUEST are designed to operate with s-polarization of the laser light circulating in their PRC. The laser light exiting the LIS is shifted to contain just s-pol using a final set of half and quarter waveplates. In a similar way, following the LIS is a mode-matching telescope used to shape the injected beam for the interferometer. A schematic of the LIS is shown in Figure 4.4.

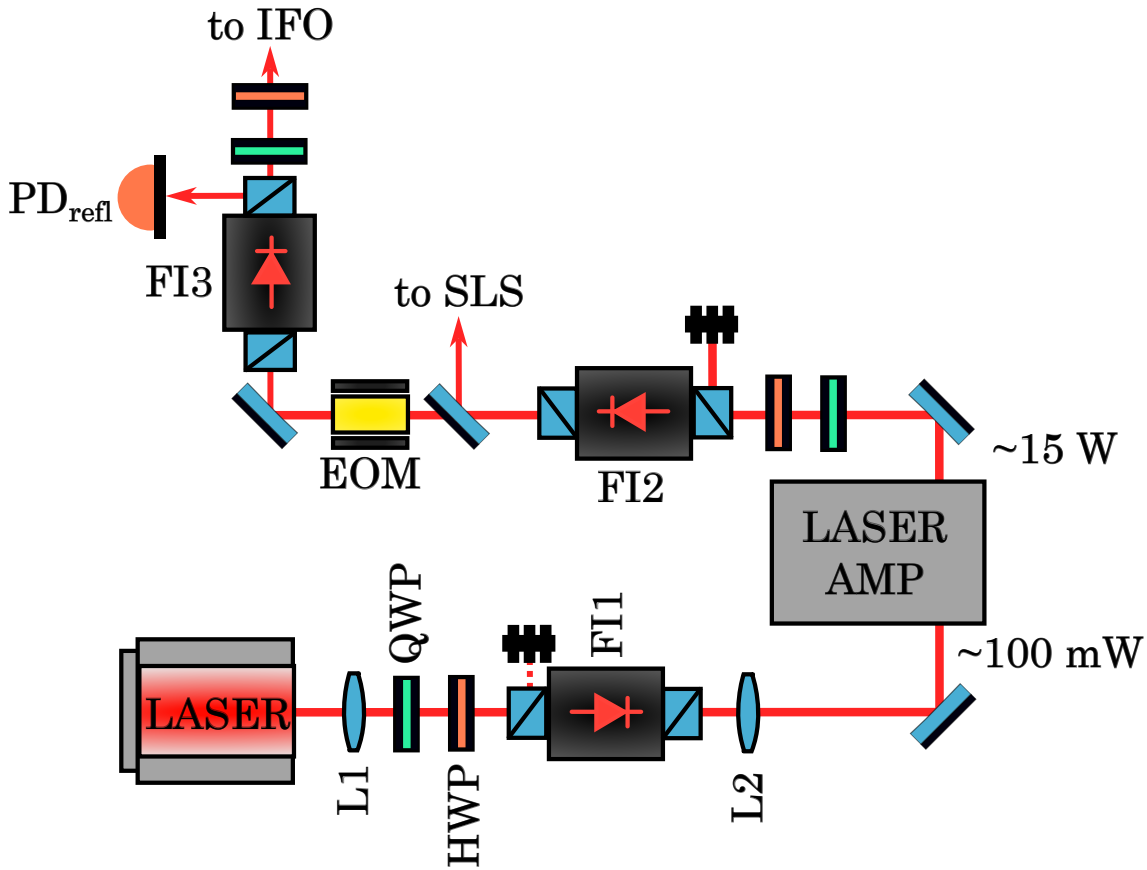


**Figure 4.4.** A schematic of the laser injection system (LIS) commissioned to be used for each interferometer in QUEST is shown. The components, including the NPRO laser, amplifier stage, Faraday isolators and half and quarter waveplates are displayed. The Faraday isolator after the laser amplifier stage (FI2) and a set of waveplates before it, are used to dump excess laser power and filter the polarization of the beam. The final electro-optic modulator (EOM) is used to introduce phase-modulation sidebands needed for the Pound-Drever-Hall locking scheme (see Section 4.2) of the PRC. A branch of the main output beam is split using a beam splitter and is used as the seed beam for the squeezed light source (SLS).

#### 4.1.4 Readout optics and fast photodetectors

The laser field exiting through the AS port of the interferometer carries the encoded signal of DARM length fluctuations. The Gaussian spatial eigenmode of the exiting beam is set by the PRC and is shown in Figure 4.5. A small portion ( $\sim 1\%$ ) of this beam is sampled to be used as a DARM control signal and for diagnostics, but the majority of the laser power is telescoped down to a beam radius of 0.25 mm and is captured using custom, high-bandwidth photo detectors.

**Fast photodetectors:** The custom detectors used for collecting the science data are modified New Focus 1811-FS photodetectors. These detectors have been modified by replacing their original photodiodes with 1 mm diameter Excelitas C30641GH InGaAs diodes. These diodes have a responsivity of  $0.8 \text{ A/W}$ , and as part of this custom

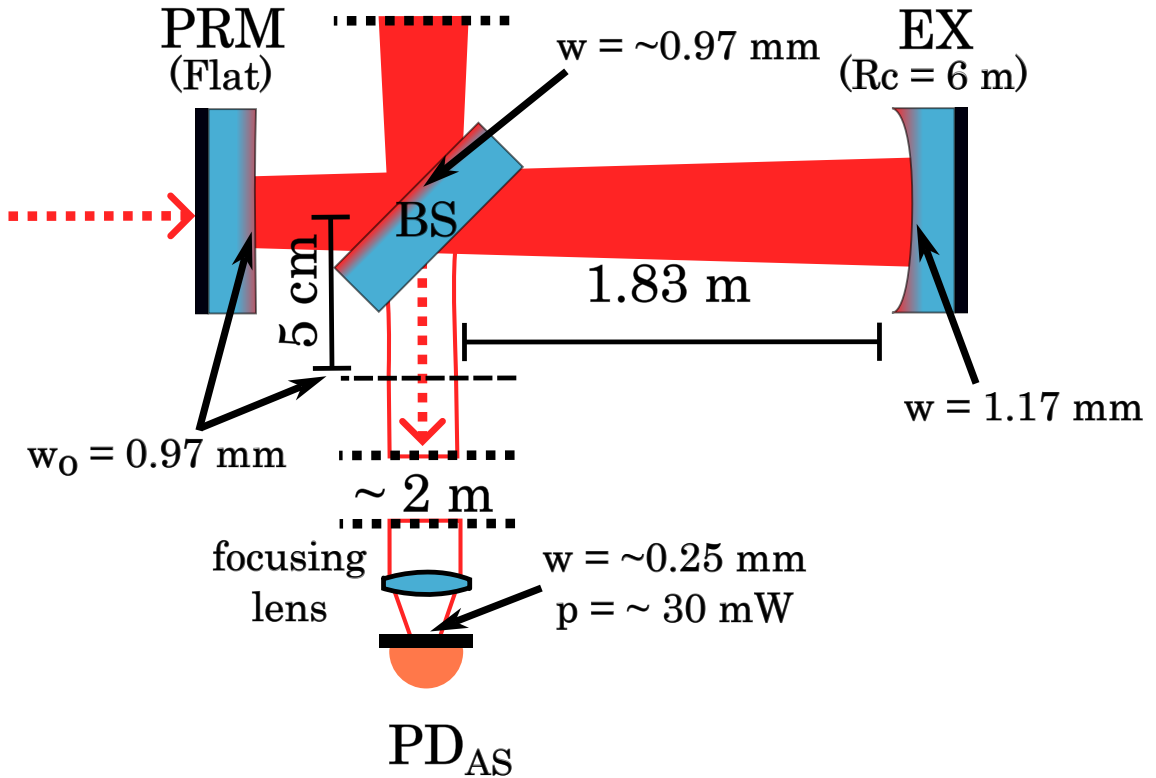


**Figure 4.5.** Beam geometry for the anti-symmetric output of a QUEST interferometer. The beam circulating in the power recycling cavity sets the size of the exiting beam. For the interferometer commissioned as part of SR1, the exiting beam was collimated with a waist radius of about 0.97 mm. The beam is focused down to a radius of about 0.25 mm before being captured by a photodetector with a 1 mm diameter active area.

implementation, they are biased with 7.5 V. The New Focus detectors implement two transimpedance amplifier signal output paths: a DC path and an AC path. The circuit diagram of the detector is presented in Figure A.5.

The AC path front-end amplification stage is decoupled from the DC photocurrent generated by the diode using a complex high-pass filter at 80 kHz. These modifications have been tested for the continuous capture of up to 40 mW of laser power with a detection bandwidth of 80 MHz. Figure 4.6 shows the dark noise of the detector, as well as the photodetector's response to shot noise from various levels of photocurrents induced using a white light source. This figure also presents the signal from the output of the interferometer, locked with a homodyne DC-offset lock at 30 mW.

#### 4.1.5 High-frequency data acquisition system

The signals from the two fast photodetectors are initially processed using analog bandpass filters (1–250 MHz) to suppress low-frequency technical noise and isolate the relevant scientific frequencies. To meet the 250 MHz bandwidth requirement of the QUEST experiment, these signals are digitized at a rate of 500 megasamples per second

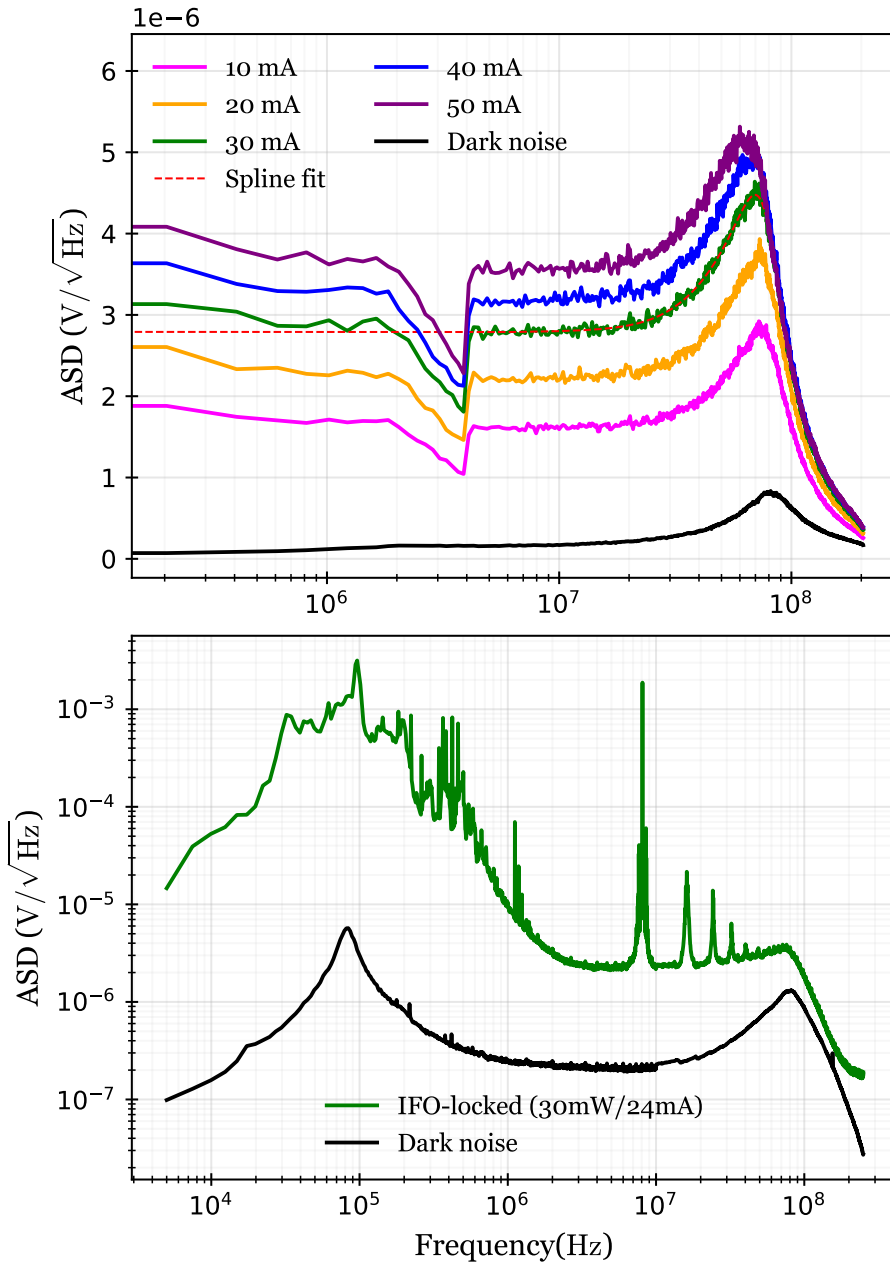


**Figure 4.6.** The top plot shows the shot noise limited spectra obtained from the AC path of the custom fast photodetectors at various photocurrent levels. The photocurrents were induced using a white light source and were measured using the DC part of the detector, which has a standard 10 mV/mA response. The anomalous notches in the shot noise measurements at about 4 MHz are a measurement artifact and not present in the detectors real response. A spline fit of the shot noise corresponding to 30 mA of photocurrent is also shown, this fit is used to calibrate the science data and correct for the photodetector response. The bottom plot shows a measurement of custom detector's dark noise amplitude spectrum and the amplitude spectrum measurement of AS-port power with the full PRMI locked at a DC-offset of 30 mW of laser power, which roughly corresponds to 24 mA of photocurrent. The 8 MHz sideband and harmonics used for the PDH lock (Section 4.2) of the PRC can be seen.

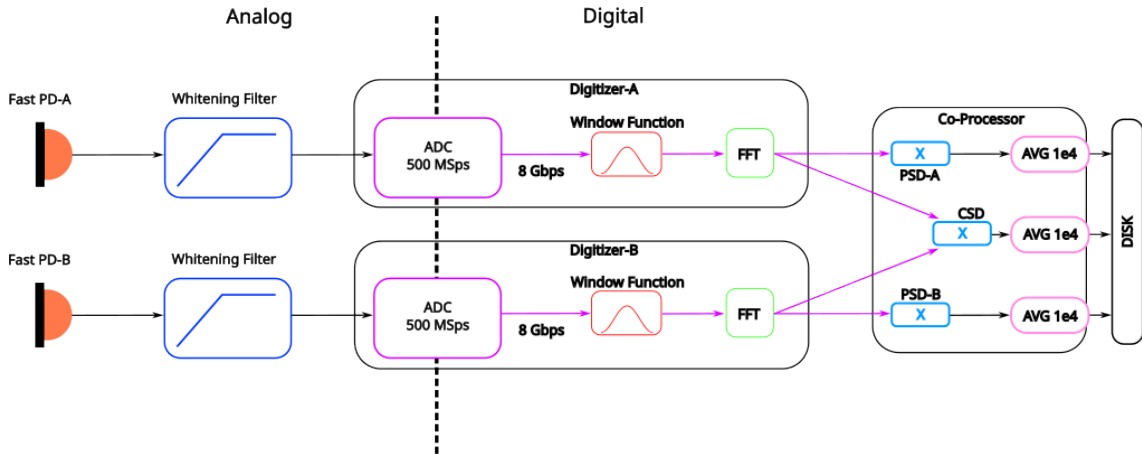


**Figure 4.7.** Schematic showing the data flow for the high-frequency data. The analog signals from the fast photodetectors are whitened and digitized at 500 megasamples per second (MS/s). Online windowing, FFT, and CSD operations are performed before the data are averaged and stored to disk.

(MS/s) with a 16-bit resolution. Digitizing two channels at this sampling rate and resolution yields a total data rate of 16 gigabits per second (Gb/s). Storing continuous time-series data at this rate is non-trivial; instead, averaging frequency-domain spectra provides a convenient method for data compression. This comes at the cost of losing the ability to search for transient signals that are shorter in duration than the averaging time.

A real-time data acquisition and processing system is implemented using a National Instruments (NI) FPGA platform, consisting of two NI PXIe-5763 digitizers and an NI PXIe-7915 co-processor hosted in an NI PXIe-1092 chassis. For both sampled channels, a window function is applied, and a Fast Fourier Transform (FFT) is computed over time segments of 32,768 samples, corresponding to  $65.54 \mu\text{s}$  of observed data. This yields a spectral frequency resolution of 15.250 kHz. To preserve information, the one-sided, complex-valued FFTs are propagated to calculate two power spectral densities (PSDs) and one cross-spectral density (CSD). The mean of  $10^4$  spectra is then calculated to compress the data, representing a total observation period of 0.655 s. These averaged spectra are subsequently written to a storage server as a single “frame”.

Offline post-processing of these frames includes correcting for the photodetector response and vetoing frames that correspond to periods of interferometer lock-loss. Finally, the frames are further averaged to produce the final displacement spectral density for the full observation period. Figure 4.7 presents a data-flow diagram for the fast data acquisition system.

The ADC-limited correlated noise floor of the high-frequency data acquisition system was experimentally evaluated. The input to the ADC channels were terminated with  $50 \Omega$  terminations and the cross-correlation pipeline was run for about 5000 samples. This measurement yielded a correlated floor measurement of about  $5 \times 10^{-20} \text{ V}^2/\text{Hz}$ ,

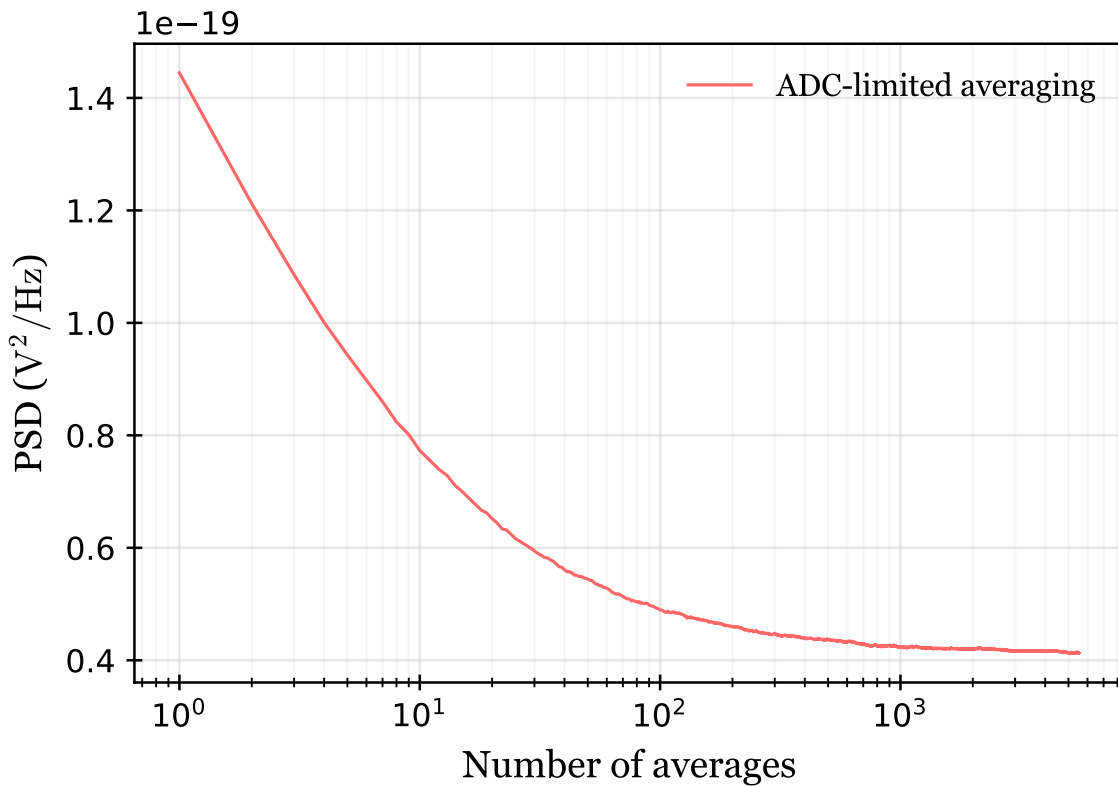


**Figure 4.8.** The ADC-limited correlated noise floor of the fast data acquisition and processing pipeline is measured. This was performed by terminating the ADC inputs with  $50\Omega$  and then averaging the resulted cross-correlation measurements. The median frequency bin ADC-limited averaging trend is shown.

shown in Figure 4.8, which is about five orders of magnitude below the required noise floor for the shot noise cross-correlation tests conducted in the QUEST experiment [52].

#### 4.1.6 Vibration isolation

The interferometers in QUEST are mounted on custom optical tables that are passively isolated from ground motion using damped pneumatic legs. The bounce modes (vertical/ $z$ -axis motion) of the tables are isolated as a result of mechanical resonances formed by the table-leg systems in the 10–100 Hz range. This effectively attenuates acoustic-band noise (100–3000 Hz) that would otherwise couple through the ground. Further care was taken to minimize ambient acoustic noise inside the cleanrooms by installing most of the noisy electronics inside acoustically insulated server racks, or on top of aluminum frames that are mechanically decoupled from the optical tables.

During SR1, the RMS DARM motion was directly dominated by acoustic pick-up from the vacuum chambers. This was confirmed by toggling the power of noisy equipment, such as the water chiller and auxiliary computers etc. One such noisy coupling was found to be from the electronic vacuum gauges used to monitor each chambers pressure. An on/off test and corresponding AS port spectra from interferometer-A has been shown in

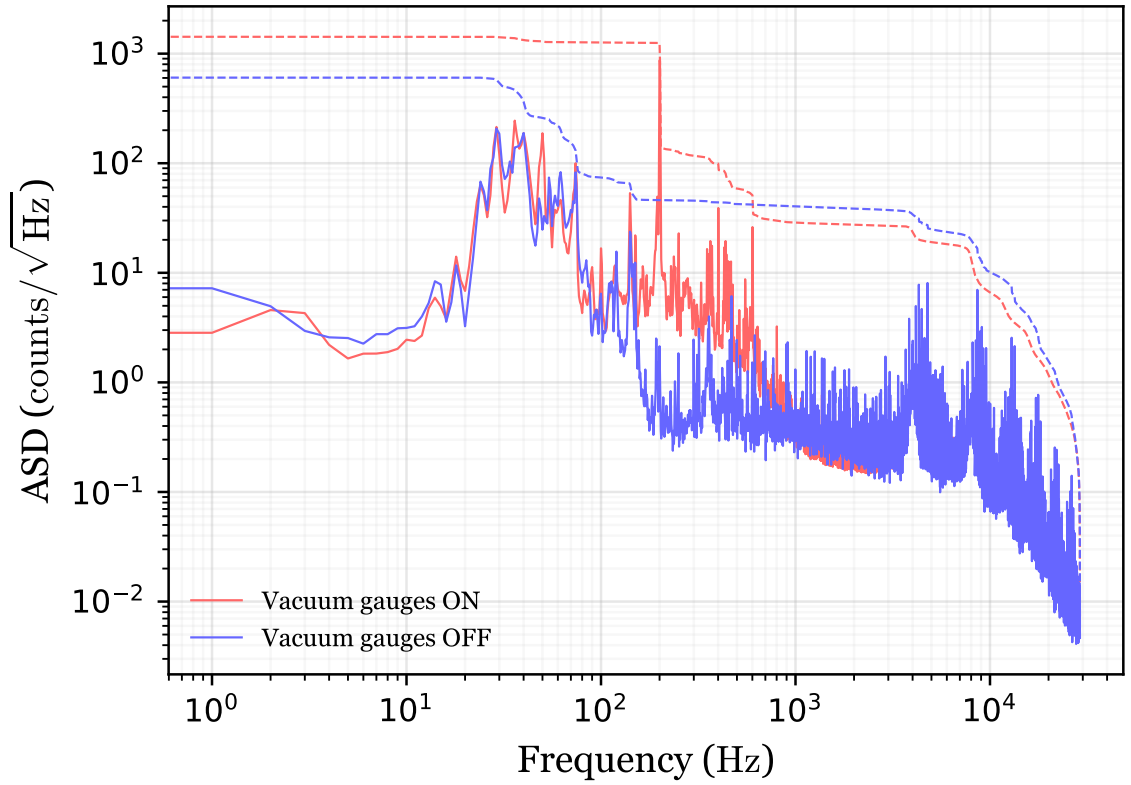


**Figure 4.9.** The AS port spectra comparing the on/off state of three vacuum gauges, one per chamber of interferometer-A, is shown. The measured spectra is in amplitude spectral density units of uncalibrated counts, but it shows a relative excess noise in the 200 - 700 Hz band of the spectra.

Figure 4.9, which shows significant additional noise at audio frequencies. Suppression of this acoustic noise pick up in the 200 - 700 Hz band strongly dictated the feedback control loop design for DARM and following SR1, in-vacuum vibration isolation have been commissioned (Section 7.2).

#### 4.1.7 Vacuum systems and environmental control

The interferometers in QUEST are housed in two separate vacuum envelopes, which are operated at ultra-high vacuum pressures of  $5 \times 10^{-8}$  mbar. Each vacuum system consists of three chambers: one beam splitter chamber and two end chambers, which are connected by arm tubes. The beam splitter chamber houses both the power recycling mirror and the beam splitter, while the EX and EY end chambers hold the EX and EY mirrors, respectively.

Each vacuum envelope is equipped with three turbo-molecular pumps, three ion pumps, and one main roughing pump, which are used to achieve and maintain ultra-high vacuum pressures. The main pump is used to evacuate the envelope from 1000 mbar down to 1 mbar, after which the turbo-molecular pumps reduce the pressure to  $10^{-7}$  mbar over a period of 24 hours. During steady-state operation, the system pressure is maintained

solely by the non-mechanical ion pumps. This allows the interferometers to operate without mechanical or acoustic noise from the vacuum system coupling into the core optic motion.

The lab space where the QUEST experiment is located is a climate-controlled, class 10,000 cleanroom. The HVAC system maintains particle counts below 1000 particles per cubic foot for particle diameters greater than  $0.3\ \mu\text{m}$ . The temperature and humidity of the lab are maintained at  $20^\circ\text{C}$  and 65%, respectively. This temperature stabilization protects the interferometers against slow drifts in their longitudinal and angular degrees of freedom.

## 4.2 Control systems design

Many systems in the QUEST experiment need to be stabilized against environmental noise that couple to the motion of the optics or cause laser frequency to drift. Real-time servo loops are engineered that lock these systems to their respective operating points. To implement these servo loops, two main systems are used:

### 4.2.1 Control hardware and software

*LIGO's Control and Data Acquisition system:* The LIGO CDS system is used to implement the controls and feedback servos at audio band frequencies, as well as to acquire analog data and keep record of the interferometer's state. The system operates a real-time sampling loop at 65 kilo-samples per second with 32 ADC and 32 DAC channels with 16-bits of resolution. This system is also used to operate high-resolution CMOS cameras to observe the beam exiting through various ports of the interferometer [53].

The state of the interferometers is managed using custom-made graphical user interfaces using Motif and Display Manager (MEDM) software and critical state parameters such as actuator offsets, loop gains, runtime sensor calibration etc. are pragmatically maintained using Experimental Physics and Industrial Control System (EPICS) and Python scripts.

The CDS system provides tools to implement infinite impulse-response (IIR) filter of arbitrary length. Internally, they are implemented as a series of biquad filters [54], each parameterizing a pair poles and zeros.

*Liquid instrument's MOKU:* The MOKU:Pro is a programmable logic instrument with four input and four output channels, operating at 300 mega-samples per second. In QUEST, Mokus are used to implement feedback loops with high control bandwidth requirements, such as the frequency stabilization loops.

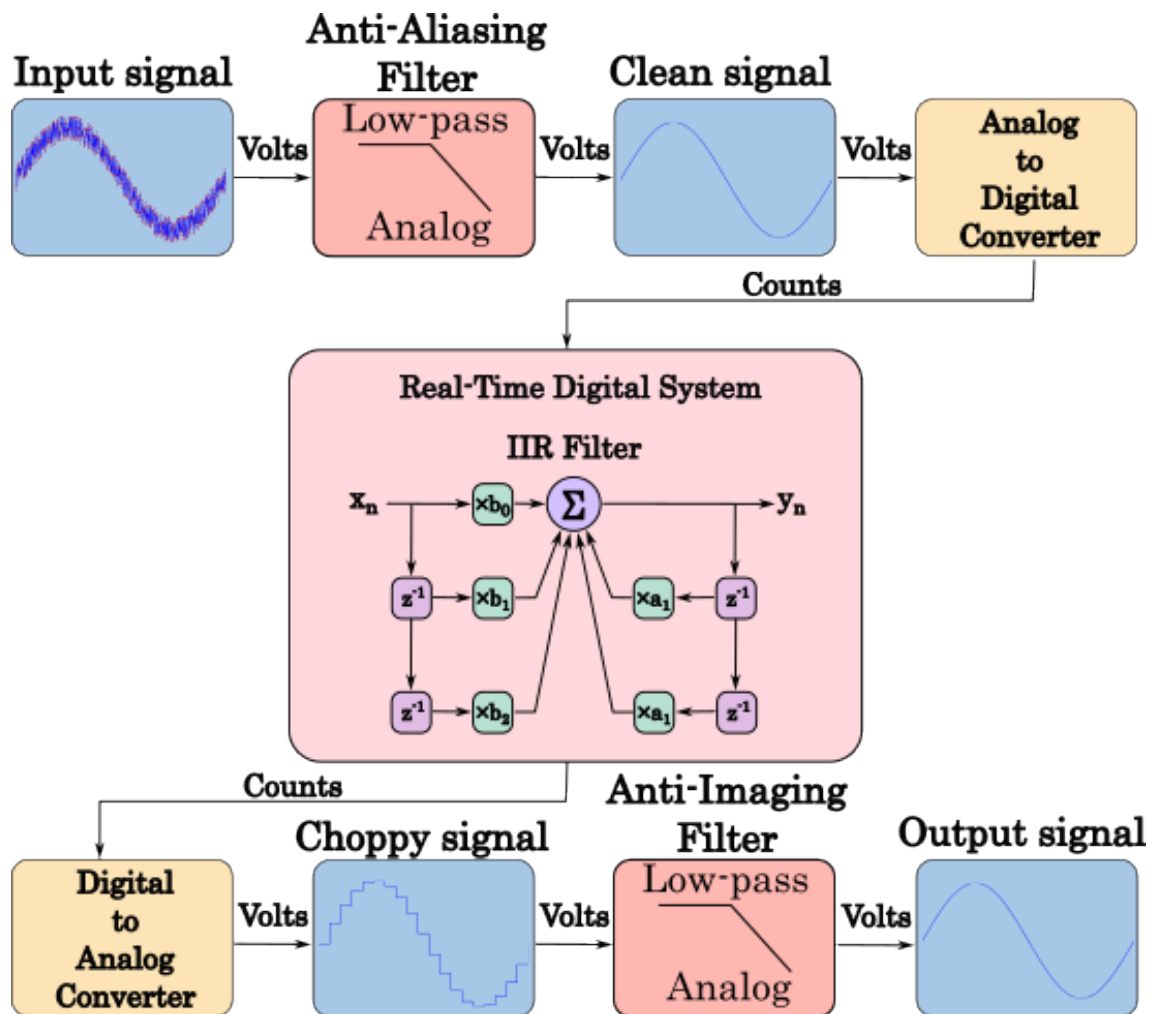


**Figure 4.10.** A flow-chart showing signal path of the LIGO CDS system. The signal domain crossing from analog to digital, the application of custom designed IIR (biquad) filters and the signal conversion back to the analog domain is shown.

### 4.2.2 Interferometer sensing and control

For power-recycled Michelson interferometers, the two main degrees of freedom to be controlled are the differential arms length (DARM) and the laser frequency to observe resonant enhancement of the power on the beam splitter.

#### 4.2.2.1 Frequency stabilization and power recycling cavity length

The response relationship between the laser frequency (or cavity length) and the power build-up for the recycling cavity, as shown in Figure 4.2, is symmetric about the optimal operating point (the resonance condition). This symmetry constrains the sensing scheme design, as a simple power build-up measurement lacks the directional information necessary to lock the laser frequency to the cavity length at resonance.

To overcome this, an optical heterodyne detection scheme, the Pound-Drever-Hall (PDH) length sensing scheme [55] is utilized, which derives the derivative of the cavity response using analog modulation-demodulation at a reference frequency offset from the carrier. This derivative is bipolar in nature, with a linear zero crossing at the resonance (maximum of the cavity response), providing an error signal that can be used to implement a high-bandwidth feedback loop.

This offset reference frequency is introduced by phase-modulating the input field at a radio frequency  $\Omega$ , creating sidebands at  $\omega \pm \Omega$ , as shown in Figure 4.4. The field reflected from the PRC is influenced by its frequency dependent complex reflection coefficient  $F(\omega)$ :

$$F(\omega) = \frac{r_{\text{PRM}} - r_{\text{MI}}e^{i\phi}}{1 - r_{\text{PRM}}r_{\text{MI}}e^{i\phi}} \quad (4.8)$$

where  $\phi = 2L_{\text{PRC}}\omega/c = 4\pi L_{\text{PRC}}/\lambda$  is the cavity's round-trip phase. By detecting the reflected power with a high-bandwidth photodetector and demodulating the signal at  $\Omega$ , we derive an error signal  $\epsilon$  proportional to the derivative of the cavity response [55]:

$$\epsilon \approx -2\sqrt{P_c P_s} \text{Im}\{F(\omega)F^*(\omega + \Omega) - F^*(\omega)F(\omega - \Omega)\} \quad (4.9)$$

Where  $P_c$  and  $P_s$  are the power in the carrier and one of the sidebands. The sideband power along with the demodulation phase are free parameters used to optimize the lock's performance and stability. Figure 5.2 shows the electro-optic layout for implementing this sensing scheme and Figure 4.11 shows an example error signal  $\epsilon$  as a function of the cavity length.

The RF generation, the demodulation and low-pass filtering necessary for the PDH sensing scheme are done using two MOKU:Pros, one for each interferometer. The phase-modulation sidebands are introduced at 8.11 MHz and 7.09 MHz for interferometers A and B respectively. The NPRO laser is driven using both the piezo and temperature actuators to lock the laser frequency to the power recycling cavity length. The servo loop

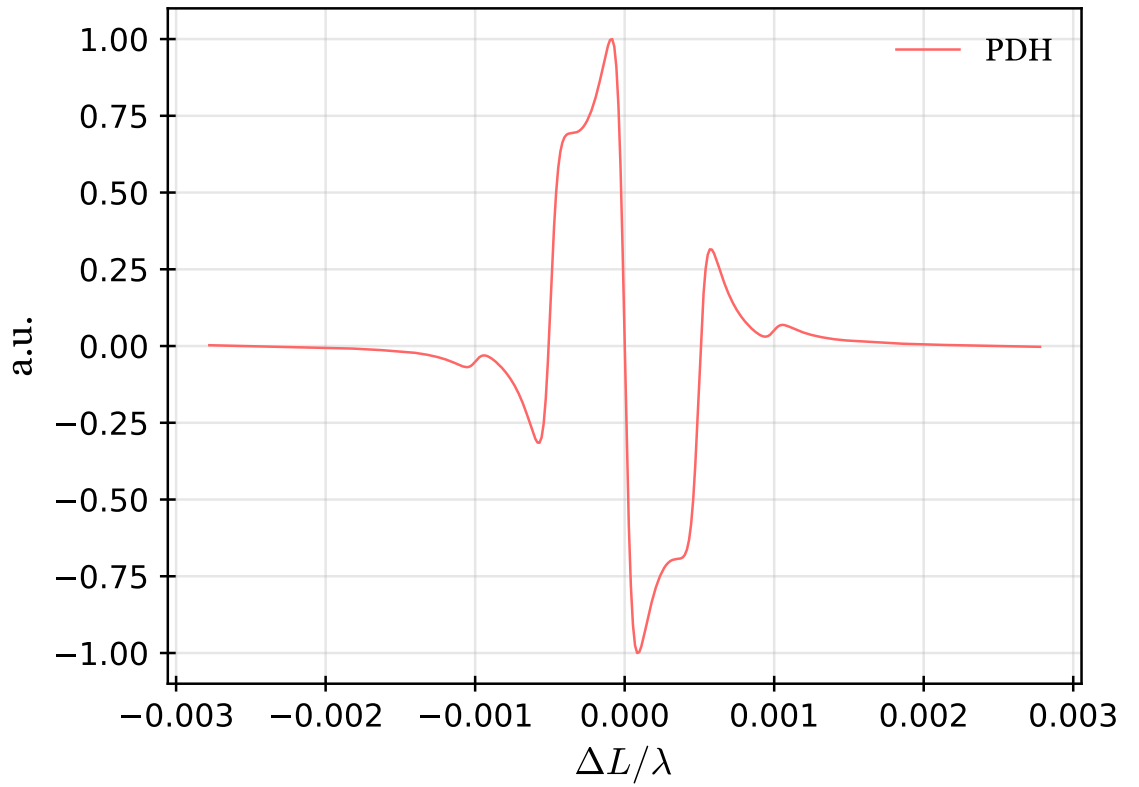


**Figure 4.11.** An example of the Pound-Drever-Hall error signal as a function of change in cavity length with respect to the laser wavelength is shown. The control and optical schematic for implementing PDH readout is shown in Figure 5.2.

is operated up to 20 kHz bandwidth and the servo filter used is a simple  $1/f$  integrator (A.2), which is unconditionally stable for a broad range of loop gains and allows the Michelson interferometer's DARM degree of freedom to be controlled independently. The loop state is managed using Moku's software as well as python scripts.

#### 4.2.2.2 Differential Arm Length sensing and control

The differential arm length (DARM) of the QUEST interferometers requires careful design of control servo loops to compensate for the audio-band noise that is mechanically coupled to interferometer's core optics. The local oscillator field critical for the homodyne readout scheme, to extract the main science signal, is derived by maintaining a small but controlled offset away from the dark-fringe condition of DARM using this feedback servo.

Each end mirror of the interferometers is equipped with three high-voltage piezo actuators, as shown in Figure 4.12. They allow for independent pointing control of end mirrors and act as actuators for DARM length. Using weight matrices implemented in CDS, the basis of actuation is changed from individual piezo action to the natural length and angular degrees of freedom of an interferometer.

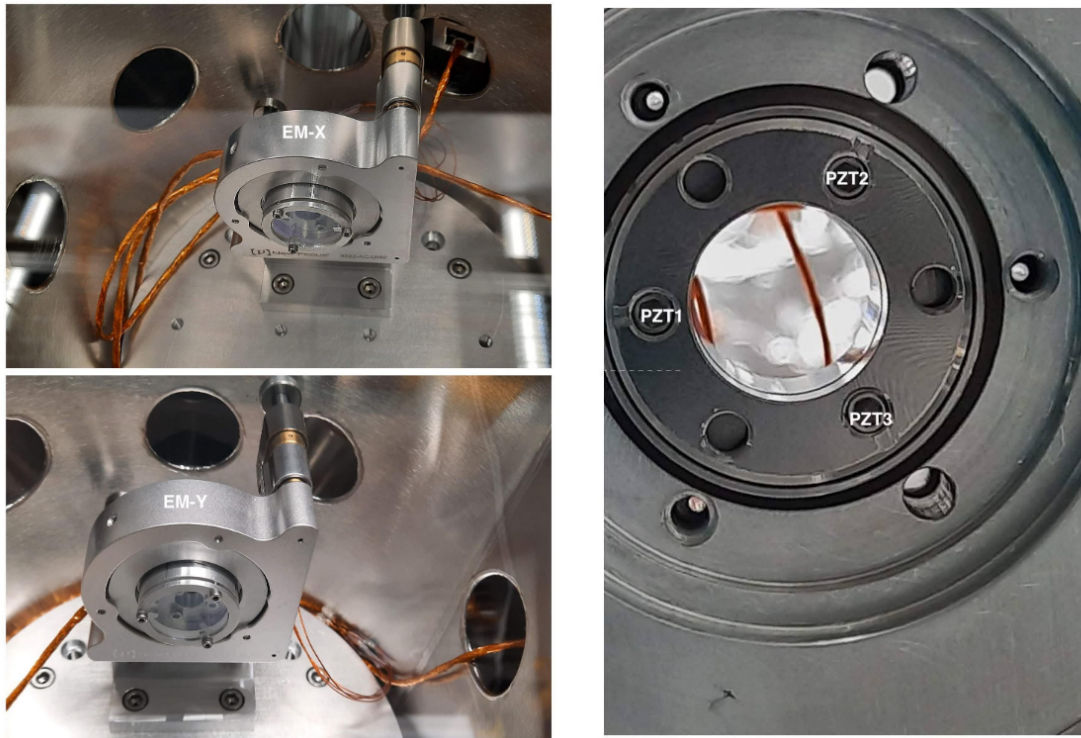


**Figure 4.12.** High-voltage piezo actuators and the end mirror mounts. Picture taken from [1].

DARM error signal extraction suffers the same challenges as the power recycling cavity, about the dark-fringe condition, the response of the system is symmetric. The following sensing schemes are implemented:

*Dither sensing:* Similar to PDH, an optical heterodyne sensing scheme is implemented. Phase-modulation sidebands are introduced onto the carrier inside the interferometer by dithering the DARM actuator and the field at the anti-symmetric port is demodulated to generate the error signal. The choice of the demodulation phase, allows for the interferometer to be locked at both the minimum (dark-fringe) and maximum anti-symmetric port power with respect to the DARM response, points A and B in Figure 4.3. The dither sensing and locking of DARM is used as part of initial interferometer commissioning and diagnostics, as well as for lock acquisition routine.

*DC readout:* The primary operating point of DARM, to allow for homodyne readout, is at an offset to the dark-fringe. The DC power measured at the  $PD_{AS}$  can directly be used as the sensing signal to control DARM length.

The closed loop response of the DARM loop is influenced not just by the optical response of the interferometer, but also the electro-mechanical response of the piezo actuators and in-vacuum optical mounts. Measurement of open-loop transfer function of the system are made in-lock, and compensation filters are designed to account for various mechanical resonances of the system, with details further discussed in chapter 5.

### 4.3 Output mode-cleaners

The detection optical layout of the QUEST interferometers utilizes high-bandwidth output mode-cleaners (OMC). This is one of the primary instrument design upgrades that will enable QUEST to surpass the displacement sensitivity limits set by the Holometer [7].

High-power laser interferometers such as LIGO and Holometer experience contrast defect due to thermally induced deformations in their core optics. This causes imperfect interference on the beam splitters, resulting in higher-order mode (HOM) light exiting the AS-port. For power-recycled Michelson interferometers such as Holometer and QUEST the thermal lens in the beam splitters is expected to be the primary contributor to contrast defect. In DC-readout this contrast defect power will contribute to quantum shot noise at readout, but will not carry signal, worsening the SNR [56, 57].

The OMCs in QUEST are triangular cavities that are locked to the fundamental Gaussian (TEM<sub>00</sub>) mode and filter out the high-order TEM modes in the output beam. Their design parameters are presented in Table 4.2, with further details presented in [1].

| Parameter                | Value     |
|--------------------------|-----------|
| Bandwidth                | 200 MHz   |
| Round-trip length        | 37.5 mm   |
| FSR                      | 8 GHz     |
| Finesse                  | 40        |
| Transverse mode spacing  | 1.1 GHz   |
| Expected HOM suppression | $\geq 60$ |

**Table 4.2.** OMC design parameters [1].

#### 4.3.1 Output mode-cleaner control and locking

Similar to the interferometers in QUEST, the OMCs are locked to their optimal point using a dither readout scheme. A reference sideband is introduced in the range 4 - 6 kHz by driving the piezo actuated mirror of the OMC and a photo detector in its reflection is demodulated at this frequency to generate the error signal necessary to lock the cavity. The servo filter used is a simple  $1/f$  integrator and is operated with a unity gain frequency of  $\sim 20$  Hz. Extended operation of this locking scheme, along with an auto-relock routine have been tested using a clean laser beam [1]. The alignment and mode-matching to the OMC were commissioned manually and have been found to be stable through out an extended lock test.

As part of setting up the QUEST experiment, four OMCs have been manufactured and characterized so far. The cavities were tested for their bandwidth and finesse and were found meet QUEST's requirements. A representative measurement of one OMC resulted in a bandwidth of  $218.5 \pm 8.4$  MHz and a finesse of  $36.4 \pm 2.4$  [1].

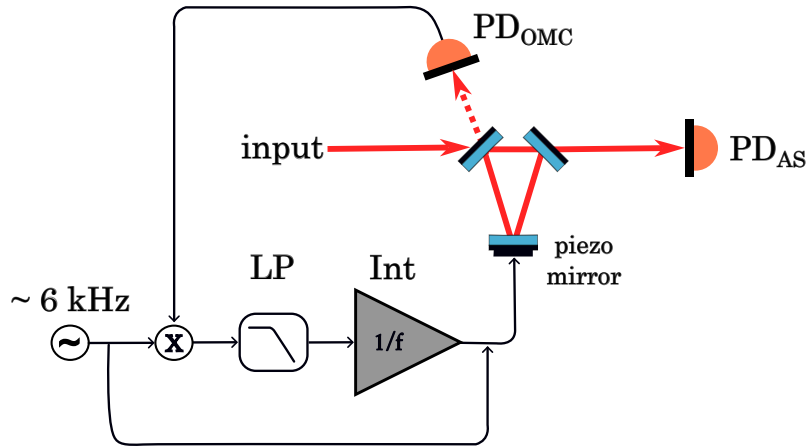


**Figure 4.13.** The optical and control layout for an output mode-cleaner is shown. A dither readout and locking scheme is implemented using the CDS. The dither modulation is induced using a piezo actuated mirror and the photo-detector in reflection ( $PD_{OMC}$ ) is demodulated to generate the error signal needed for the lock.

## 4.4 Quantum shot noise and calibration

In the frequency domain where the interferometer readout is shot-noise-limited, sensitivity towards changes to DARM length is estimated by following Eq 3.19 and substituting the relations  $\omega = 2\pi c/\lambda$ , thus calculated shot-noise-limited is given by [48, 36]:

$$\delta L_{\min} = \frac{\lambda \delta \phi_{\min}}{4\pi} = S^{\text{sn}} \quad (4.10)$$

$$\Rightarrow S^{\text{sn}} = \frac{\lambda \delta \phi_{\min}}{4\pi} = \sqrt{\frac{c\hbar\lambda}{4\pi P_{\text{BS}}}} \quad (4.11)$$

$$\approx \left( 5 \times 10^{-19} \frac{\text{m}}{\sqrt{\text{Hz}}} \right) \left( \frac{10 \text{ kW}}{P_{\text{BS}}} \right)^{1/2} \quad (4.12)$$

where  $P_{\text{BS}}$  ( $= 2P_{\text{arm}}$ ) is the power on the beam splitter. In the science frequency band of QUEST (1 - 250 MHz) the sensitivity of the interferometers is expected to be shot-noise-limited, as such Eq. 4.12 can be used to calibrate the measurements.

## 4.5 Squeezing generation and injection system

Along with OMCs and higher circulating power, the use of quantum squeezed light is an important instrument design upgrade in QUEST that is expected to aid in improvement over the displacement sensitivity limits set by the Holometer [7]. Squeezed light is a non-classical state of light in which the quantum noise in phase and amplitude quadratures can be engineered to improve the sensitivity of an interferometer [58].

The injection of engineered quantum squeezed states of light through the AS port of interferometers using a Faraday isolator as an optical circulator (see Figure 5.1). This

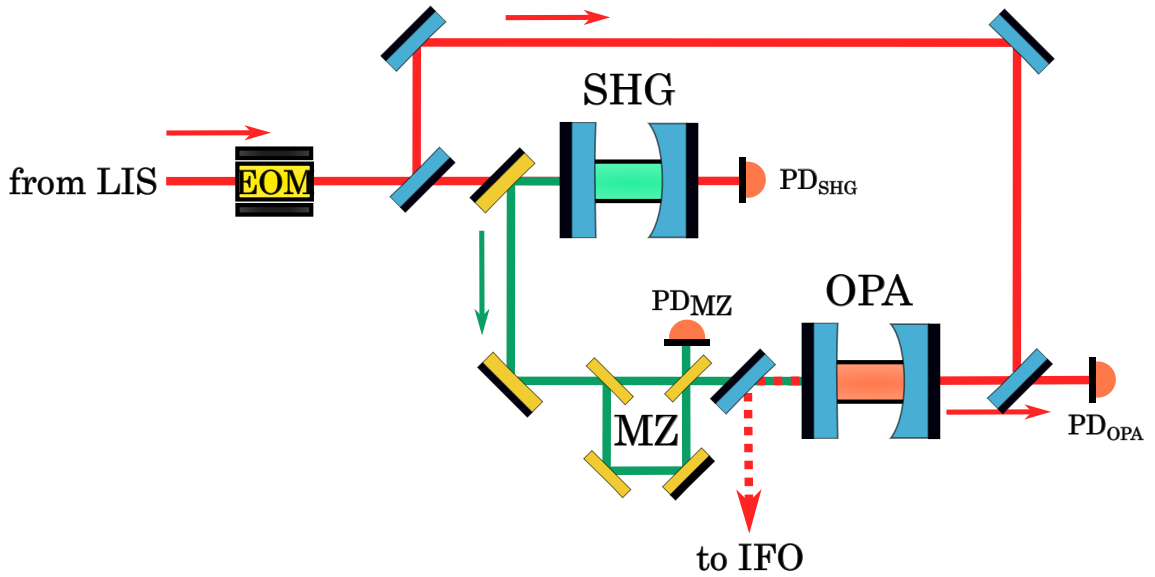


**Figure 4.14.** A 470 mW, 1064 nm seed field from the LIS is used as the input for the squeezed light source (SLS). The optical layout of the SLS shows: the EOM that is used to introduce the phase-modulation sidebands for control, the second-harmonic generator (SHG), the opto-parametric amplifier (OPA) and a Mach-Zehnder interferometer (MZ) that is used to control the intensity of the green (532 nm) light entering the OPA. The generated squeezed field that is shown in dashed red line is sent to the interferometer (IFO).

method has been demonstrated with instruments such as LIGO, to replace the coherent vacuum and has become a standard technique with gravitational wave interferometers over the last decade. It has been demonstrated to improve the quantum shot noise limited sensitivity of interferometers by 6 dB [59–61]. The shot noise limited amplitude spectral density obtained from the cross-correlation of the two interferometers in QUEST decreases with the fourth root of the integration time. Therefore, reducing the initial noise by a factor of two, corresponding to 6 dB of squeezing, shortens the integration time required to reach a given correlated sensitivity by a factor of 16.

The layout of the QUEST's squeezed light sources (SLS), one per interferometer, is shown in Figure 4.14. The SLSs were fully assembled and shipped by the squeezing team from AEI Hannover, Germany. The system is built on top of a 60 by 60 cm optical breadboard and is sealed with in an enclosure. To operate the SLS a seed laser beam of 470 mW power and 1064 nm wavelength is supplied from the main LIS of each interferometer.

In QUEST's SLSs the generation of the squeezed light is done via a parametric down-conversion process using a optical parametric amplifier (OPA). To drive this process, a 532 nm wavelength green beam is generated by driving a second-harmonic generator (SHG). The SHG is formed by a piezo-actuated mirror and plano-convex periodically poled potassium titanyl phosphate (PPKTP) crystal, shown in Figure 4.14, both of which

are coated to form a resonant linear hemilithic cavity for 1064 nm wavelength. From the 470 mW of input power, 340 mW is sent to the SHG and upto 240 mW of 532 nm green beam is generated.

The generated 532 nm field is used as the pump to drive the parametric (de-)amplification within the OPA. Similar to the SHG, the OPA is also a linear hemilithic cavity with a PPKTP crystal, but operated with different pseudo phase-matching by driving on the crystal temperature. This phase-dependent parametric interaction is mediated by the second-order nonlinear optical susceptibility,  $\chi^{(2)}$ , of the PPKTP crystal, which couples the 532 nm pump field with the 1064 nm field to effectively squeeze its quantum noise fluctuations. Along with the 532 nm seed field, about 5.1 mW of 1064 nm field is injected into the OPA to generate a displaced squeezed state, commonly known as bright squeezing [11].

### 4.5.1 Squeezing system controls

The SLSs have been commissioned with stand-alone analog electronics that implement four control loops and automated relock routines. Two Pound-Drever-Hall length sensing and control schemes, similar to the frequency control of the interferometers, are used to lock the SHG and OPA cavity lengths. An intensity stabilization loop for the 532 nm green field is implemented using a Mach-Zehnder interferometer. Phase-lock loops are implemented for the 532 nm green field that is input to the OPA to choose between parametric amplification and de-amplification states. Phase-modulation sidebands are introduced onto the input 1064 nm light at 89.9 MHz and demodulated with different phase at various points in the control topology to generate corresponding error signals [11].

One of the two SLSs has been commissioned with a balanced-homodyne detector and has been used to perform tomography of the generated squeezed state of light. Further details of this work are presented in section 7.5 and [11].

## 4.6 Time Synchronization

The NI PXIe-1092 chassis that hosts the fast NI digitizer FPGA cards, is also used as the master clock source to synchronize the high-frequency data acquisition and the the LIGO CDS systems. This is done through custom electronics, that divide the standard 10 MHz PLL wave provided by the NI system to generate a 65 kHz reference that is used as the external clock source for the multi-channel ADC/DAC cards of the CDS system.

Along with implementing the audio-band control servos, the LIGO CDS system is also used to acquire data upto 65 kHz. This data is used for various post-processing tasks, such as determining the lock state of the interferometers and vetoes for the science data because of lock loss, making the time synchronization between these two systems critical.

The Mokus, as they implement the high-bandwidth frequency stabilization control loops and generate the RF frequencies necessary for the PDH sensing scheme, are isolated and not part of a common time sync network.



## Chapter 5

# Science Run 1

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Similar to the instrument upgrade cycles and observation run schedules established by the large gravitational-wave interferometers in the LIGO-Virgo-KAGRA collaboration, QUEST also adopts a staggered commissioning schedule for its various subsystems. This staggered process facilitates the commissioning of heavily interdependent systems and the troubleshooting of various limitations that arise during integration.

The first science run (SR1) of QUEST was the culmination of parallel work on various subsystems and their subsequent integration. All critical systems were commissioned and tested to a minimum operational stage, with the main control architecture and lock acquisition being the time-limiting subsystems to commission. As part of SR1 a total of 10,000 seconds of data was collected and analyzed. This chapter describes the state of the various subsystems in preparation for and during the run, while the subsequent chapter presents the data analysis and a discussion of the results.

### 5.1 Commissioning details

Due to the distributed and parallel commissioning of QUEST's various subsystems, at the time of SR1, the laser injection system of interferometer-B was fully commissioned with the laser amplifier in place and tested up to 24 W of operating power. In contrast, the injection system of interferometer-A was commissioned to operate with only the main coherent laser source, providing a maximum output of 350 mW.

The interferometer-A setup was used as a testbed to commission the control loops necessary to operate the interferometers and to establish the lock acquisition routine for the full PRMI. Meanwhile, the interferometer-B laser injection systems were set up to provide the seed beam necessary for the squeezed light generation system. As a result, during the science run, the interferometers were operated with an input laser power of just 300 mW.

#### 5.1.1 Core optics and initial alignment routine

The power recycling mirrors used during SR1 had a reflectivity of 99.5%. The core optics were cleaned using isopropanol and First Contact polymer, a standard optics

cleaning solution, under a clean-air laminar flow bench, and swiftly transferred to their mounts inside the vacuum chambers. Once the core optics were in place, an initial alignment routine was performed in air.

First, with only the simple Michelson interferometer commissioned, the contrast of the laser power reaching the AS-port photodetector ( $PD_{AS}$ ) and the reflection photodetector ( $PD_{refl}$ ) was measured simultaneously. This was done by driving the DARM actuators through multiple fringes using a triangular sweep at a frequency of 1 Hz. The picomotors on the core-optic mounts were then used to adjust individual mirrors, simultaneously achieving good contrast and high peak power on both photodetectors.

Following the alignment of the simple Michelson interferometer, the power recycling mirror was installed. Using the picomotors on the PRM mount, the light reflected back into the injection path was aligned to maximize the power reaching  $PD_{refl}$ .

The photodetectors  $PD_{AS}$  and  $PD_{refl}$  were used as position references; if the power reaching them was maximized by aligning the core optics, it was expected that the laser alignment to the cavity was sufficient to observe a cavity response.

Once the power on  $PD_{refl}$  was maximized, a laser frequency scan spanning multiple free spectral ranges (FSRs) was engaged by driving the laser crystal temperature. If a cavity response was observed, either as high power reaching  $PD_{AS}$  or as a Pound-Drever-Hall (PDH) error signal from the cavity, the commissioning proceeded to the next step.

An in-air alignment routine for the core optics was necessary during SR1 because the in-vacuum mounts, and the internal constraints of the optics within those mounts, allowed significant freedom. Simply mounting the optics did not guarantee that the laser beam would cleanly traverse the vacuum tubes; in some instances, the laser hit the vacuum chamber walls and missed the optics entirely. For similar reasons, there were cases where no light exited through the anti-symmetric port of the chambers.

### 5.1.2 Acquiring vacuum

Following the installation of the cleaned optics and the initial alignment, all three vacuum chambers per interferometer envelope were closed using a fresh set of copper gaskets. Evacuating the system to a vacuum level of approximately  $10^{-6}$  mbar took 24 hours. This was achieved using the mechanical roughing and turbomolecular pumps, after which the system was transitioned to the ion pumps. The system took an additional week to reach pressures on the order of  $1 \times 10^{-7}$  mbar. Science data collection was performed at these pressures.

### 5.1.3 Detection optics

During SR1, Faraday isolators and half-wave plates were commissioned as part of the detection optics chain for each interferometer. In this setup,  $\sim 1\%$  of the power

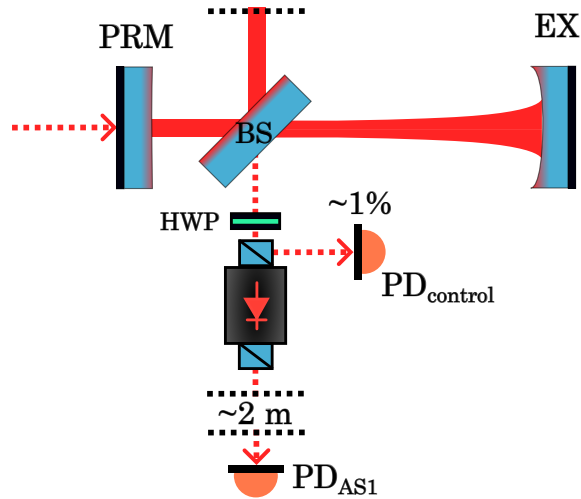


**Figure 5.1.** Schematic of the detection optics used during SR1. A Faraday isolator and a half-wave plate were used to pick off about 1 % of the AS-port power onto the control photodetector, this setup is known as an optical circulator and is also part of the squeezed light injection path to the interferometer. The majority of light was captured by the high-bandwidth science photodetectors.

exiting the AS port was picked off and used for locking the interferometers; the remainder was directed to and captured by high-bandwidth photodetectors for science data collection. A schematic of this setup is shown in Figure 5.1.

## 5.2 Commissioning control loops

As described in Section 4.2, the two main feedback control systems necessary for the operation of each QUEST interferometer are the frequency stabilization control loop and the length stabilization control loop (specifically for the DARM degree of freedom). This section presents the work done in preparation for SR1 to establish design parameters—such as loop gains, feedback filter designs, and optical layouts—necessary to achieve robust control of the interferometers and compensate for environmental noise during operation.

### 5.2.1 Frequency stabilization

A Pound-Drever-Hall (PDH) sensing and feedback scheme (Section 4.2.2.1) is implemented to lock the laser frequency to the power recycling cavity (PRC) of the interferometers. The phase modulation sidebands needed for the PDH scheme are introduced at 8.11 MHz and 7.09 MHz for interferometers A and B, respectively. For each interferometer, the signal from  $PD_{\text{refl}}$  is captured by the Moku, demodulated, and passed through a low-pass filter with a corner frequency of 150 kHz. The demodulation phase is experimentally optimized to maximize the gain of the carrier resonance. The generated error signal is then passed through a feedback filter, a simple  $1/f$  integrator, the gain of which is a tunable parameter adjusted during lock acquisition (see Section 5.3). The

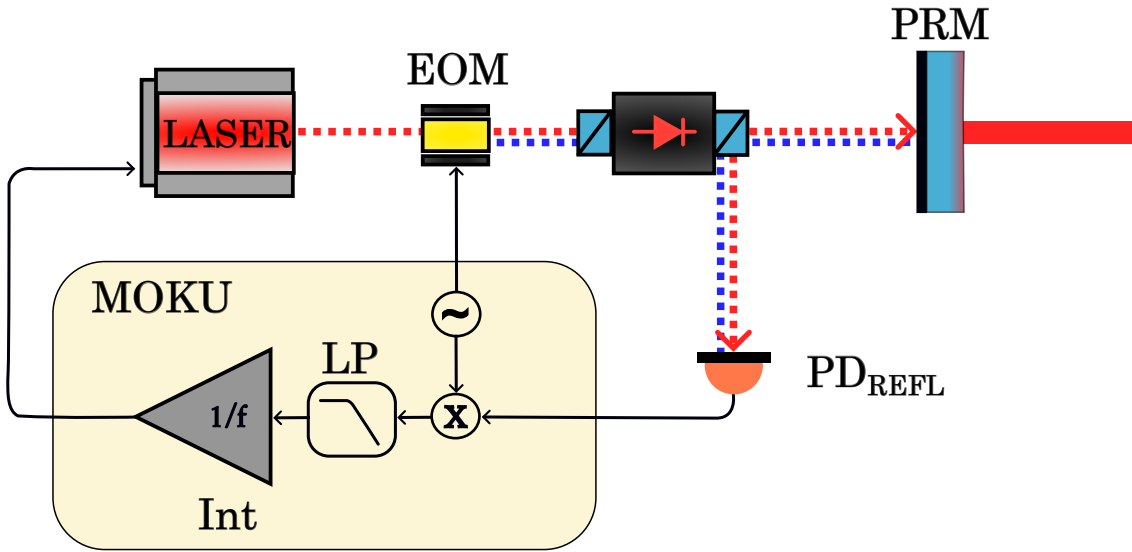


**Figure 5.2.** Implementation of the Pound-Drever-Hall control loop used to lock the laser frequency to the PRC length. The loop is implemented using a Moku, with a reference phase-modulation signal of 8.11 MHz in interferometer-A and 7.09 MHz in interferometer-B. An electro-optic modulator is used to induce these reference sidebands, and the light reflected from the PRM is captured by  $PD_{\text{refl}}$ . The Moku drives the laser piezo and an independent loop in CDS stabilizes the laser temperature.

error signal is then fed back to the laser frequency piezo actuator. A copy of this same signal is sent to the CDS to control the NPRO cavity's temperature. Figure 5.2 shows the optical schematic and signal flow for the frequency stabilization loop.

### 5.2.2 DARM length stabilization

Figure 5.3 shows the feedback control loop architecture for the interferometer's DARM degree of freedom. In control theory the system being controlled is known as the “plant”. In the case of DARM length stabilization, the physical plant corresponds to the anti-symmetric port response of the interferometer, as shown in Figure 4.3. The error signal for the plant is generated using either a dither or a DC readout scheme, and the feedback is applied via in-vacuum piezo actuators. The noise entering the system is expected to be dominated by the motion of the core optics at audio frequencies (200–1000 Hz).

In practice, the frequency responses of the optical plant, sensors, and actuators are consolidated into a single “compound plant” to be controlled. The frequency response of the controller (or feedback filter) is then treated as a tunable parameter used to shape the in-loop noise of the system. Measuring the frequency response of this compound plant is an essential step in designing the feedback filter. This is achieved by measuring the injection response of the system at various frequencies to determine the open-loop transfer function (OLTF). In the cases of QUEST interferometers this compound plant includes the electro-mechanical response from various systems: piezo-mirror mechanical

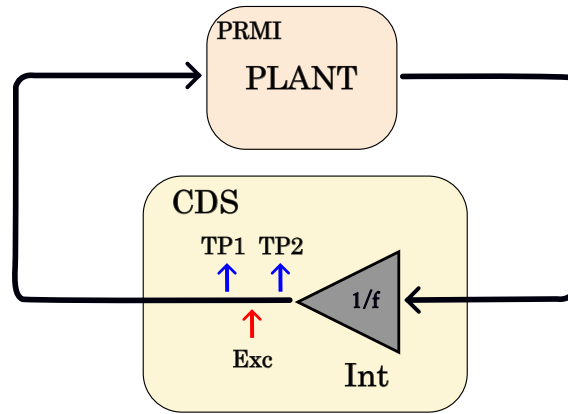


**Figure 5.3.** DARM control loop architecture.

systems and their resonances, the high-voltage piezo drivers and the electronic response of the photodetectors ( $PD_{AS}$ ).

#### 5.2.2.1 DARM loop - OLTF measurement

As the power recycled Michelson interferometer is a resonant optical system, the DARM response of the interferometer is drastically different depending on the PRC resonance condition. Such systems are called out-of-loop unstable and the measurement of the system response, like the OLTF, has to be done with the system in lock. To achieve this in QUEST the full PRMI is locked with a sub-optimal feedback filter, that does not optimally compensate for the electro-mechanical, noise causing, features present in the DARM loop but allows for the OLTF measurements to be made.

The Full PRMI lock is acquired as shown in section 5.3 with the DARM length control loop is locked using a DC-offset lock and a simple  $1/f$  integrator with relatively low unity gain frequency (UGF) of about 100 Hz. Then sinusoidal injections are done in between two test points (TP1 and TP2) in the control loop and the response to the injections are measured at these test points, as shown in Figure 5.3. The frequency of this injections is swept and the ration  $TP2/TP1$  is measured at each step to estimate the OLTF of the system, which includes the response of the entire compound plant. One such OLTF measurement is shown in Figure 5.4.

As the feedback filter used for this measurement is a simple  $1/f$  integrator, any shaped features observed in the OLTF, such as the once around 250 Hz and 2 kHz in Figure 5.4 are a result of the compound plant and its response. The observed sharp features observed, likely mechanical resonances of the various in-vacuum optical mounts, are compensated for by fitting a zero-pole-gain (ZPK) model and introducing its inverse response as part of the feedback filter. This ZPK fit is done using a vector fit [62], where the number of zeros and poles can be chosen to achieve the necessary compensation of the compound plant.

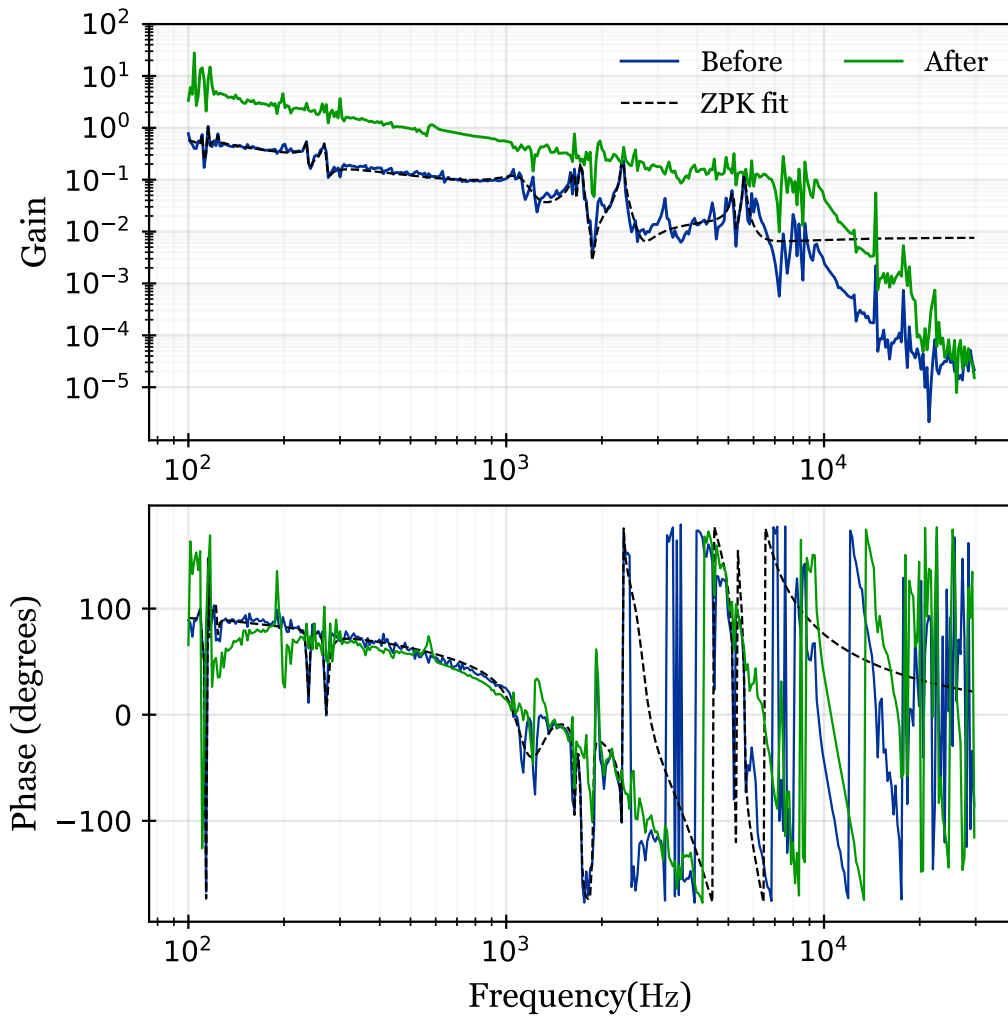


**Figure 5.4.** The open-loop transfer function (OLTF) measurement with and without the custom designed feedback filter is shown. The “Before” measurement is a result of the PRMI being locked without custom ZPK filter to compensation for various features of the compound plant. This measurement is followed by fitting with a ZPK model, which is shown, and the ZPK coefficients are used to design a new feedback filter to achieve the “After” OLTF. This particular ZPK model fit was done using 28 pairs of complex poles and zeros. It is important to note that the UGF of this system is limited to about 800 Hz by CDS delay.

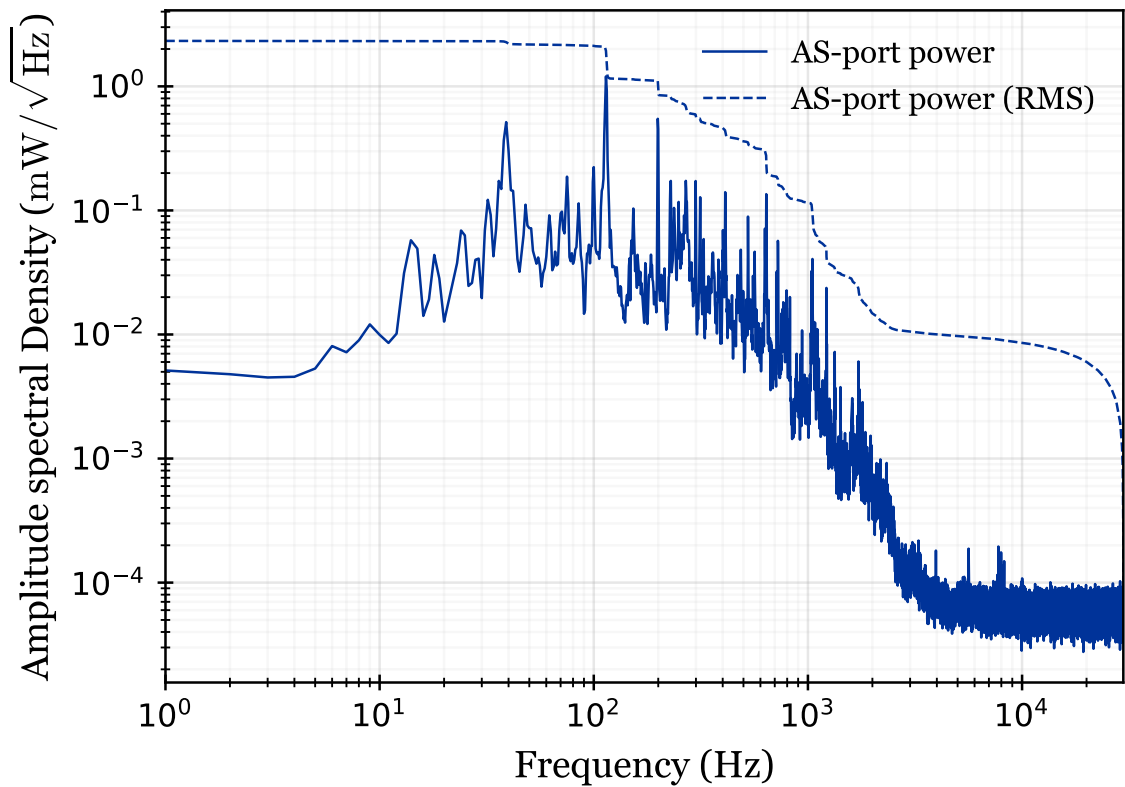


**Figure 5.5.** The in-loop amplitude spectra of the AS-port power of interferometer-A during SR1, is shown. With the custom designed ZPK filter, a RMS of under 3 mW was achieved.

### 5.2.2.2 DARM loop - Feedback filter design

The ZPK models of the measured features of the compound plant are inverted and introduced into the feedback filter design to compensate for the share features while the loop is active. In the case of QUEST interferometers, the CDS system that is used to control DARM, accepts feedback filters as direct ZPK coefficients. The goal for the filter design is to achieve an OLTF of the system that is close to a simple  $1/f$  integrator, whose UGF can be used as a design freedom to compensate for the noise experienced by the system (see Figure 5.4). In practice it was found that the UGF is limited by the digital delay caused of the CDS system. An estimated delay of 0.18 ms, corresponding to 12 cycles at 65 kHz, of the feedback signal was measured. The gain of this filter is adjusted to be as high as possible with out leading to instabilities. As part of commissioning for SR1 the loop has been tested up to an UGF of 1 kHz but during the run a UGF of about 800 Hz was used. The observed AS power spectra with this custom designed feedback filter is shown in Figure 5.5

The motion of the core optics at audio band frequencies, 200 - 700 Hz, poses a particular challenge for the DARM control loop. But, further increase of UGF to compensate for this noise is limited by the CDS group delay. As the observed RMS noise

in the AS spectra, about 3 mW, is 1/10 of the DC-offset, 30 mW, this work was assessed to be sufficient to proceed with a science run.

### 5.3 Lock acquisition routine

During science run 1 the lock acquisition of the QUEST interferometers was done manually. The laser frequency was scanned and the DARM offset was brought close to the dark fringe manually, then the frequency stabilization loop was closed followed by the DARM loop.

The angular degrees of freedom are fine-tuned once the interferometer is locked to the dark fringe using a dither lock to improve the contrast observed. The gaussian beam mode exiting the AS port of the interferometer carries with it the information of the differential angular mismatches in the system. A custom-made MEDM control screen was used for manual fine tuning using the piezo actuators, it is shown in A.4.

It was empirically verified that the interferometers' differential angular degrees of freedom and their injection angular degrees of freedom were stable for the order of hours. The mode-matching was stable for order of days.

The lock acquisition routine for the QUEST interferometers is as follows:

- Turn on laser frequency scan. This is done through Moku's graphical user interface. A 25 Hz scan is engaged that drives the laser frequency through a  $\pm 15$  MHz range, using the laser piezo actuator. This scan is expected to drive the laser frequency through a cavity resonance, which can be seen in the PDH error signal and the power circulating through the interferometer. The laser temperature is manually actuated if an error signal is not observed. This results in a macroscopically shifts the scan of the laser piezo to a different part of the laser frequency.
- Once some error signal is observed, the DARM offset is acted upon to bring the interferometer close to the dark-fringe, this increases the finesse of the PRC and PDH error signal becomes sharper.
- Once a good PDH error signal is observed, the frequency loop is closed in Moku and the laser temperature loop is closed in CDS. The same PDH error signal is used by both the Moku and CDS to keep the laser frequency in lock to the cavity length. The cross-over for the actuation between the laser piezo actuator and laser temperature is about 0.1 Hz. The laser frequency lock is stable for a wide range of loop gains, as such it is stable as the DARM offset moves, changing the cavity finesse drastically.

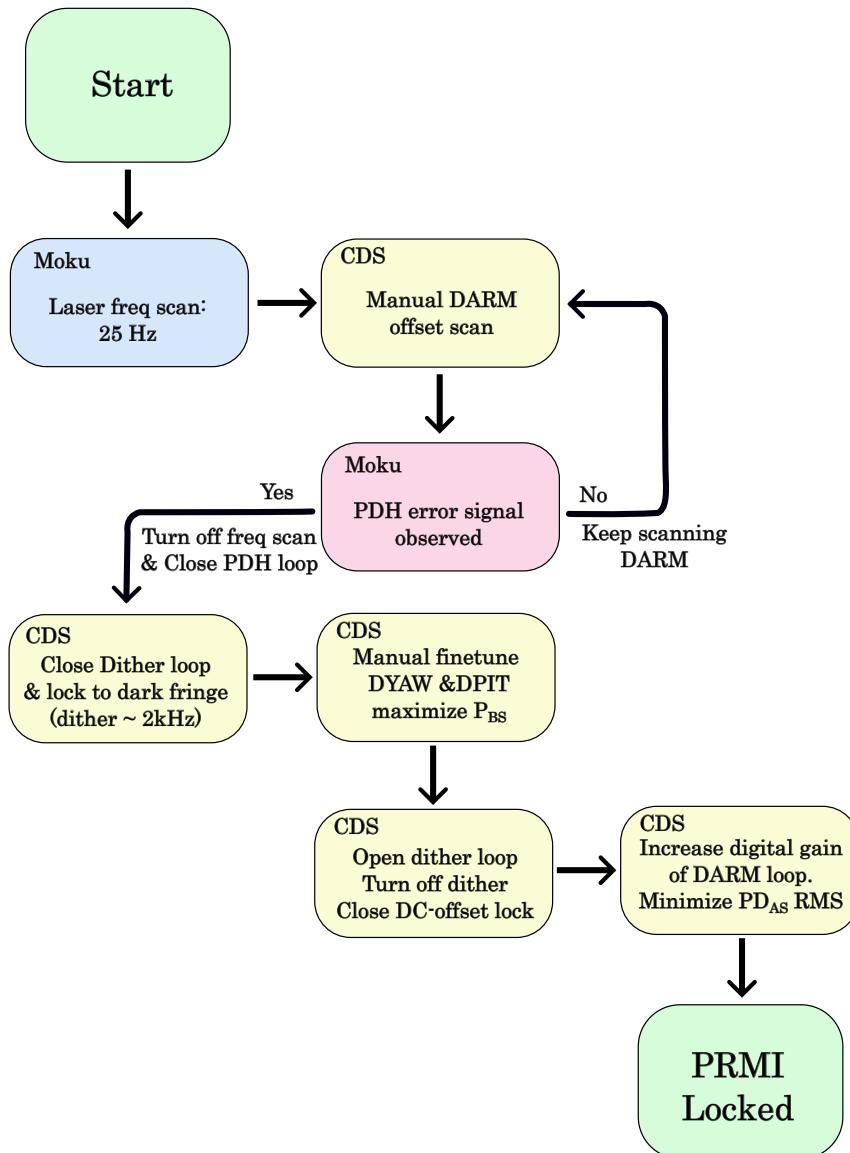


**Figure 5.6.** A flowchart that shows the lock acquisition routine for QUEST's full PRMI system. This flowchart assumes the start position to be after the initial alignment routine of the interferometer, as shown in Section 5.1.1, has been completed.

- A dither sweep necessary for locking DARM degree of freedom is activated. The dither injected is at 1.8 kHz and 150 counts of amplitude (corresponding to about 20 nm peak-to-peak). The DARM loop is engaged and the interferometer is locked to the dark fringe. The dither lock loop is engaged with a relatively low unity gain frequency (UGF) of about 20 Hz.
- Then the differential angular degrees of freedom are finetuned using the end-mirror piezo actuators. This is done to minimize the dark fringe contrast and improve the power build-up.
- Once the optimal contrast is achieved – during SR1 the minimum was about 3 mW corresponding to 32 ppm of contrast defect – the system is transitioned to DC-offset lock.
- The dither is turned off, the loop is opened and DARM length is manually acted to bring the AS-port power close to the DC-offset. The loop is closed and the integrator is turned on to firmly hold the DC-offset. During SR1, an offset of about 30 mW was used. This power level was chosen as it is sufficiently higher than the contrast observed and with-in the 50 mW power limit accepted by the modified photo-detectors.
- Following the successful transfer of the DARM lock to DC-offset lock, the loops digital gain is increased to achieve a UGF of about 800 Hz. This increase of digital gain is done slowly with steps of fact 2 and over 30 seconds.
- Finally, the injection alignment mirrors and mode-matching telescope lenses were manually finetuned while observing the transmitted power through the end-mirrors to optimize the input power being coupled into the system and the observed power build-up. During SR1 a power build-up achieved was 83.3 W and 96 W on the beam splitters of interferometers A and B respectively. Further details are discussed in Chapter 6.

## 5.4 Long-term stability of the system

In preparation for SR1 the control loops needed to operate the interferometers were commissioned to stably operate the system for order of hours. The limiting reasons that determined the long-term operation were:

- *Laser temperature actuator* - While the laser temperature actuator of the NPRO lasers have multiple GHz of range, corresponding to 10's of FSRs of recycling cavity. The output voltage from the CDS is limited using an analog voltage divider to only a range of  $\pm 1$  V, corresponding to about  $\pm 300$  MHz in laser frequency. This was done as a safety step, so as to not accidentally drive an impulse into the laser temperature drive. During the commissioning phase of SR1, it was discovered that this limitation in frequency range led to saturation of the digital output in CDS, resulting in lockloss. The typical duration a laser frequency lock could be held was empirically observed to be about 2 hours.
- *Environmental noises* - The main reason for lockloss for the interferometers was environmental noises, more specifically acoustic noise. Loud impulses such as elevators, doors and tools falling on the floor have caused locklosses. Along with being a reason for lockloss, acoustic noise coupling has also led to a challenge in suppressing noise in the DARM loop. To mitigate this further work is being done, see section 7.2.



## Chapter 6

# Science Run 1 - Results & discussion

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The first science run (SR1) was conducted on March 30, 2024, from 19:00 to 23:00. This chapter presents the details of operating the interferometers during the run, the collection of high-frequency data, and the data analysis performed to arrive at the final results.

### 6.1 Data collection and cleaning

During SR1, three hours (approximately 10,000 seconds) of high-frequency data were collected. The interferometers and the high-frequency data acquisition system were operated manually.

The high-frequency data acquisition system, operating an acquisition loop at 500 megasamples per second, was set up to average  $10^4$  frequency spectra and output a data frame containing the results of this averaging. Each data frame consists of two power spectral density (PSD) frequency series corresponding to the measured AS-port spectra of interferometers A and B, and one complex-valued cross-spectral density (CSD) resulting from the real-time cross-correlation between the two signals. The saved data are in units of  $V^2/\text{Hz}$  and require calibration to be converted into displacement spectra.

Interferometers A and B were locked and operated with circulating powers on the beam splitters of  $83.32 \pm 1.02 \text{ W}$  and  $96 \pm 0.89 \text{ W}$ , respectively. The circulating power was estimated using the power transmitted through the EX end mirrors for both interferometers. These estimated circulating powers resulted in an absolute displacement sensitivity of about  $5.5 \times 10^{-18} \text{ m}/\sqrt{\text{Hz}}$  in both interferometers, calculated using Eq. 4.12.

A time series of the AS-port power, the transmitted power, and the derived power on the beam splitters is shown in Figure 6.1. The data presented were recorded using the CDS at a rate of 16.384 kHz. Key features of the data include the following:

- The lock acquisition process can be seen during the first 1,000 seconds of the time series. Interferometer B required multiple attempts to acquire lock.

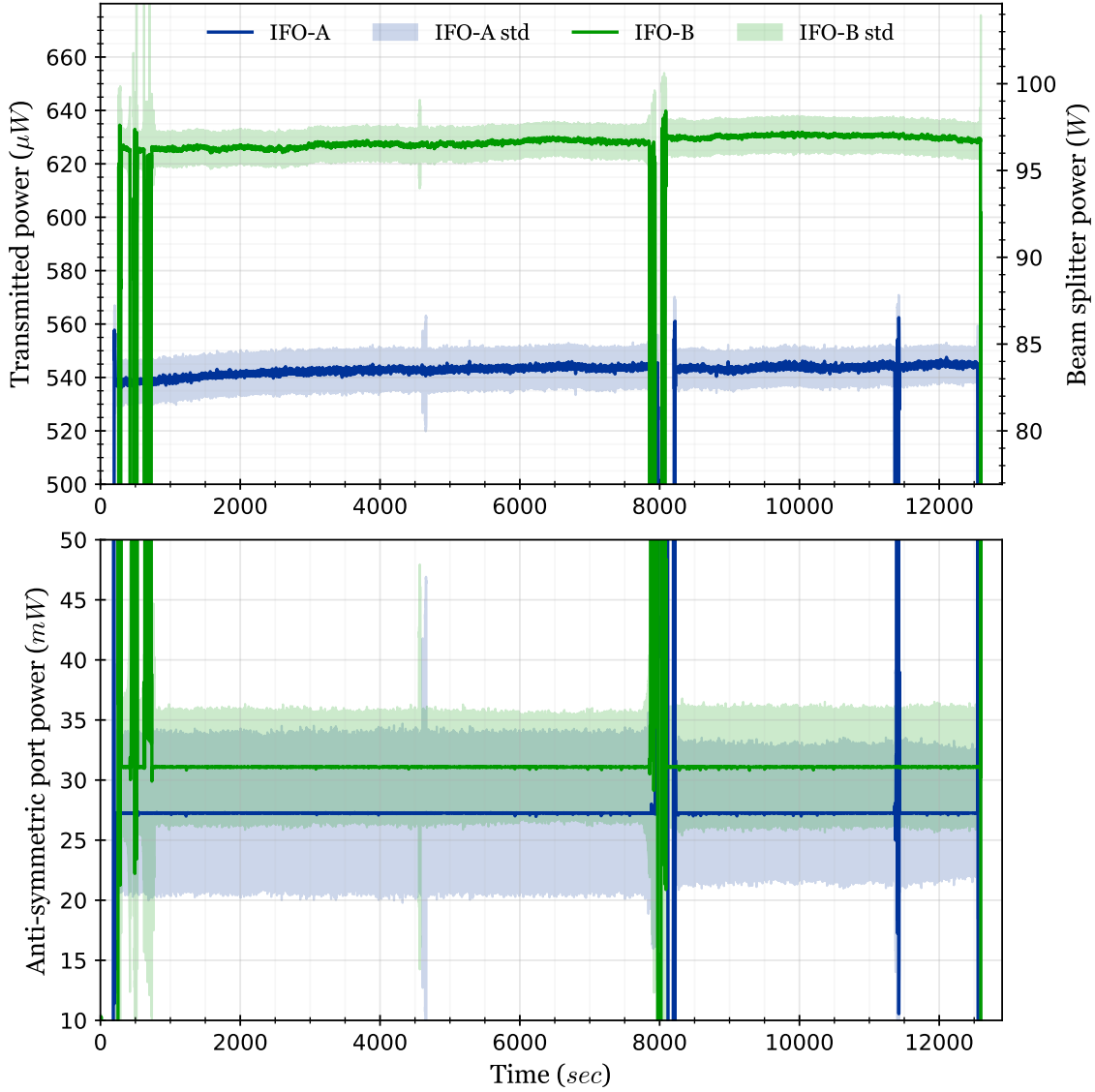


**Figure 6.1.** Time-series data from SR1 corresponding to both interferometers A and B. The top plot shows the mean and standard deviation of the power transmitted through the EX end mirrors, which translates to the power build-up on the beam splitters. The bottom plot presents the same metrics for the power exiting through the AS ports of both interferometers.

- The drop-outs in the power build-up around 8,000 seconds were caused by an intentional reset of lock in both interferometers. This was done to reset the laser temperature actuators and reduce the offset being held by them.
- The only true lock loss event during the run was observed in interferometer A at around the 11,500-second mark.
- A coincident “glitch” can be seen in both interferometers at 4,600 seconds. It is visible in both the AS-port power and power build-up time series. This was likely due to an acoustic impulse that was not loud enough to cause a complete lock loss.

The high-frequency data acquisition system was turned on around the 1,000-second mark and was turned off right before the intentional lock reset at 8,000 seconds. It was left on for the remainder of the run. The high-frequency data frames corresponding to the interferometer A lock loss at 11,500 seconds and the glitch at 4,600 seconds were vetoed. This resulted in a total of 16,462 frames, corresponding to 10,048 seconds of usable high-frequency data. Additionally, because the main photodetectors used in the measurement have a calibrated bandwidth of 80 MHz, the frequency bins corresponding to measurements above this frequency were vetoed.

## 6.2 Calibrating high-frequency data

Along with vetoing, calibration is the other critical data post-processing step performed on the high-frequency data. The data acquisition system performs real-time cross-correlation and averaging between the spectra measured from interferometers A and B. These measurements, as well as the consequent CSDs, are recorded in units of volts.

Following the vetoing process, the measured PSDs and CSDs were corrected for the photodetector response. This response was obtained via a smooth spline fit of the measured shot-noise-limited spectra that is shown in Figure 4.6.

Equations 6.1 and 6.2 were used for calibrating the PSDs of interferometers A and B, while Eq. 6.3 was used to calibrate the magnitude of the CSDs that are a results of the cross-correlation and averaging process. Note that because the CSD is a complex frequency series, only the magnitude is calibrated; its phase does not require any further calibration. The calibration of both the PSDs and the resulting CSD was performed by normalizing the measurement at 40 MHz to the expected shot-noise-limited sensitivity. This normalization accounts for the differences in the powers measured by the high-bandwidth photodetectors at the AS ports, which result in different shot-noise levels for the power measurements. As discussed in Section 3.3, this difference does not contribute to the overall shot-noise-limited displacement sensitivity of the interferometers.

The laser power transmitted through the end mirrors is used as an estimator for the power on the beam splitters, and Eq. 4.12 is used to calculate the shot-noise-limited-sensitivity conversion factors  $C_A$  and  $C_B$  for each interferometer. The conversion of the spectra to absolute displacement in power density units is shown below:

$$S_{AA}(f) \left[ \frac{\text{m}^2}{\text{Hz}} \right] = \left( C_A \left[ \frac{\text{m}}{\sqrt{\text{Hz}}} \right] \right)^2 \cdot \left( V_{AA}(f) \left[ \frac{\text{V}^2}{\text{Hz}} \right] \right) \cdot \left( V_{AA}(40 \text{ MHz}) \left[ \frac{\text{V}^2}{\text{Hz}} \right] \right)^{-1} \quad (6.1)$$

$$S_{BB}(f) \left[ \frac{\text{m}^2}{\text{Hz}} \right] = \left( C_B \left[ \frac{\text{m}}{\sqrt{\text{Hz}}} \right] \right)^2 \cdot \left( V_{BB}(f) \left[ \frac{\text{V}^2}{\text{Hz}} \right] \right) \cdot \left( V_{BB}(40 \text{ MHz}) \left[ \frac{\text{V}^2}{\text{Hz}} \right] \right)^{-1} \quad (6.2)$$

$$S_{AB}(f) \left[ \frac{\text{m}^2}{\text{Hz}} \right] = \left( C_A \left[ \frac{\text{m}}{\sqrt{\text{Hz}}} \right] \cdot C_B \left[ \frac{\text{m}}{\sqrt{\text{Hz}}} \right] \right) \cdot \left( |V_{AB}(f)| \left[ \frac{\text{V}^2}{\text{Hz}} \right] \right) \cdot \left( \sqrt{V_{AA}(40 \text{ MHz})} \left[ \frac{\text{V}}{\sqrt{\text{Hz}}} \right] \cdot \sqrt{V_{BB}(40 \text{ MHz})} \left[ \frac{\text{V}}{\sqrt{\text{Hz}}} \right] \right)^{-1} \quad (6.3)$$

where  $V_{AA}$ ,  $V_{BB}$ , and  $V_{AB}$  are the measured voltages in power spectral density units, and  $S_{AA}$ ,  $S_{BB}$ , and  $S_{AB}$  are the calibrated displacement spectra.

Due to calibration uncertainties that cannot be accounted for current technical limitations a fiducial 15% calibration error is assumed for these sensitivities. These uncertainties maybe due to unaccounted-for losses of the fast photodetector and data acquisition detection chain, such as the quantum efficiency of the fast photodetectors etc. The uncertainty in the reflectivities of the core optics (deviation from manufactures specifications), the non-linearity of the PRMI response (caused by the RMS motion of the optics at audio frequencies) and the contrast defect also contribute to this error.

The calibration was applied at the individual data frame level, corresponding to  $10^4$  averaged spectra, or about 0.65 s of observation time per frame.

### 6.3 Data analysis and averaging

Following the calibration of the cross-spectra from all frames, a total of  $1.64 \times 10^8$  spectra were averaged together. The results from this averaging are presented in Figure 6.2.

In Figure 6.2a, the absolute displacement sensitivities (in amplitude units) of interferometer A ( $\sqrt{S_{AA}(f)}$ ) and interferometer B ( $\sqrt{S_{BB}(f)}$ ) are shown as blue and green solid lines, respectively. The resulting CSD ( $\sqrt{S_{AB}(f)}$ ) averaged over all spectra is shown in light red, and the 95<sup>th</sup> percentile of the averaged CSD, a purely statistical metric assuming a null detection of correlated signal, is shown as a solid red line. The CSD from the Holometer experiment [6] is shown in cyan, and the design sensitivity for the QUEST experiment [7], as a result of 10 kW of laser power on the beam splitters and

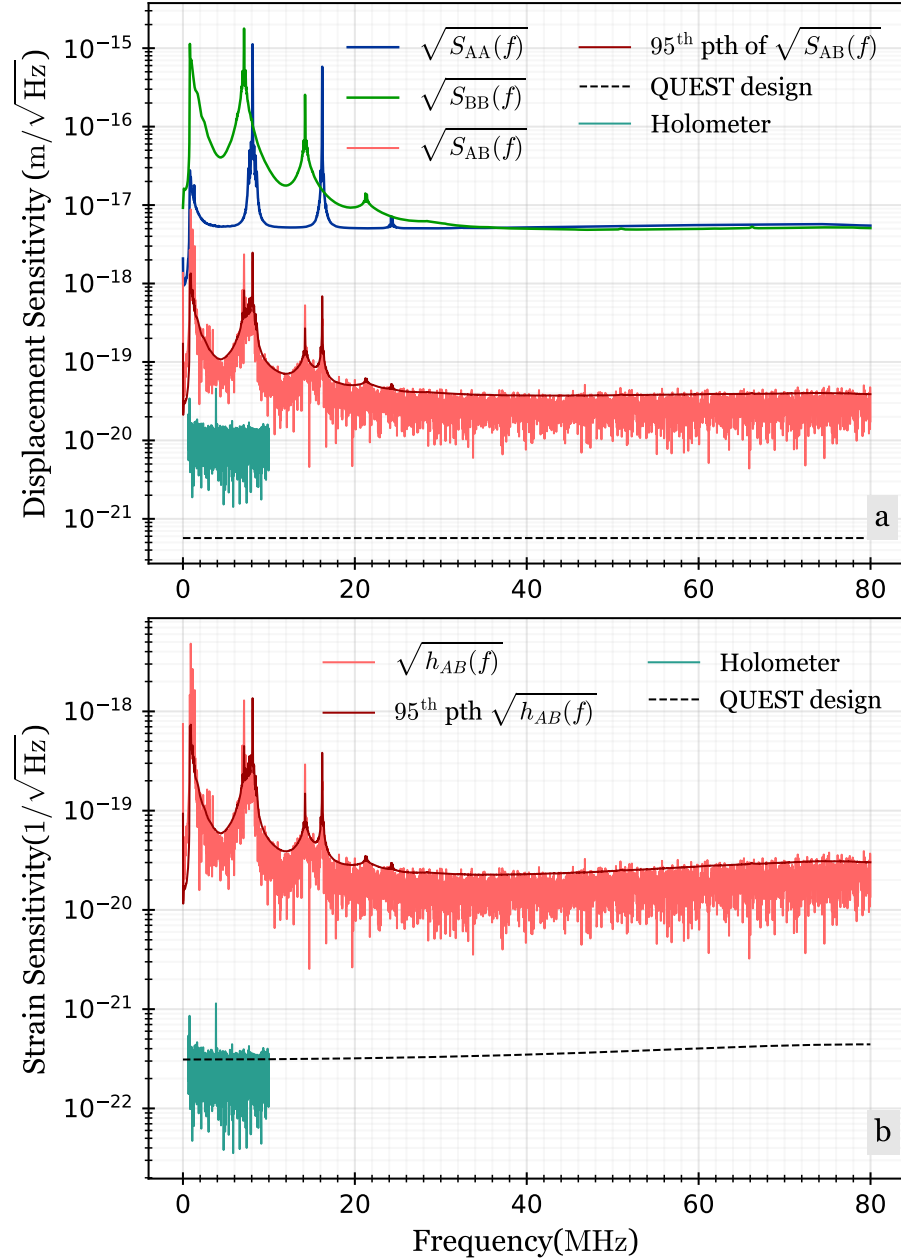


**Figure 6.2.** The top plot displays the absolute displacement sensitivity of interferometer-A ( $\sqrt{S_{AA}(f)}$ ), interferometer-B ( $\sqrt{S_{BB}(f)}$ ), their averaged CSD ( $\sqrt{S_{AB}(f)}$ ) over the observation period, and its 95<sup>th</sup> percentile statistic. The CSD from the Holometer experiment [6] and the design sensitivity of QUEST [7] are also shown. The bottom plot shows the translation of these displacement sensitivity spectra into strain units.

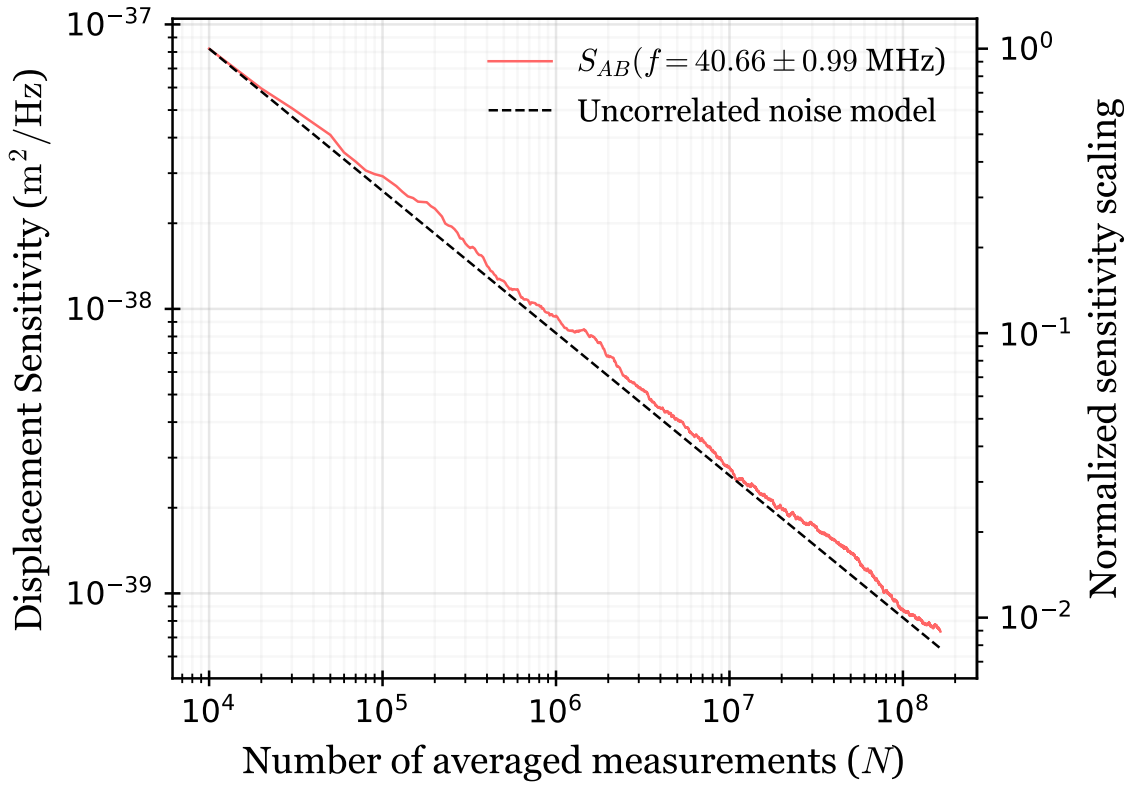


**Figure 6.3.** The averaging-scaling trend of the cross-correlated spectra  $S_{AB}$  for the  $40.66 \pm 0.99$  MHz frequency bin, shown in PSD units ( $\text{m}^2/\text{Hz}$ ) alongside the normalized sensitivity scaling. The expected trend for uncorrelated noise is also shown.

6 dB of squeezing and 1 million seconds of observation time, which corresponds to about  $5.7 \times 10^{-22} \text{ m}/\sqrt{\text{Hz}}$ , is shown with a dashed black line.

The observed absolute displacement spectra set new upper limits for stationary length fluctuations in the 13 to 80 MHz frequency band. Figure 6.3 shows that the mean of the  $40.66 \pm 0.99$  MHz frequency bins follows a  $\sqrt{N}$  trend for a growing number of averaged spectra,  $N$ . This verifies that no correlated signals were found between the interferometers, and that the behavior of the signals was “shot-noise-like” (uncorrelated).

In Figure 6.2b, the strain sensitivity that is derived from the absolute displacement sensitivities after sky-position and polarization averaging is shown. The design strain sensitivity of the QUEST interferometers (similar to the level of the Holometer but with tabletop-scale arm lengths) will ultimately require higher absolute displacement sensitivities. Achieving this will yield a better SNR accretion via time-averaging to test current quantum gravity models [63, 40].

Other interferometric experiments that have set limits at radio frequencies include the Holometer experiment [6], which set limits for the 1 to 13 MHz frequency band with a strain sensitivity of about  $4 \times 10^{-22} 1/\sqrt{\text{Hz}}$ , and a pair of co-located synchronous recycling interferometers [64], which set a narrow-band limit at 100 MHz with a strain sensitivity of about  $10^{-16} 1/\sqrt{\text{Hz}}$ . QUEST explores the frequency band between these

two experiments, setting new limits from 13 MHz to 80 MHz with a strain sensitivity of  $3 \times 10^{-20} 1/\sqrt{\text{Hz}}$ . Further commissioning is underway to improve both the observation frequency band and the strain sensitivity of the experiment.

### 6.3.1 Constraints on Fundamental science signals

The observed strain sensitivity enables the placement of experimental constraints on three main fundamental science targets: the stochastic gravitational-wave background, scalar field dark matter candidates and quantum gravity models.

First, using Eq. 2.11, upper limits are set on the dimensionless, Hubble-constant-normalized gravitational energy density,  $h_{100}^2 \Omega_{\text{GW}}(f)$ . Figure 6.4 presents these stochastic background limits obtained from SR1 and compares the data from QUEST, Holometer and LIGO. The 95th percentile strain sensitivity as observed in SR1, shown in Figure 6.2b, was used to set this limit. Even though the absolute displacement sensitivity of the QUEST experiment is comparable to that of LIGO, the strong frequency dependence of the gravitational energy density (Section 2.1.1), favors low frequencies. As such, a high frequency detector such as QUEST will likely not be able to surpass the limits set by LIGO.

Additionally, the same strain sensitivity data, SR1 and QUEST's design, are used to constrain scalar field dark matter candidates based on the theoretical framework presented in Section 2.2. Figure 6.5 shows the resulting upper limits on the inverse photon and electron coupling constants,  $1/\Lambda_\gamma$  and  $1/\Lambda_e$  respectively. These limits span across QUEST's sensitive frequency band, which can be mapped to corresponding particle masses. The limits from the SR1 data roughly correspond to a limit on the inverse coupling constant of about  $10^{-11} \text{ GeV}^{-1}$  across particle mass range about  $4 \times 10^{-9}$  to  $3 \times 10^{-7} \text{ eV}$ .

The absolute displacement sensitivity observed during SR1 is also used to set a limit on the scalar, scale factor  $\alpha$  for Zurek's geotropic noise model for quantum gravity. These limits are calculated using Eq 3.37. A  $3\sigma$  exclusion limit can be set for  $\alpha = 61.2$ , for the without IR cutoff model of geotropic fluctuations (see Section 2.3). Figure 6.6 presents the sensitivities and the modeled signal in the QUEST interferometers. The design sensitivity of QUEST (as shown in Figure 6.2), along with the same observation bandwidth of 80 MHz yields a  $3\sigma$  exclusion limit for  $\alpha = 1$ . These limits, even for the design sensitivity, fall short of the limits set by the Holometer or LIGO [4], but this work provides a framework to verify other theories of irreducible quantum space-time fluctuations, such as the Kwon's model [41], that are only possible to explore using QUEST's planned 3D configurations [7].

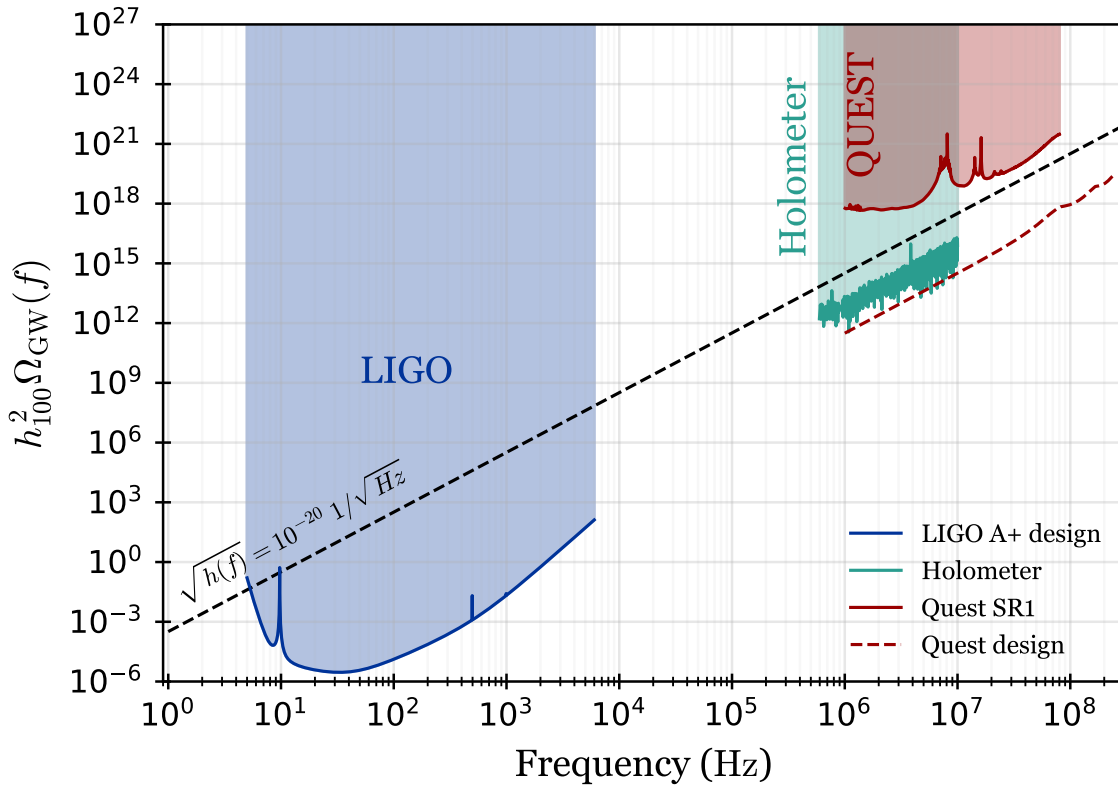


**Figure 6.4.** Upper limits on the stochastic gravitational-wave background. The limits obtained from QUEST SR1 are shown in comparison with existing constraints from the Holometer [6] and LIGO A+ design. To show the  $f^3$  dependence of the dimensionless gravitational energy density,  $h_{100}^2 \Omega_{\text{GW}}(f)$ , the limits corresponding to a strain sensitivity  $\sqrt{h(f)} = 10^{-20} 1/\sqrt{\text{Hz}}$ , spanning a wide range of frequencies, is shown in dashed black trace.

## 6.4 Classical noise beyond the quantum noise

The cross-correlation analysis performed so far has been between the shot-noise-limited signals from two interferometers. The averaging of the CSDs has thus far presented an absence of a common signal between them. In a similar way, the same cross-correlation analysis and averaging is performed using the output of a single interferometer to probe for noises beneath the shot-noise-limited sensitivity [65]. The expectation mean of the averaged cross-spectra will trend toward the technical, classical noises that limit the interferometer's sensitivity below the shot noise level.

To demonstrate the functionality of the high-frequency cross-correlation pipeline and to analyze these noise sources below shot noise for a single interferometer, a one-interferometer data collection run was conducted.

### 6.4.1 Single-interferometer auto-correlation run

Interferometer A was operated with a DC-offset readout scheme, and the output was split onto two photodetectors using a beam splitter. Each photodetector sampled 50 %

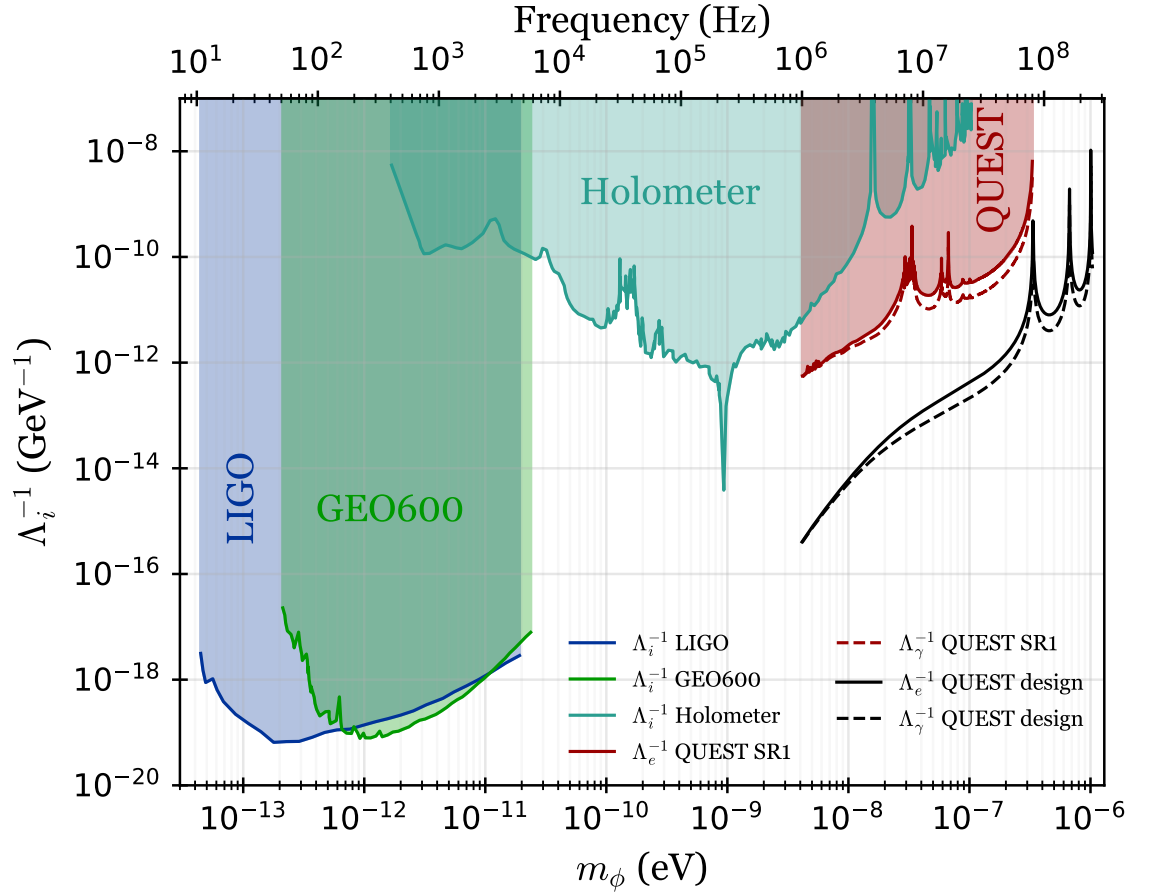


**Figure 6.5.** Exclusion limits for scalar field dark matter candidates as a result of their interaction to the interferometer optics. The plot shows the constraints on the photon and electron inverse coupling constants derived from 95th percentile strain sensitivity of SR1 data, contextualized against QUEST’s design sensitivity and existing limits from Holometer [8], GEO600 [9] and LIGO [10].

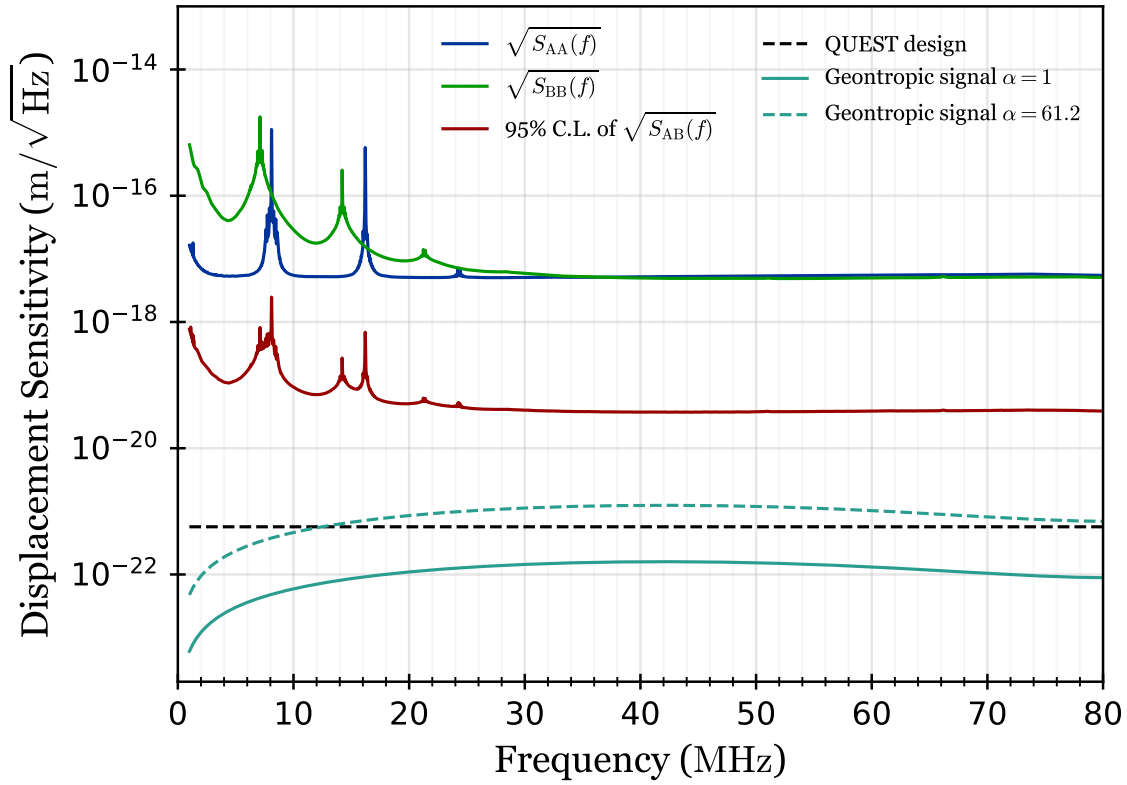


**Figure 6.6.** Limits on geotropic signal from SR1 and QUEST’s design sensitivity. SR1 yields a  $3\sigma$  exclusion limit of the geotropic fluctuations with a scale factor  $\alpha = 1$ . The design sensitivity of QUEST, shown in dashed black trace, is expected to set a  $3\sigma$  exclusion for  $\alpha \approx 1$ .

of the beam power exiting the interferometer, and a cross-correlation analysis—identical to that of SR1—was performed between the two signals. The shot noise and detector dark noise of each individual photodetector are expected to be uncorrelated, and are thus suppressed by the averaging of the cross-spectra. After post-processing similar to SR1, approximately  $1.4 \times 10^8$  individual CSD spectra were collected; the resulting average is shown in Figure 6.8.

The classical noise observed at sub-shot-noise sensitivities comprises laser frequency and intensity noises, thermo-refractive noise, and bulk-thermal noise from the core optics. The thermally driven, stochastic motion of the atoms of the interferometer’s core optics sets an irreducible sensitivity floor for a single interferometer. A characteristic comb of 470 kHz lines and harmonics are visible as a result of this thermal noise. The phonon modes from the 6 mm thick fused silica core optics used in the QUEST result in this unique spectral shape and the height of the peaks is set by the temperature and the Q-factor of the solid. This constitutes a unique thermal noise measurement for a fused silica optical element in this frequency range. The peaks at 8 and 16 MHz are the phase-modulation sidebands (and their harmonics) injected for length sensing and control of the interferometer. The peak at about 30 MHz is due to the first TEM mode resonance

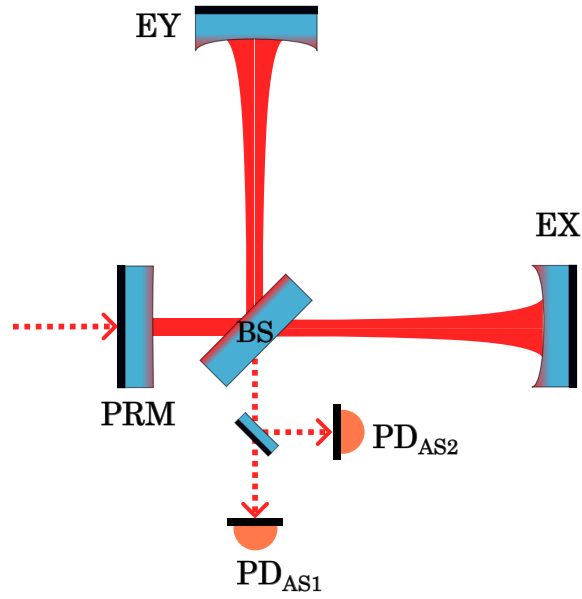


**Figure 6.7.** The readout optical layout used to measure classical noise below shot noise. Interferometer-A was locked using a DC-offset lock (with a 30 mW offset) that was split onto two photodetectors—the same ones used during SR1.

of the power recycling cavity, while the origin of the 15 MHz peak is currently unknown, though it is likely caused by the interaction of the control sidebands with laser technical noise. The amplitude modulation envelope of these peaks, seen in Figure 6.8, is unknown and will be studied further. A similar technique is adopted in LIGO to estimate the limiting classical noises of an interferometer [65].

The results from this single-interferometer data run were used to plot the scaling trend of the median bin within the 1 to 40 MHz range as the number of averaged spectra,  $N$ , increased. This trend is shown in Figure 6.9. Unlike the outcome for SR1, a clear saturation is observed, which is consistent with a correlated noise floor of about  $7 \times 10^{-20} \text{ m}/\sqrt{\text{Hz}}$ . It is important to note that the two-interferometer cross-correlation results of SR1 already surpass this limit, further indicating the necessity of using two distinct instruments to achieve better sensitivities.

## 6.5 Limitations

As part of the first science run, QUEST sets new limits for the absolute displacement sensitivity from 13 to 80 MHz. These new limits were achieved with only powers of order 100 W circulating on the beam splitters. This limitation in the power build up in the interferometers is one of the main limitations in the current iteration of the QUEST experiment. The observed power build-up in the interferometers is a factor 4 lower than ideal case and if accounted for known losses it is still a factor 2 lower than the expected. Understanding these unexplained losses is the primary commissioning and instrument development goal for the second science run.

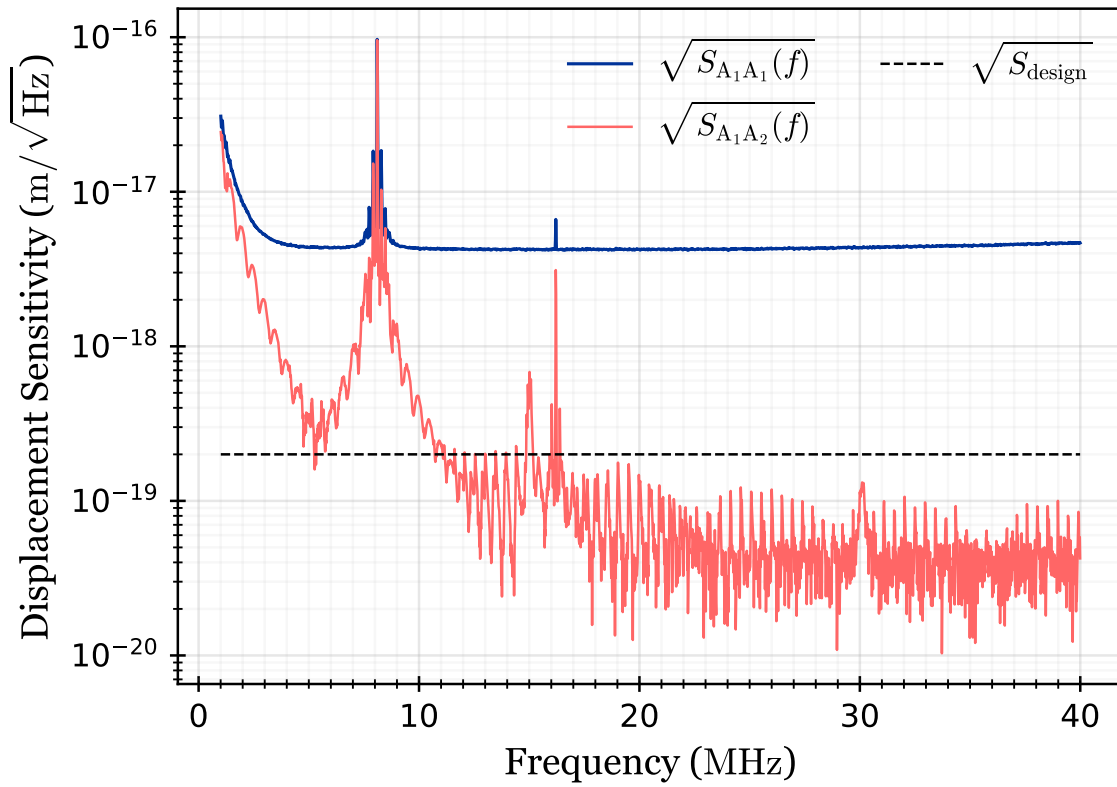


**Figure 6.8.** The two-photodetector cross-correlation measurement,  $\sqrt{S_{A_1A_2}(f)}$ , from the output of interferometer-A is shown in red. The currently observed shot-noise-limited sensitivity,  $\sqrt{S_{A_1A_1}(f)}$ , is shown in blue, and the shot-noise-limited design sensitivity,  $\sqrt{S_{\text{design}}}$ , of a single interferometer is shown as a dashed black trace. The peak at about 30 MHz corresponds to the first-order TEM mode resonance in the power recycling cavity; the origin of the peak at 15 MHz is unknown.

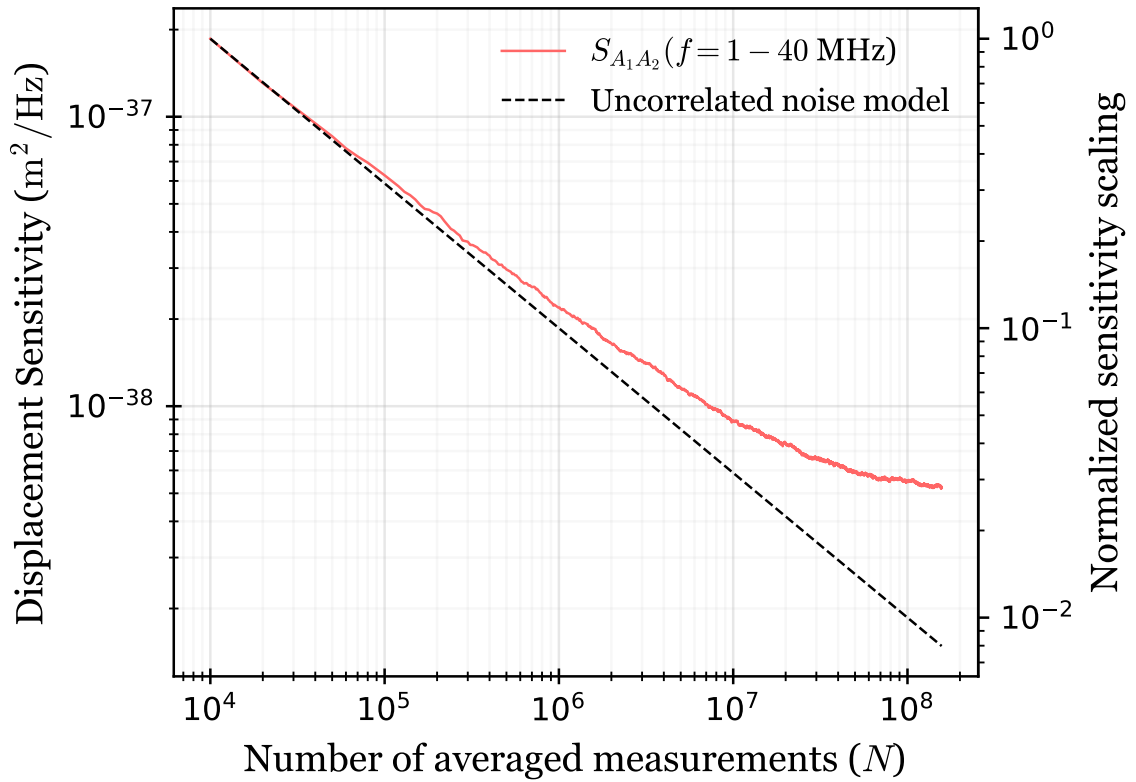


**Figure 6.9.** The averaging trend of the median bin, measured as part of the single-interferometer, two-photodetector data run. The trend is consistent with a correlated noise floor of  $5 \times 10^{-39} \text{ m}^2/\text{Hz}$ , corresponding to a displacement sensitivity of  $7 \times 10^{-20} \text{ m}/\sqrt{\text{Hz}}$ .

The sensitivity of the interferometers-A and B is different at frequencies below 20 MHz. Interferometer-B shows elevated noise levels that are not completely explainable with the current state of instrument characterization. During SR1, interferometer-B was operated with the laser amplifier stage as part of its laser injection system, where as in interferometer-A the system was operated with just the NPRO laser. So naturally, laser intensity and frequency noise are the primary suspects for this additional noise and they will be carefully charactraized as part of the next science run.

The modified fast photodetectors were characterized, but their response was found to be limited to about 80 MHz, above which the measured response did not scale as expected, see Figure4.6. This response was measured using shot noise levels induced using different levels of photocurrent, the expected square root scaling deviated for frequencies above 80 MHz and about 50 mA of photocurrent. This has led to the science frequency band to be limited to just 80 MHz for the science data. Additionally, as seen in Figure 6.2, the observed shot noise level above 20 MHz is not completely flat. This unexpected observation is currently unexplained. The calibration of the photodetector response or parasitic reflection in the signal transmission line from the fast photodetectors to the data acquisition system are the likely suspects. Although the photodetector, the transmission

line and the data acquisition system are RF systems designed for  $50\Omega$  impedance, a more granular, and direct measurement of the transmission line's transfer function will further improve the confidence of the observed features in Figure 6.2.

The current architecture of the high-frequency data acquisition is limited to capturing only two analog channels in real-time. This limitation is due to the fixed compute in FPGA systems to compute real-time FFTs. The same limitation of the FPGAs also limits the length of FFTs that can be computed, which limits the resolution of the frequency domain spectra to just 15 kHz. For calculating real-time cross-correlation matrix for  $n \times n$  channels, and at a finer resolution, a new data acquisition architecture is currently being commissioned.

As part of the first science run, the output from the two interferometers were calibrated using their shot noise level and the observed power build up. While this works, this leaves room for uncertainty caused by laser noise that might hide the shot noise in the observation frequency band, the photodetector response or because of unknown parasitic reflection is either the optics or RF electronics. An external calibration scheme that could induce known phase modulations in to the interferometer arm lengths would overcome all of these limitations in calibration and improve upon the 15 % fiducial error we currently assume.

## Chapter 7

# Science Run 2 & further

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At the time of writing, commissioning and instrument development work for various sub-systems is underway with the goal of conducting Science Run 2 (SR2). SR1 helped us understand various instrument limitations of QUEST and structured an upgrade path towards our science goals. This current work aims to achieve both better interferometer sensitivity and the capability to sustain longer observing runs, ultimately improving the bounds on space-time correlated signals set during SR1.

This chapter presents a record of the ongoing testing and upgrade work across various QUEST sub-systems.

### 7.1 High-power operation tests

To troubleshoot the anomalous power build-up factor observed during the first science run (see Section 6.5), we performed a series of tests using the injection and vacuum systems of Interferometer-B.

#### 7.1.1 Single cavity power-up test

First, the beam splitter was removed, and a simple linear Fabry-Perot cavity was commissioned between a new power recycling mirror (PRM) with 0.1 % transmissivity and the EX mirror with 13 ppm transmissivity. By fine-tuning the alignment and mode-matching, the cavity was successfully locked using the same Pound-Drever-Hall readout scheme and hardware employed for the full interferometers.

With the cavity locked, the injection laser power was swept while the transmitted power through the EX mirror was measured, allowing us to estimate the power build-up. The resulting estimated cavity gains are presented in Table 7.1.

Notably, an input power of 2 W yielded an observed power build-up of 2.13 kW. This corresponds to a cavity gain of 1064, which falls significantly short of the expected gain of 3900. Using these results, we estimated a round-trip loss of approximately 900 ppm (excluding the input coupler transmission) by fitting the data to a numerical model of the cavity response [5]. For the purposes of this analysis, these measured losses are assumed to be distributed equally between the PRM and the EX mirror.

| Input power (mW) | Trans power (mW) | Power build-up (W) | Cavity gain |
|------------------|------------------|--------------------|-------------|
| 300              | 3.85             | 296.15             | 987         |
| 571              | 7.16             | 550.77             | 965         |
| 1000             | 13.97            | 1074.62            | 1075        |
| 2000             | 27.66            | 2127.69            | 1064        |

**Table 7.1.** Observed power build-up with various input laser powers in a simple Fabry-Perot cavity formed by the PRM and EX mirrors.

### 7.1.2 Power recycling Michelson interferometer power-up test

To estimate the round-trip losses in a complete system, we conducted a test similar to the one described in Section 7.1.1, but using a full power-recycled Michelson interferometer (PRMI). After venting the vacuum system and installing a set of cleaned optics, we performed the initial alignment routine and pumped the system back down. The PRMI was locked to the dark fringe using a dither lock, and the power build-up was recorded across various input powers.

| Input power (mW) | Trans power (mW) | BS Power (W) | Cavity gain |
|------------------|------------------|--------------|-------------|
| 234              | 0.321            | 49.4         | 211         |
| 389              | 0.644            | 99.1         | 255         |
| 575              | 0.780            | 120.0        | 209         |
| 888              | 1.010            | 155.4        | 175         |
| 1200             | 1.470            | 226.2        | 189         |
| 1510             | 1.910            | 293.8        | 195         |
| 2020             | 2.860            | 440.0        | 218         |

**Table 7.2.** Measured power build-up in a full power-recycled Michelson setup. As in the test described in Section 7.1.1, and unlike during SR1, a PRM with 0.1 % transmissivity was used.

Data taken at an input power of 2.02 W were used to estimate system losses using a numerical model of the system response [5]. Excluding the input coupler transmission, we measured a total round-trip loss of 3250 ppm. Factoring in the measured loss per optic from Section 7.1.1 (three optics at 450 ppm each), this total yields an estimated loss of 1900 ppm attributable to the beam splitter. Known loss mechanisms account for approximately 400 ppm—specifically, two passes through the beam splitter’s anti-reflective coating (180 ppm per pass) and the interferometer contrast defect (about 40 ppm). This leaves an unexplained beam splitter loss of roughly 1500 ppm.

### 7.1.3 Table-top characterization of the beam splitters

To further understand the losses in the beam splitters, a table-top setup was commissioned. These characterization tests included measurements of reflectivity and transmissivity, along with the scatter from both surfaces of a sample beam splitter.

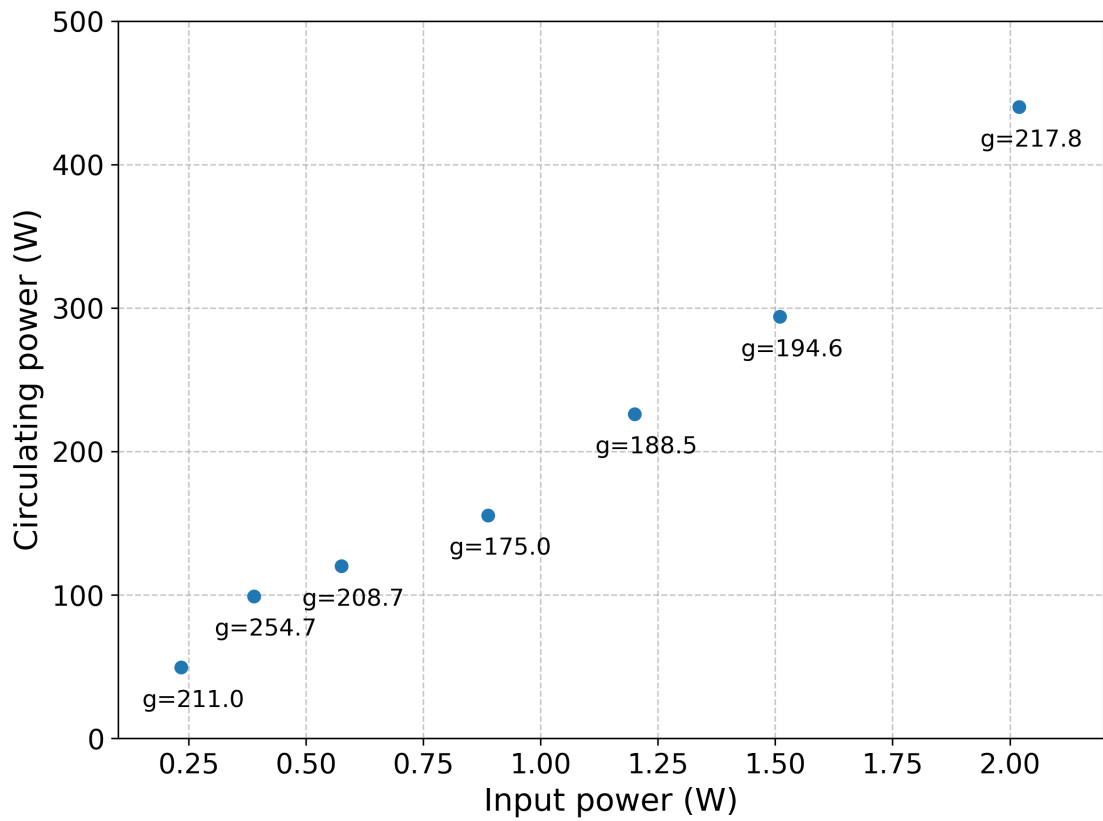


**Figure 7.1.** Observed resonantly enhanced power on the beam splitter as a function of input power. Data are presented in Table 7.2.

A dedicated NPRO laser and a beam-shaping telescope were commissioned to generate a collimated reference laser beam with a diameter of  $500\ \mu\text{m}$ . A half-wave-plate and PBS stage were set up to control the beam's power. A Thorlabs PDA20CS2 photo-detector was calibrated with an amplitude modulation at 888 Hz, generated by driving the current channel of the laser.

The attenuation measured at this reference frequency line served as the sensor for characterizing the optical properties of the beam splitter. For the 50:50 side, the measured ratio of transmission to reflection to loss was 0.494 : 0.504 : 0.002. The loss estimate represents the missing power not captured in either reflection or transmission. This estimated loss is approximately 0.2 % (2000 ppm), of which 180 ppm is known to be caused by the AR coating. Additionally, although the beam splitter coating is designed for s-polarized light, a simple test with a p-polarized beam revealed a reflection-to-transmission ratio of approximately 0.7 : 0.3.

To evaluate surface scatter, power lost due to surface irregularities and coating imperfections causing non-specular reflections, the same reference frequency line and photo-detector setup were utilized. A converging lens with a 25.4 mm focal length was placed 50 mm away from the optic's surface, as shown in Figure 7.2. This lens



**Figure 7.2.** Optical setup for BS scatter power estimation. A beam block is used behind the BS mount to minimize stray scattered light. The measurement was performed with all ambient light sources in the room turned off.

configuration accumulated scattered light over a solid angle of 0.188 steradians. Direct measurement of the 50:50 surface yielded a scatter of 3.4 ppm; integrating this value over a full hemisphere results in approximately 80 ppm. Scatter from the AR side (excluding the wedge reflection) was roughly equivalent to the 50:50 side (80 ppm). This yields an estimated total wide-angle scatter loss of about 160 ppm, leaving roughly 1660 ppm of beam splitter losses unexplained.

It is important to note that this measurement sets a lower bound for scatter losses by assuming an isotropic distribution. Literature suggests that scatter from ultra-polished surfaces is highly anisotropic and concentrates at narrow angles [66]. Achieving a more accurate measurement would require dedicated apparatus, such as an integrating sphere, which is planned for future work.

An *in situ* measurement of scatter losses with the full PRMI locked was attempted by integrating over the image captured by a CMOS camera. However, stray laser power diffused by the metallic mount of the optic dominated the image frame. The dynamic range of the sensor was insufficient to isolate the scatter originating exclusively from the optic. Compounded by the lack of a direct method to accurately calibrate pixel brightness to laser power, this attempt was put on hold.

The high estimated round-trip loss in the core optics was unexpected. Even utilizing our highest transmissivity input couplers (0.5%), the system cannot reach a critically coupled state, meaning a portion of the input field will reflect without entering the cavity. Despite this, we have decided to proceed with the next science run using the current set of core optics. The data from this characterization process will help further constrain the specifications and requirements for the next iteration of QUEST.

## 7.2 Damped in-vacuum optical bench

The commissioning work presented in section 7.1 is targeted at increasing the power on the beam splitter,  $P_{BS}$ , with a goal to improve the shot-noise-limited sensitivity of the interferometers at radio frequencies. However, the power exiting the AS-port,  $P_{AS}$ , is a function of the DC-offset used for the homodyne readout and the residual DARM fluctuations that are not suppressed by the DARM feedback loops. Ignoring any radio frequency signal, the power exiting the AS-port can be approximated as:

$$P_{AS} = P_{BS} \sin^2 \left( \frac{4\pi}{\lambda} (\Delta L_{\text{ext}} + \delta L_{\text{res}}) \right) \approx P_{BS} \left( \frac{4\pi}{\lambda} \right)^2 (\Delta L_{\text{ext}} + \delta L_{\text{res}})^2 \quad (7.1)$$

where  $\delta L_{\text{res}}$  represents the residual seismic and acoustic noise induced changes in DARM length. As  $P_{BS}$  increases, the coupling of this audio-band noise also increases linearly. As a result, the RMS power exiting the AS-port poses a technical limitation for the stability for the homodyne (DC-offset) readout scheme.

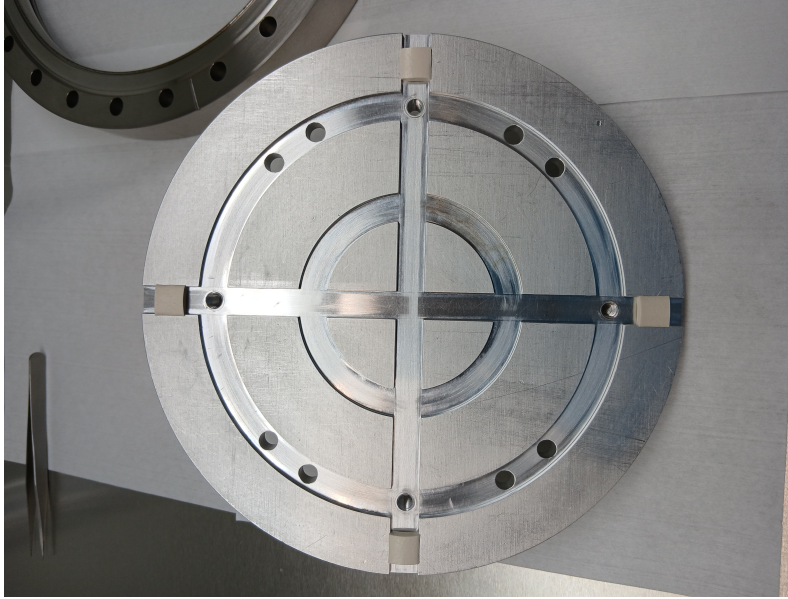


**Figure 7.3.** A picture showing the installed viton pads underneath the optical base plate of one of the end-chamber.

This scaling of noise pick-up presents a significant challenge for the DARM control loop. To suppress the increased audio-band fluctuations, a higher unity gain frequency (UGF) of the DARM servo would be required. However, the current control bandwidth (UGF), while using the CDS system, is limited to about 800 Hz because of digital delay in the system.

To address this, in-vacuum viton vibration isolators were commissioned in all six vacuum chambers, in preparation for SR2. By placing four viton pads under each optical base plate (shown in Figure 7.3), the entire bench assembly was lifted by approximately 0.5 mm, effectively decoupling the optics from the acoustic and seismic vibrations of the chamber floors. This viton-optical base plate system acts as a second-order low-pass filter with a mechanical resonance at approximately 70 Hz. As a result of this commissioning, significant passive isolation in the 300 to 700 Hz band has been observed, where acoustic noise pick-up was previously dominant. This reshaping of the AS-port noise spectrum, as shown in Figure 7.4, has resulted in substantial reduction in the DARM control loop bandwidth requirements. A carefully shaped feedback filter, with additional gain at frequencies less than 200 Hz has resulted in about an order of magnitude lower in-loop RMS in the measured  $PD_{AS}$  power.

### 7.3 Automatic lock acquisition and alignment

The improvements in absolute displacement sensitivity in SR2 are expected due to higher circulating powers along with a longer integration time. To operate the interferometers for long observing runs, order  $10^6$  s, an automated lock acquisition and auto-relock scheme is essential. Such a scheme has been commissioned and tested,

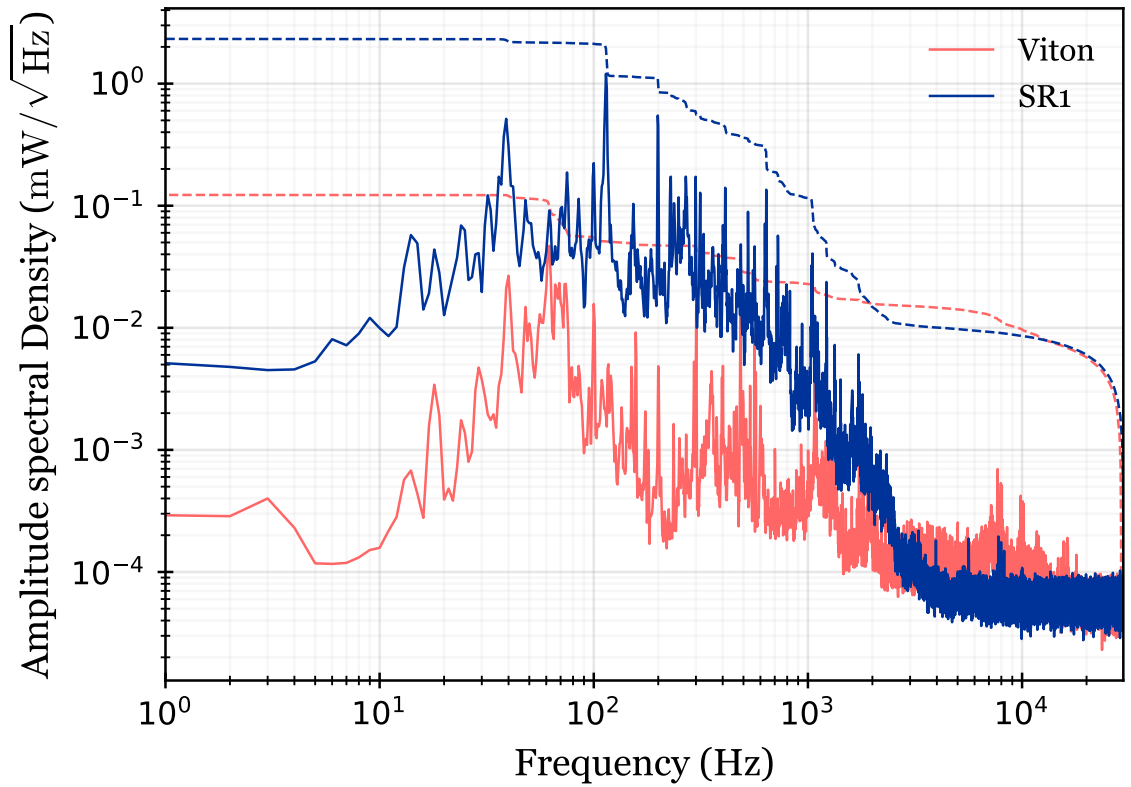


**Figure 7.4.** The anti-symmetric port ASD comparison of with and without the in-vacuum viton isolators.

the details of which are presented in this section. To demonstrate the scheme working, interferometer-B was locked and operated for a stretch longer than 24-hours.

Along with lock acquisition, auto-alignment is necessary for long-term operation. To achieve this, an auto-angular finetuning routine was also commissioned. Unlike LIGO, where complete feedback loop architecture is implemented to maintain various angular degrees of freedom at their operating points, this work tests a simple automatic angular finetuning script that is run at regular intervals to check and maintain the angular degrees of freedom of the interferometer and at their optimal condition. During the 24-hour demonstration, automated fine-tuning of the differential angular degrees of the interferometer was run to maintain optimal dark-fringe condition of the interferometer. This simplified approach is possible because the angular degrees of freedom in QUEST interferometers have empirically observed to be stable on the order of several hours during the commissioning period for SR1.

The automated routine is implemented in Python, which communicates with the CDS system via EPICS channels and with the Moku by its application programming interface over ethernet. Broadly, the commissioned automated routine has four unique tasks: catching lock, transition from dither lock to a DC-offset lock, transition from a DC-offset lock to a dither lock and finally optimizing alignment.

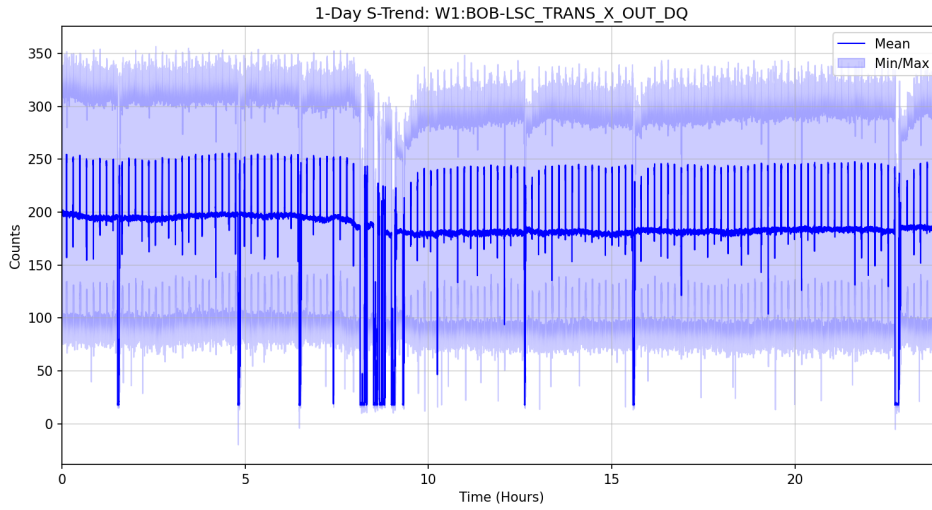


**Figure 7.5.** One day long test of the auto-relock routine. The time-series of transmitted power through the EX end-mirror is shown, the repeating peaks at every 10-minutes is the auto-alignment routine running after transitioning to the dark-fringe using a dither lock. The interferometer was lock at mid-fringe with a DC lock for operation. The test was performed both with and without the viton isolators.

The system is prepared with initial alignment and mode-matching, similar to section 5.1.1, to a state where lock can be achieved manually and power build-up can be observed. With the interferometer either locked or unlocked, the automation script is engaged. The script monitors the transmitted power (proxy for power build-up) of the interferometer (via CDS) to determine the lock state of the system. If the transmitter power is below a threshold, which is set empirically, the interferometer is declared as unlocked and the following steps are performed:

- Both frequency stabilization and DARM control loops are opened and the offsets for their actuators are set to zero.
- The dither injection needed for DARM readout and locking is engaged. At 1800 Hz with 150 counts of amplitude during this test run.
- A laser frequency scan is engaged at 25 Hz with a range of  $\pm 65$  MHz using MOKU.
- The DARM length is swept through one FSR of range (about 2500 counts) using a triangular sweep at 1 Hz.
- The data from one cycle of DARM length sweep is recorded and the DARM length offset is set to the value corresponding to maximum power at  $PD_{AS}$ .

- Then immediately, laser frequency sweep is stopped and the frequency stabilization loop is engaged, followed by the dither lock for DARM to lock to the maximum, corresponding to point B in Figure 4.3.
- The transmitted power is used to determine the lock state of the interferometer, if the measured power is below the threshold (150 counts in the test), the system waits for 5 s and repeats this routine from the first step.
- Once the interferometer is locked, the script transitions the system from dither lock to the maximum  $PD_{AS}$  to dither lock to dark fringe (minimum  $PD_{AS}$ ), corresponding to point A in Figure 4.3. This is done by first, finding the appropriate direction to move the DARM actuators.

A small triangular sweep (100 counts amplitude) is injected into DARM length, while locked at point B, and the corresponding response in transmitted power is measured to determine the direction for dark fringe (increase in trans-power). The sign of the loop gain is flipped and an offset is added to DARM, in the appropriate direction, to transition the lock to dark fringe.

- Once locked at dark fringe the DARM lock is transitioned to DC-offset. This is done by opening the DARM loop, tuning off the dither and adding the appropriate DC-offset (5000 counts during this test run) and closing the loop with a small gain (corresponding to UGF of about 1 Hz), and in a span of 5 seconds the loop gain is ramped up to fully operational state (UGF of 300 Hz during this test run).
- At any point in this lock acquisition routine, if the lock is lost and the transmitted power falls below the threshold, the routine is started back from the first step.

After every lock acquisition step an angular finetuning routine is performed. The lock is transitioned into a dither lock at dark fringe and the  $PD_{AS}$  power is used as a measure for contrast. DYAW and DPIT degrees of freedom are independently swept with a triangular wave with 100 counts of amplitude and the appropriate offset. Following which, the DYAW and DPIT offsets corresponding to the minimum of  $PD_{AS}$  are selected. This script took 40s to complete and for the 24-hour test run this auto-alignment script was run every 10-minutes.

A duty cycle of about 90 % was achieved using this auto-relock scheme, with the system typically acquiring back lock in about 2-minutes. A breakdown of the duty-cycle is presented in Table 7.3 and the transmitted power during the run is shown in Figure 7.5.

| Status                   | Time (seconds) | duty-cycle (%) |
|--------------------------|----------------|----------------|
| Locked                   | 77430          | 89.6           |
| Auto-alignment           | 4800           | 5.5            |
| Unlocked/Relock attempts | 4170           | 4.8            |

**Table 7.3.** The distribution of various steps during the 24-hour run.

## 7.4 High-frequency data acquisition system testing

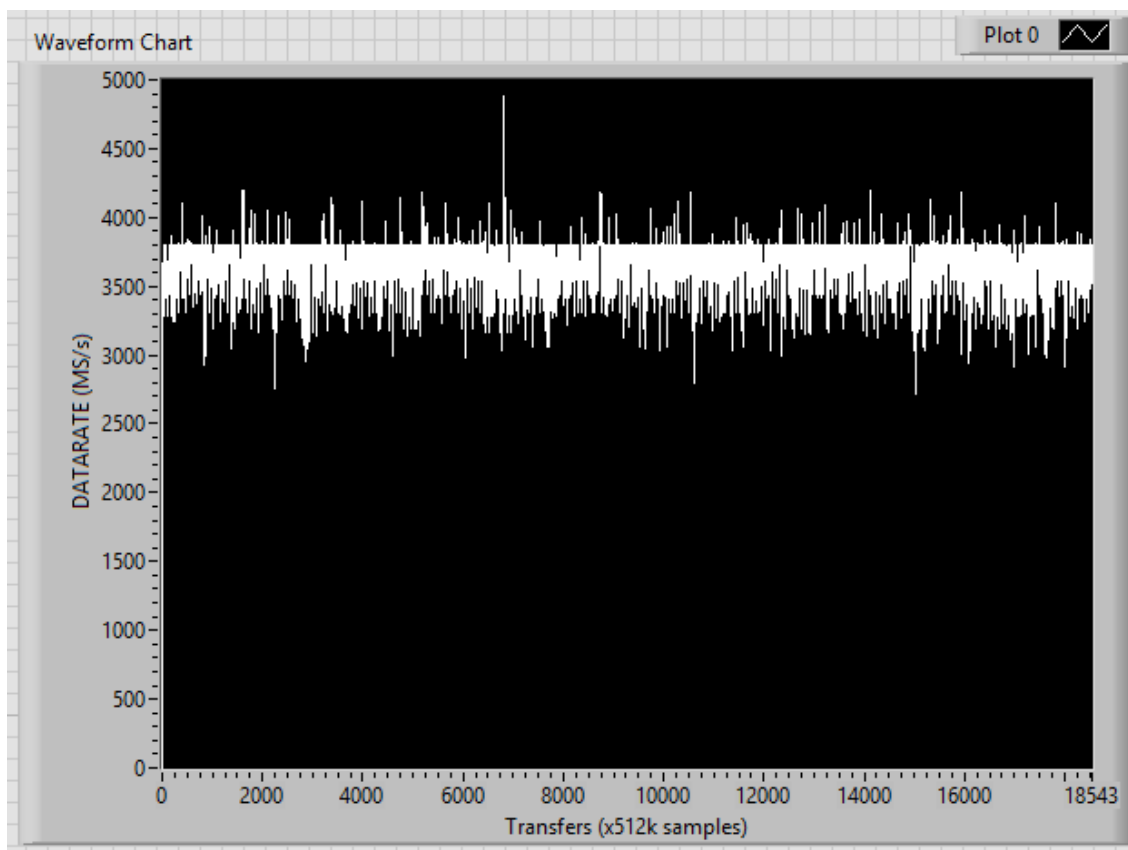


**Figure 7.6.** The data throughput trend observed during the HFDAQ loop-back test. Each data point represents a transfer of 512k 16-bit samples. A transfer rate greater than 3500 mega-samples per second was achieved, demonstrating that the full data rate of transferring four channels sampled at 500 mega-samples per second to the host CPU is attainable.

Implementing real-time FFT operations on FPGA systems limits both the number of channels that can be processed simultaneously and the number of samples per FFT operation. During SR1, only two real-time channels were captured at the full science data rate of 500 mega-samples per second. For upcoming science runs, the AS-port power from each interferometer will be split equally onto two photo-detectors, as described in Section 6.4. Both the auto-correlation of the two interferometers and the cross-correlation

between them will be computed simultaneously. The high-frequency data acquisition (HFDAQ) system is currently being upgraded to accommodate this change, alongside several quality-of-life improvements.

**Data throughput test:** The computational bottleneck of calculating real-time FFTs on the FPGA can potentially be bypassed by transferring the raw data to the host CPU for processing. To verify the feasibility of this approach, a data loop-back test was conducted.

A LabVIEW program was developed to write to a direct memory access (DMA) first-in-first-out (FIFO) data structure, which passes data into the FPGA of the high-frequency digitizer card. The FPGA was then programmed to echo the same data back. These two data transfer steps were performed continuously in a non-blocking loop, with monitors in place to check for buffer overflows and data loss. A data throughput of 7 GB/s was achieved, corresponding to roughly 3500 mega-samples per second (as shown in Figure 7.6). This performance is close to the hardware's theoretical limit of 8 GB/s, which is constrained by the PCIe Gen3x8 link between the FPGA and the host. Most importantly, this test established that data from all four channels of a digitizer can be reliably transferred to the host memory at the full acquisition rate of 500 mega-samples per second.

Further testing of real-time FFT calculations on the CPU is required to determine the exact number of parallel channels that can be processed simultaneously and the total number of cross-correlations that can be computed.

An additional quality-of-life upgrade was successfully commissioned and tested. During SR1, averaged data frames were simply labeled with serial integers as they were stored to disk. The host-side data processing has now been updated to label these frames with their corresponding GPS timestamps. The latency from when a sample reaches the analog front-end of the digitizer card to when the frame is saved to disk is expected to be dominated by the CSD averaging step performed on the FPGA co-processor. Because this absolute latency is sufficiently small for QUEST's experimental use case, it can be safely ignored during GPS time stamping.

## 7.5 Squeezer characterization

Before undertaking the integration and commissioning work of the squeezed light sources (SLS) with the interferometers, one of the SLS was characterized. A balanced homodyne detector (BHD) was implemented to perform tomography of the quantum state generated. The schematic of the full optical layout of SLS and the BHD detector are presented in [11].

The local oscillator (LO) needed for the BHD is extracted directly from the main laser source and then mode-matched to a low-finesse reference cavity. The reference

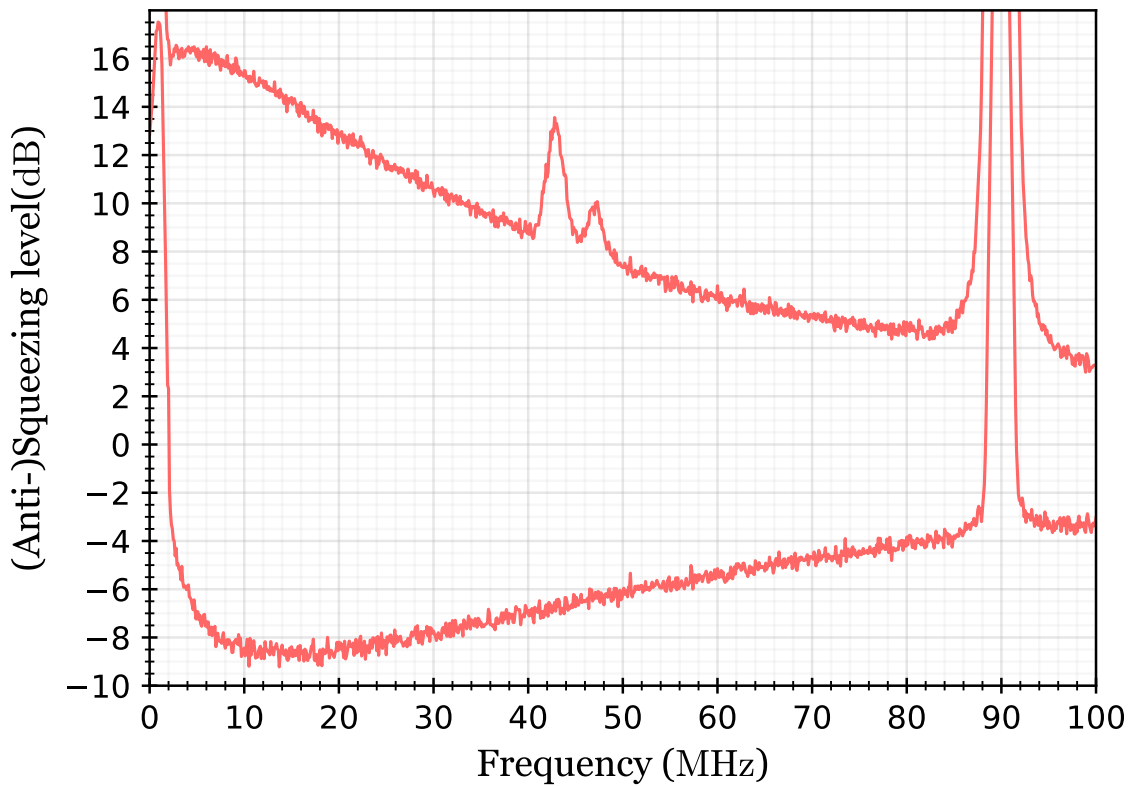


**Figure 7.7.** The observed squeezing and anti-squeezing levels using a balanced homodyne detector setup [11]. The control sideband carried by the bright squeezed beam is seen at about 89.9 MHz. The change in observed squeezing level across the band is due to the bandwidth of the OPA.

cavity used is an OMC commissioned for use in QUEST’s detection optical layout. The bright alignment beam from the OPA was mode-matched and aligned to the LO, the contrast between the two beams was used as the sensor for this alignment. The BHD sensor is formed using two fast photo-detectors, commissioned for QUEST readout, with real-time digital subtraction of their signals using a MOKU:pro.

The squeezing and anti-squeezing levels and the bandwidth of squeezed field generated by the OPA were measured by locking the phase difference between the LO and the bright squeezed fields with opposite phase. The error signal for the phase lock was generated by demodulating at the 89.9 MHz control frequency carried by the bright squeezed field as well as the contrast seen at DC. The measurement of squeezing and anti-squeezing level from 1 to 100 MHz is shown in Figure 7.7 and further details of the measurement are presented in [11]. The frequency bandwidth of the measurement was limited by the photo-detector bandwidth.

## 7.6 Other commissioning work

**Fast photodetectors:** To overcome the frequency bandwidth limitation of the fast photodetectors seen during SR1, the photo-diodes used in the detectors have

been replaced with low-capacitance InGaAs diodes (Excelitas C30641GH-LC). The characterization and response measurement for these new detectors is underway, they are expected to yield at least 100 MHz of detection bandwidth.

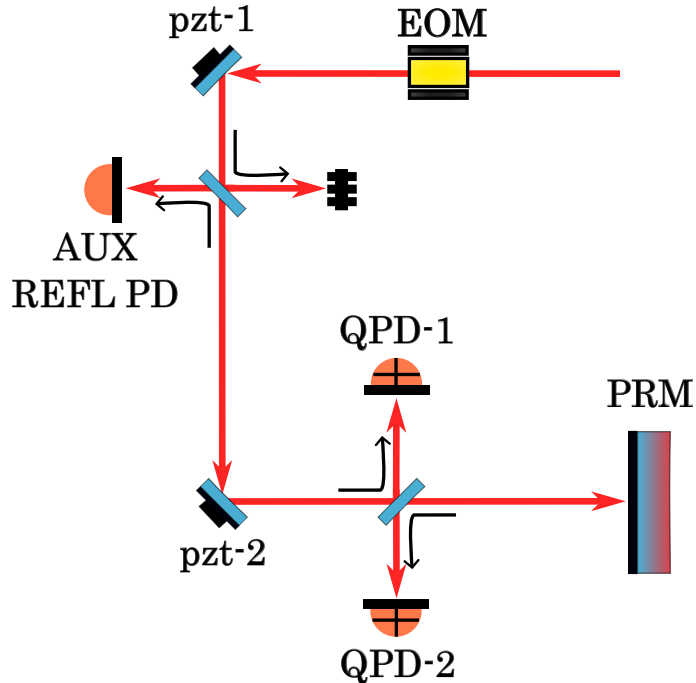


**Figure 7.8.** A schematic of the injection piezo actuators and QPD sensors is shown. This setup has been commissioned in the injection path of interferometer-B. The optics used to pick-off power are AR-coated filters, that have a reflectivity of 0.5 %. Integration and testing of these systems as part of auto-relock and alignment routines is ongoing.

**Injection path sensors and actuators:** The tip-tilt alignment mirrors in the injection path to the interferometer-B have been replaced with piezo actuated tip-tilt mounts, similar to the in-vacuum mounts for the end mirrors. Two 0.5 % pick-off mirrors and quadrant photo-diode detectors have also been commissioned in the path. An extended lock with these sensors and actuators integrated with the auto-alignment routine is planned to measure injection alignment in the interferometers. If successful, a similar system will be commissioned for interferometer-A. A schematic of this setup is shown in Figure 7.8.

**Laser injection system:** The LIS for interferometer-A has been fully commissioned with a NeoLase laser amplifier and has been brought to parity with that of interferometer-B.

## 7.7 SR2 - plans and goals

At the time of writing, the commissioning work for science run 2 is underway. A high-power engineering run is planned, where the auto-relock scheme will be tested

along with the viton isolators simultaneously. The goal for this engineering run would be to operate one of the interferometers for a period of 24-hours and at a higher circulating power than SR1, about 300 W on the beam splitter. A two photo-detector cross-correlation measurement, similar to section 6.4, will be performed. The primary objective for this test run is to commission and troubleshoot the auto-relock and alignment scheme with higher sensitivity and bring all the systems up to an operational state.

The science run 2 is planned as an extended data-taking run, where both the interferometers are operated at 1 kW of circulating power resulting in an absolute displacement sensitivity of about  $1.58 \times 10^{-18} \text{ m}/\sqrt{\text{Hz}}$ , in both. At least 1-million seconds of data taking, corresponding to  $1.53 \times 10^{10}$  spectra being averaged, at the same FFT frequency bin-width resolution as SR1 (15.26 kHz) is planned. This data-taking will yield a probe for correlated space-time signals upto a sensitivity of  $4.5 \times 10^{-21} \text{ m}/\sqrt{\text{Hz}}$ , which is about an order of magnitude better than the limit set during SR1 and about a factor 5 better than the absolute displacement limit set by the Holometer [6].

Along with new limits set for fundamental science goals, similar to section 6.4, the data from SR2 will be used to probe two technical goals. Another measurement of bulk-thermal modes, but with better sensitivity and a direct measurement of the thermo-refractive noise spectra at radio frequencies.

## Chapter 8

# Conclusion

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The QUEST experiment has successfully concluded its first science run (SR1) and setting a record for the absolute displacement sensitivity for a table-top interferometric system. During this run, approximately 10,000 seconds of coincident, high-frequency data were collected from two co-located, independent interferometers. Operating with circulating beam-splitter powers of order 100 W, the instrument achieved an absolute displacement sensitivity of  $5.5 \times 10^{-18} \text{ m}/\sqrt{\text{Hz}}$  in both interferometers.

As part of this science run  $1.64 \times 10^8$  cross-correlation spectra were measured and averaged. The observed cross-spectra scaled with the characteristic  $\sqrt[4]{N}$  scaling concluding the absence of any correlated signals between the two interferometers and allowed QUEST to reach a strain sensitivity of  $3 \times 10^{-20} 1/\sqrt{\text{Hz}}$  across the 13 to 80 MHz frequency band.

The absolute displacement and strain sensitivities allowed us to set experimental constraints on several fundamental physics targets. First, SR1 allowed us to set upper limits on the dimensionless energy density of the high-frequency stochastic gravitational-wave background,  $h_{100}^2 \Omega_{\text{GW}}(f)$ . Second, the data constrained scalar field dark matter candidates by setting limits on the inverse photon and electron coupling constants ( $1/\Lambda_\gamma$  and  $1/\Lambda_e$ ) of approximately  $10^{-11} \text{ GeV}^{-1}$  for particle masses ranging from  $4 \times 10^{-9}$  to  $3 \times 10^{-7} \text{ eV}$ . Finally, SR1 provided empirical bounds on theoretical models of quantum spacetime fluctuations, yielding a  $3\sigma$  exclusion limit for Zurek’s geontropic noise model for a scale factor of  $\alpha = 61.2$ .

Beyond fundamental science constraints, SR1 allowed us to develop a path for instrument development, laying a path for the upcoming iterations of the QUEST experiment and allowing us to better understand the limitations. A dedicated single-interferometer cross-correlation measurement successfully probed classical noises below the shot noise limit, revealing the unique thermal noise comb characteristic of the phonon modes within the 6 mm thick fused silica core optics, yielding a direct measurement of the bulk-thermal noise of fused silica at radio frequencies.

For SR2, the interferometers will be operated with a target circulating power of 1 kW on the beam splitters, which is expected to improve the baseline shot-noise-limited sensitivity to  $1.58 \times 10^{-18} \text{ m}/\sqrt{\text{Hz}}$  per interferometer. Coupled with a planned observation period of 1 million seconds, this upgraded configuration aims to explore cross-correlated sensitivities on the order of  $4.5 \times 10^{-21} \text{ m}/\sqrt{\text{Hz}}$ . Achieving these design parameters [7] will allow QUEST to probe deeper into the fundamental nature of spacetime, setting unparalleled limits on irreducible quantum gravity models, high-frequency gravitational waves, and dark matter candidates.

## Appendix A

### Appendix

#### A.1 Comprehensive QUEST layout

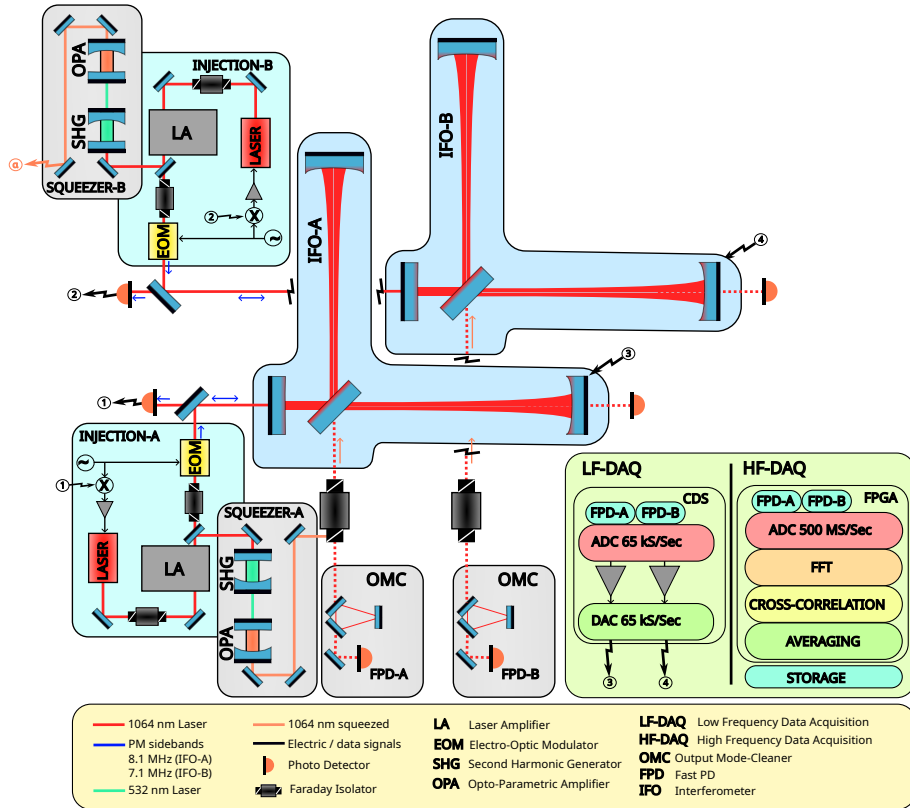


**Figure A.1.** A comprehensive schematic of various subsystems of the QUEST apparatus are presented. The two interferometers, their core optics and vacuum envelopes are shown. The two laser injection systems, squeezed light sources and the output mode-cleaners and the data acquisition system are also shown.

## A.2 Simple $1/f$ integrator

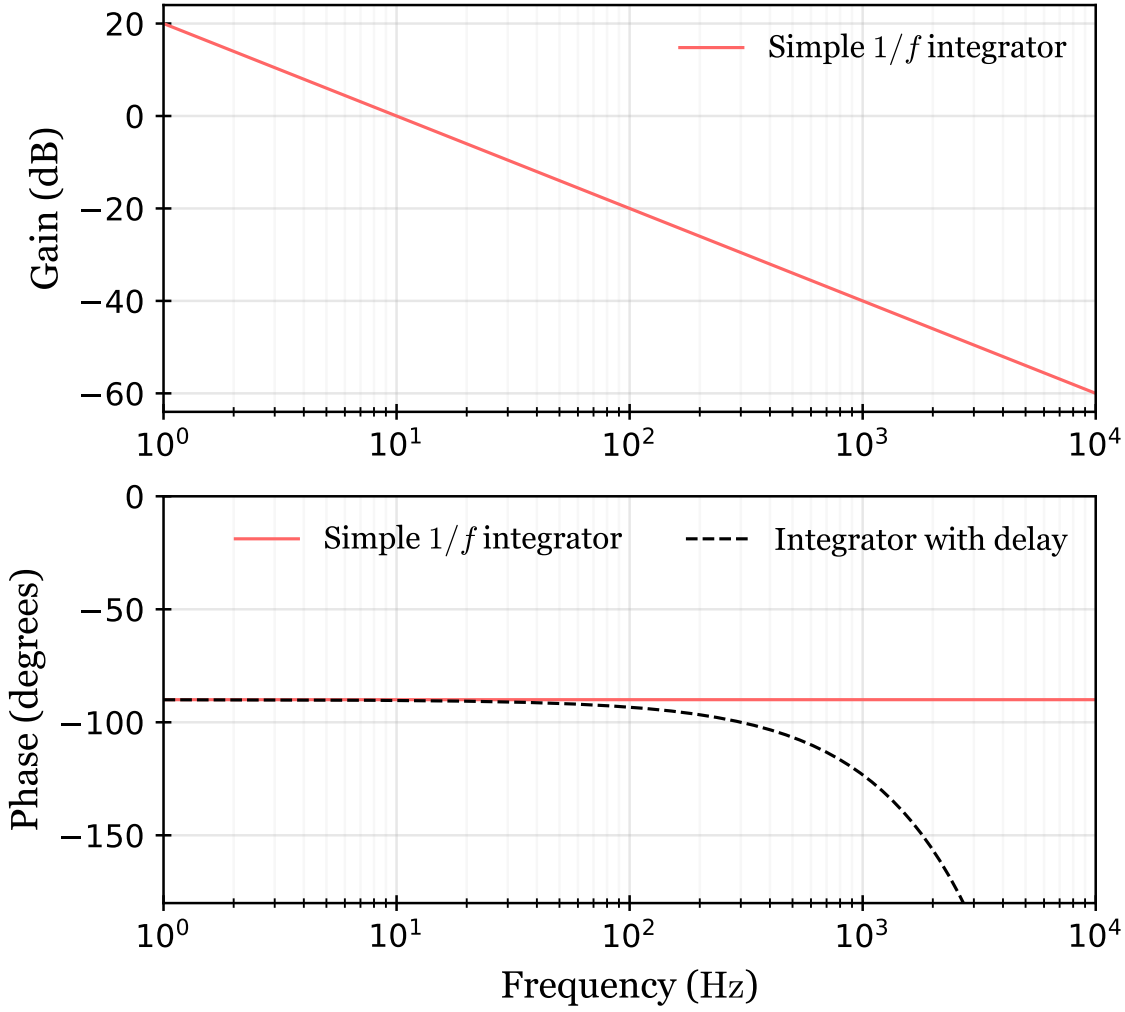


**Figure A.2.** The frequency response, both magnitude and phase, of a simple  $1/f$  integrator is shown. The  $1/f$  frequency response results in a gain drop of 20 dB per decade. In the absence of any delay the phase of a simple integrator is constant. In the CDS system used in the QUEST experiment a delay of 12 cycles was measured, and the corresponding phase of an integrator with this additional delay is shown in the black dashed trace.

A simple  $1/f$  integrator is represented by the following frequency response:

$$H(s) = \frac{2\pi k_u}{s} \quad (\text{A.1})$$

where  $k_u$  is the gain of the integrator. This frequency response is also shown in the form of a Bode plot in Figure A.2. An integrator is simply represented by a pole at zero Hz, and in the zero-pole-gain representation, can be represented as  $\text{ZPK}([ ], [0], k_u)$ .

The response of simple  $1/f$  integrator results in fixed phase delay at all frequencies. As a result if a system can be engineered to have a simple integrator like frequency

response under constant feedback control, it will be unconditionally stable. In practice, the stability of a system is limited by limited gain or digital delay of the control system. In QUEST, most feedback loops aim to be as close to a simple  $1/f$  integrator as possible, but are limited by the CDS system's digital delay.

### A.3 Visible scatters

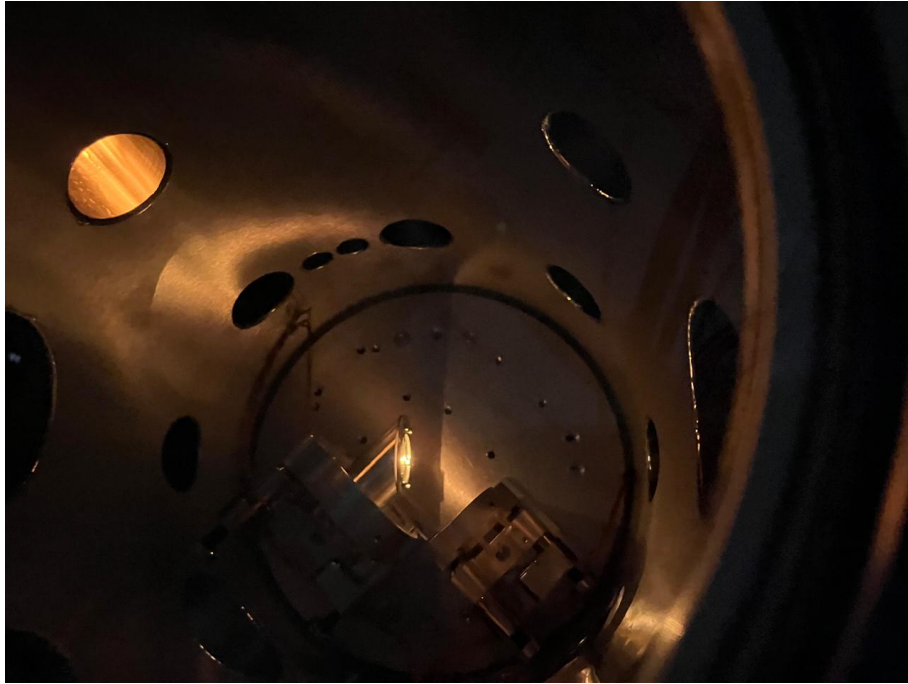


**Figure A.3.** A picture showing a failed attempt to power-up a full PRMI. The beam splitter can be seen glowing in visible wavelengths.

As part of achieving high-circulating power on the beam splitters, the interferometer were lock and injected with high laser powers (up to 5 W of 1064 nm laser beam). The power recycling cavity of the interferometers defines a spatial eigenmode that results in a Gaussian beam with radius about 1 mm on the beam splitter. While this power-up tests were being performed, at about  $7 \text{ kW/cm}^2$  intensity, visible scatter was observed from the beam splitter, Figure A.3. This visible scatter was observed multiple times as part of high-power PRMI commissioning. Various systematic changes were tested to find the root cause of this visible scatter, it is likely from a bad batch for First contact cleaning compound used for preparing the core optics. Following this test, with the use of a new batch of cleaned mirrors, more than 1 kW of steady state circulating power, corresponding to more than  $30 \text{ kW/cm}^2$  of power density was achieved.

### A.4 Commissioning MEDM screen

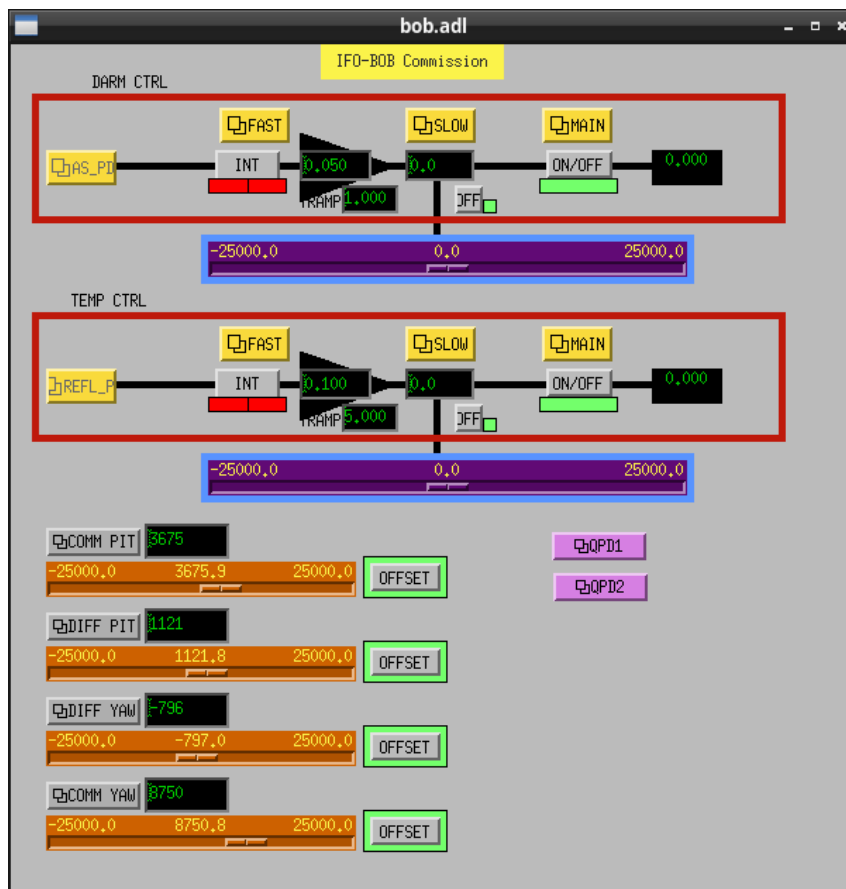
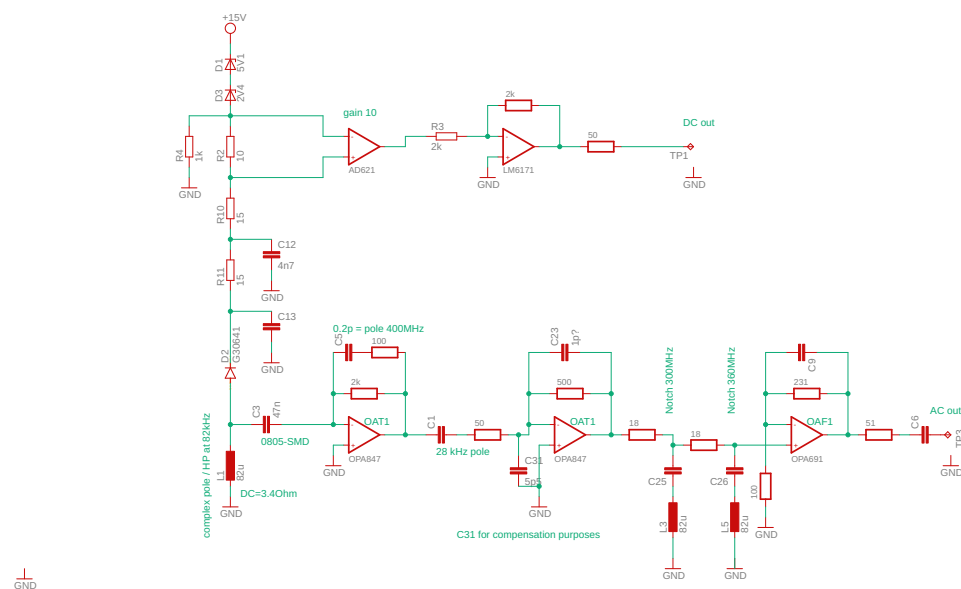


**Figure A.4.** Commissioning MEDM screen used for lock acquisition routine. The sliders used for driving the DARM and angular degrees of freedom using the piezo actuators can be seen.

## A.5 Fast Photodetector circuit schematic



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**Figure A.5.** The circuit schematic diagram of custom fast photodetectors used to capture QUEST's science data is shown. The schematic show the DC and AC paths of the detector along with transimpedance and various amplification stages. The zener diode ladder at the top of the schematic sets the 7.5V DC bias used across the photo-diode.



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