

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Technical Note	LIGO-T2600151-v5	2026/09/28
Measuring Photon Bunching in Next-Generation Adaptive Optics		
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1 Abstract

The FRONt Surface Type Irradiator (FROSTI) is a new wavefront actuator for LIGO that will enable higher laser power and reduce quantum noise. FROSTI uses an infrared heating pattern projected by a blackbody source onto the highly-reflective surfaces of the LIGO test-masses. FROSTI is named for its ability to return the optic to its cold optical state. Thermal radiation is used as it is the only source with sufficient intensity stability which meets LIGO's strict requirements. An upper limit has been set on the displacement noise caused by intensity fluctuations in FROSTI [13], but even higher sensitivity measurements are necessary. This project will develop an optical testbed to measure photon bunching described by the Hanbury-Brown-Twiss effect. The result of this measurement would be a demonstration that FROSTI can operate at its theoretical noise minimum.

2 Introduction

2.1 History of LIGO

In 1905, Poincaré made the first explicit mention of gravitational waves; stating that special relativistic gravity could have waves which travel at the speed of light [10]. Ten years later, Einstein formulated his theory of general relativity. In this new theory, he asserted that gravity was not a force, rather a curvature of spacetime itself. Einstein also found that the linearized weak field equations had wave solutions [7]. These wave solutions were transverse strain waves which travel at the speed of light, generated by variations of the mass quadrupole moment of the source. With gravitational waves theorized and a mathematical solution presented, the world was left to confirm this phenomenon with experiments.

Detecting gravitational waves on Earth is exceptionally difficult, as their strain amplitude is extraordinarily small (10^{-21}). Gravitational waves interact weakly with matter in the universe, making them a fascinating complement to observational astronomy. This unique property allows gravitational waves to reveal insights about astrophysical objects that are not seen with traditional telescopes.

Experiments began in the 1960s to detect gravitational waves with Joseph Weber, who pioneered resonant mass detectors [17]. Four decades later, the first interferometric detectors came to be: TAMA 300 (Japan), GEO 600 (Germany), LIGO Livingston and LIGO Hanford (U.S.), and Virgo (Italy) [1]. These detectors worked for a decade to set upper limits on gravitational wave sources.

Finally, in 2015, a new era of gravitational wave astronomy was ushered in when Advanced LIGO (aLIGO) began operations. In just two days of runtime, aLIGO made history by providing the first direct observation of gravitational waves [1]. Since then, aLIGO has been joined by two other detectors – Advanced Virgo (Italy) and KAGRA (Japan). Together, they form an international network of highly sensitive detectors, enabling localization of gravitational wave sources and opening new windows to physics.

The Laser Interferometer Gravitational-wave Observatory (LIGO) employs a Michelson interferometer design. Its 4km arms are enhanced with Fabry-Pérot cavities to artificially

increase the effective arm length. These cavities are formed between the reflective surfaces of the input test mass (ITM) and the end test mass (ETM). Inside these arms, up to 750 kW of circulating power can theoretically be stored, but during the most recent observing run, LIGO only saw between 250-350 kW [3, 5]. LIGO’s Michelson interferometer also includes two additional mirrors: the power recycling mirror (PRM) and the signal recycling mirror (SRM). The power recycling mirror is placed between the laser and the beam splitter, and reflects light that has already traveled through the arms back into the interferometer [2]. In this way, the PRM increases the power in the interferometer cavities. Placed in the antisymmetric port, the signal recycling mirror works to resonantly build up the GW signal. Through a process known as resonant sideband extraction (RSE) [2], the SRM differentially extracts signals from a passing gravitational wave. In summary, light from the laser source is split into two paths by the beam splitter, reflects off the end mirrors, and is recombined at the beam splitter. When a gravitational wave passes through, it induces a phase shift on the laser light, which is then extracted as a signal at the detection output [2].

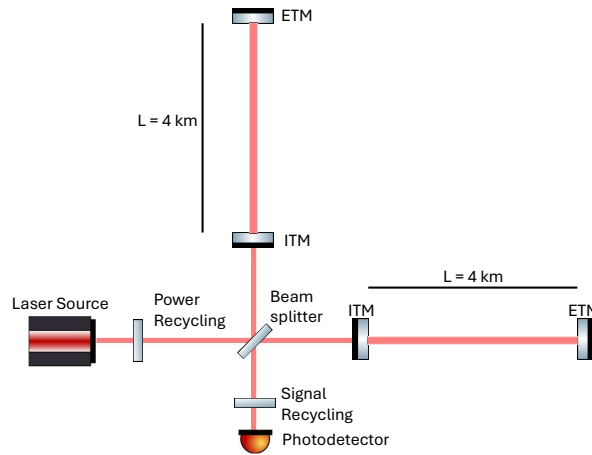


Figure 1: LIGO’s Michelson Interferometer design with Fabry-Pérot cavities, power recycling mirrors, and signal recycling mirrors.

2.2 Planned upgrades

As of writing, LIGO has completed four observation runs, and both detectors are now in a period of upgrades and commissioning. The fifth observing run (O5), set for 2028, will occur after a brief, six-month intermediate run (IR1) in 2027 [11].

Prior to the fifth observing runs, an incremental upgrade to aLIGO will leverage existing technology to improve the detectors. This upgrade is known as LIGO A+, and is intended to be a stepping stone to third generation detectors. A+ will bring the following enhancements: improved coatings, frequency dependent squeezing, boosted optical efficiency, balanced homodyne readout, an enlarged beam splitter, and improved suspension fibers [12]. In the batch of upgrades following A+, referred to as A#, LIGO will receive new optical coatings, larger 100 kg test masses, and reach significantly larger 1.5 MW of laser power [6].

These changes intend to push gravitational wave sensitivity by an order of magnitude each, see Fig. 2. More sensitive detectors can detect compact binary merger events at further

redshifts, and observe more events per year. A# detectors will see past a redshift of 5, and detect several thousand binary black holes and several hundred binary neutron stars annually [14]. Acquiring the sensitivities necessary to enable this science relies on reducing quantum noise.

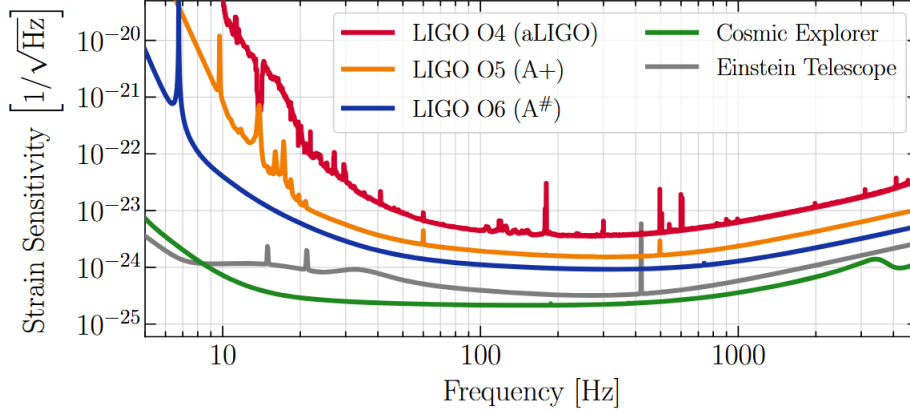


Figure 2: Planned sensitivities of upcoming LIGO upgrades. Projected sensitivities for Cosmic Explorer and Einstein Telescope are included as well [14]

The most significant noises in LIGO come in two types: thermal noise and quantum noise. Although the thermal noise contributes more in the mid-band, quantum noise dominates both low and high frequency regimes [5]. The origin of quantum noise lies in the quantization of the electromagnetic field used in the interferometer’s arms. Quantum noise is largely dominated by radiation pressure noise at low frequencies, and shot noise at high frequencies. In lower frequencies, amplitude-quadrature fluctuations physically displace the test masses by radiation pressure [2]. Higher frequency quantum noise is dominated by phase-quadrature fluctuations that result in shot noise [2]. In Fig. 3, it is easily seen that the quantum noise (shown in dashed purple) dominates the noise budget across most of LIGO’s detection frequencies.

Quantum noise can be mitigated with increased laser power and squeezing. Higher laser power can reduce the shot noise as $1/\sqrt{P_{arm}}$. With the increased power, there is also increased radiation pressure noise as $\sqrt{P_{arm}}$ [2]. To mitigate the increased radiation pressure noise, frequency-dependent squeezed light is injected to the arms. This injection reduces amplitude fluctuations in the low frequencies, reducing the radiation pressure. It simultaneously reduces the phase fluctuations at high frequency, which reduces the shot noise [2].

LIGO’s planning upgrades (A+,A#) seek to improve LIGO’s sensitivity by one order of magnitude each. As quantum noise dominates most of the detection band, it is critical to suppress this as much as possible. Without this, LIGO cannot reach the design performance of A+ and A#. Techniques to achieve this rely on maximizing laser power and implementing squeezing techniques in the interferometer.

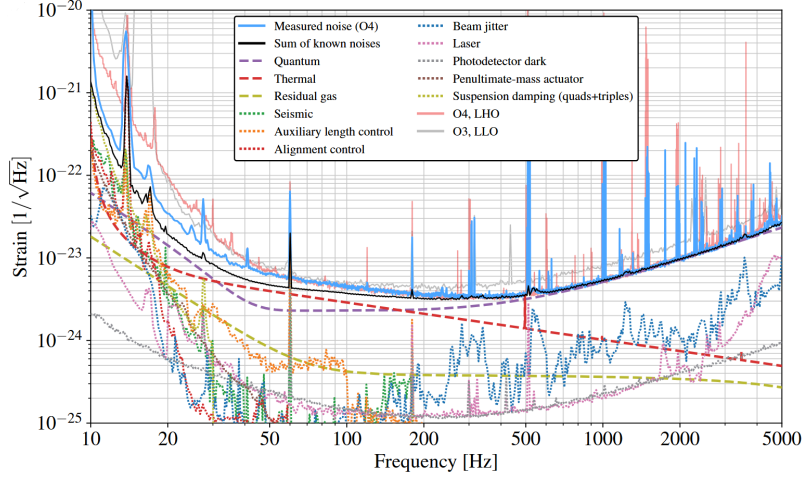


Figure 3: Noise budget for the LIGO Livingston observatory in the fourth observing run [5]

2.3 Thermal effects and FROSTI

Thermal effects in the optics limit both achievable laser power and squeezing levels. Absorption of higher laser power within the coatings of the test masses results in a radial temperature gradient in the optics and thermo-elastic surface deformation in the test mass [3]. Both of these effects result in thermo-elastic deformations of the optical surfaces and thermo-refractive lensing within the substrate. Higher levels of squeezing become ineffective if thermo-refractive lensing inside the ITM introduces too much wavefront distortion [13]. To mitigate the wavefront errors, LIGO currently uses the Thermal Compensation System (TCS).

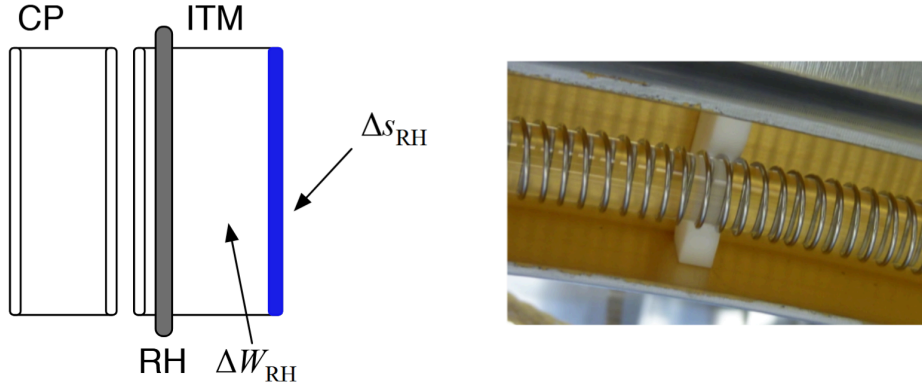


Figure 4: Overview of aLIGO ring heaters mounted as part of the Thermal Compensation System (TCS) [3]

As a part of the LIGO TCS, ring heaters (seen in gray and labeled RH in Fig. 4) are mounted along the barrel of the Initial Test-Mass ITM and End Test-Masses (ETMs). These ring heaters heat the optic to alter the surface curvature and substrate lenses. This results in a radially quadratic correction on the substrate and surface lenses, which is designed to mitigate the wavefront error in the center of the optic. Looking forward, the correction

provided by the TCS is not sufficient for A# requirements. The residual wavefront errors on the LIGO's ITM can be seen in Fig. 5. Even with optimal TCS corrections, hundreds of nm of wavefront error persist. This residual wavefront error prevents A# targets of 1.5 MW of power and 10 db of squeezing [6].

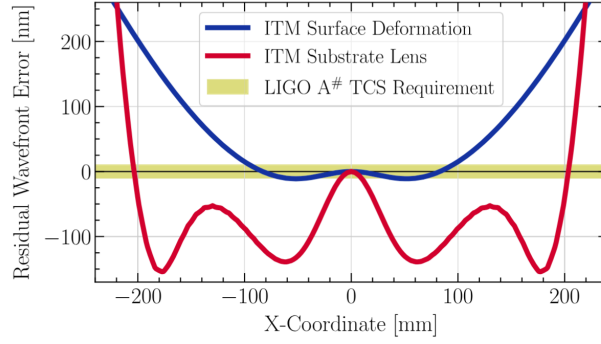


Figure 5: Residual wavefront error in LIGO A# 100 kg Initial Test-Masses (ITMs). [14].

The need to correct the remaining wavefront errors demands a new method of active wavefront control. The group at University of California, Riverside has developed a system known as the FROnt Surface Type Irradiator (FROSTI). This active wavefront control is named for its ability to return the optic to its optically *cold* state [14]. It works by projecting 3-14 μm thermal radiation in an annular spatial pattern onto each test-mass. In air, the peak black-body emission of FROSTI lies around 7.7 μm . The heat is produced by an internal graybody source, and is reshaped by non-imaging reflectors which create the annular pattern. A gray-body source is chosen for its ability to radiate with intensity stability near the shot-noise limit. FROSTI represents a new method of adaptive optics designed to operate under higher laser power [13].

A major experimental challenge is posed by the fact that the corrective heating is applied directly onto the highly-reflective surface of the test-masses. As these are the most displacement sensitive optics, intensity noise from FROSTI will couple into optomechanical and photothermal displacement noise [2, 13]. The dominant source of noise coupling stems from photothermal "bending" caused by thermoelastic motion of the HR surface relative to its center of gravity. Quantifying FROSTI's relative intensity noise (RIN) is essential to ensure it meets LIGO stringent requirements.

For this purpose, we seek to develop an optical test bed designed to set improved upper limits on FROSTI's RIN (see Fig. 7 for current upper limit, seen in red). We can measure photon bunching, described the Hanbury-Brown-Twiss effect, which lies just above the shot noise produced by FROSTI's radiation. Detecting this relatively small effect would provide critical information about the system's noise performance. Successfully measuring this would demonstrate that FROSTI can operate near its theoretical noise floor.

3 Approach/Method

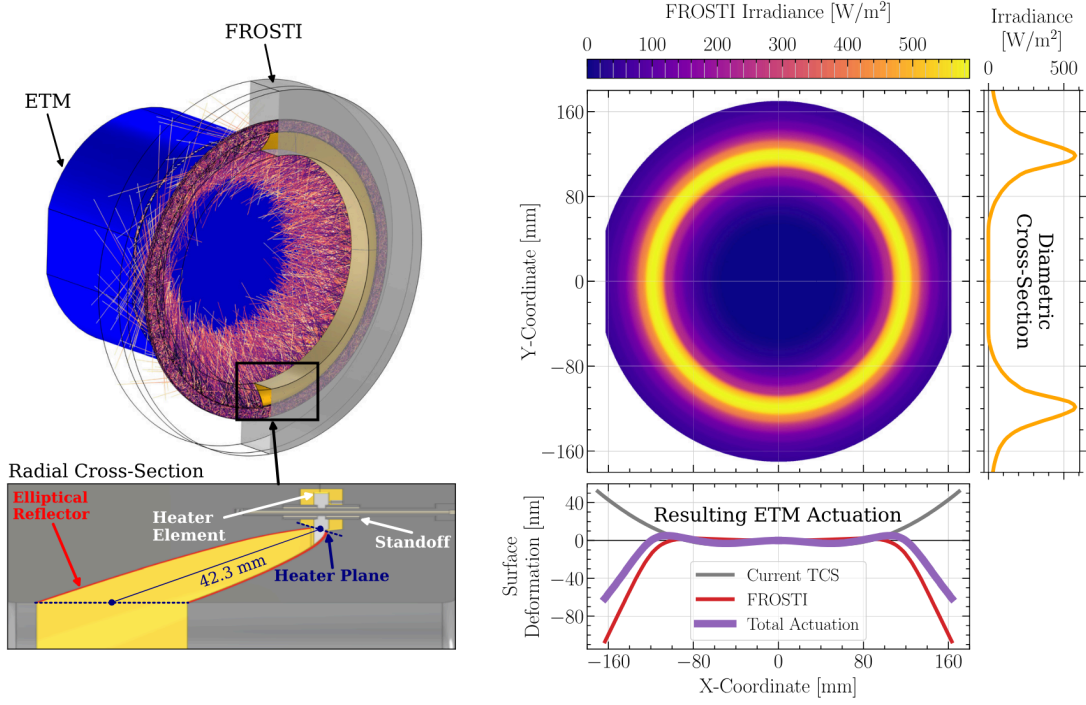


Figure 6: Ray tracing (left) and FEA (right) simulations of the FROSTI concept. Resulting surface deformation shown in the bottom right. The annular irradiance pattern designed to reduce thermal aberrations at the edges can be clearly seen [14].

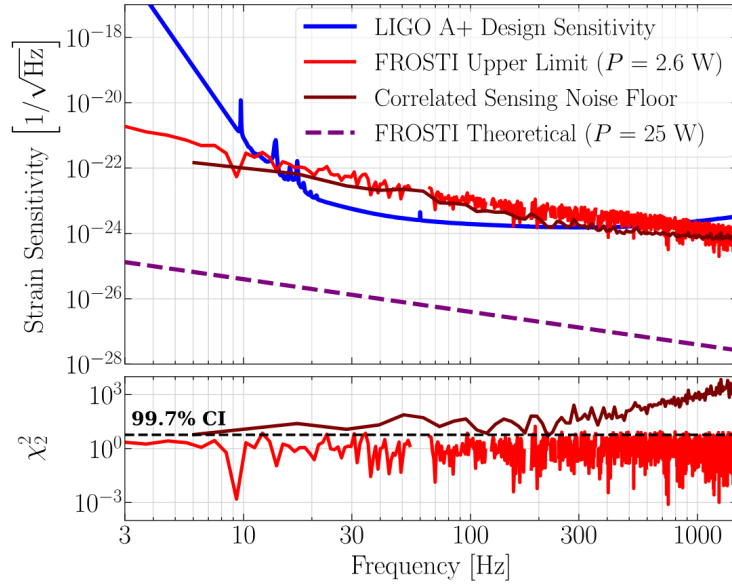


Figure 7: Measurement of relative intensity noise (RIN) of FROSTI prototype project into strain sensitivity. In blue, the LIGO A+ sensitivity target. In red, the experimental upper limit measured. In dashed purple, the theoretical noise limit of FROSTI. Finally, in maroon is the correlated sensing noise floor. Bottom figure is the reduced chi-squared statistic for the cross-spectra based measurements.[13]

3.1 Measurement of photon bunching

The cardinal objective of this project is to probe the measurement of Hanbury Brown and Twiss (HBT) correlations from photons in FROSTI's radiation [4]. This measurement would set upper limits on the Relative Intensity Noise floor of FROSTI. The cross correlations described in this experiment come from temporal correlation of photons (which obey Bose-Einstein statistics) using an HBT apparatus.

An HBT apparatus is built such that photon bunching noise can be transformed to a signal [18]. A schematic of the optical setup can be seen in Fig. 8. Radiation from the FROSTI radiation is focused using a lens, and sent to the beam splitter. A 50/50 beam splitter directs half of the light to each respective identical photodetector.

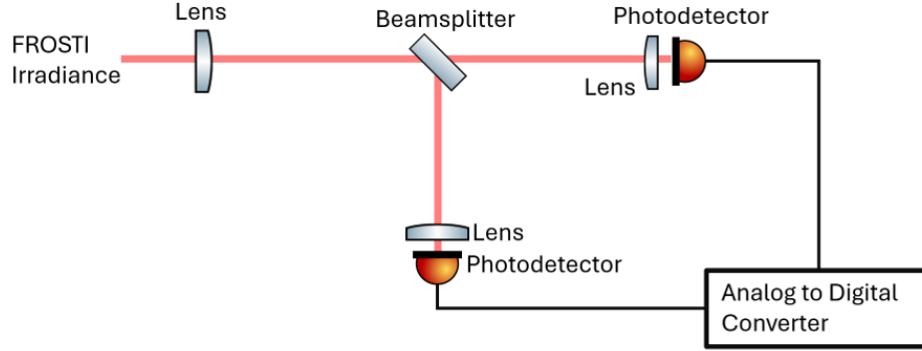


Figure 8: Apparatus designed used to measure photon bunching described by the Hanbury-Brown-Twiss effect.

The principal measurement of a photon "bunch" is as follows. As FROSTI uses a graybody source, photon emission is governed by the Bose-Einstein distribution [8]. This allows n photons to be excited for a given mode at a given frequency with a certain probability. A photon "bunch" contains $n > 1$ or significantly more incident photons on the beamsplitter [18]. When this bunching occurs, it is likely that some photons within the bunch are split to two different paths by the beam splitter. As this happens, the photodetectors along the two paths will read a *coincident* spike. Finally, an analog-to-digital converter (ADC) digitizes the data for further analysis.

The amplitude of the Cross Spectral Density (CSD) of the two time-domain data streams will suppress uncorrelated noise and reveal correlated thermal fluctuation in FROSTI's greybody radiation. [9]. If found, this measurement would demonstrate FROSTI's ability to operate below LIGO's displacement noise requirements.

3.2 Cross Spectral Density

The analysis starts with two time series, $x_1(t)$ and $x_2(t)$ which contain an uncorrelated shot noise term and a correlated photon bunching term,

$$\hat{x}_1 = \hat{x}_{shot_1} + \hat{x}_{bunching} \quad \hat{x}_2 = \hat{x}_{shot_2} + \hat{x}_{bunching} \quad (1)$$

The Power Spectral Density (PSD) would contain both the shot noise and the bunching term,

$$PSD[\hat{x}_1] = \mathcal{F}(\hat{x}_1)\mathcal{F}^*(\hat{x}_1) = |\mathcal{F}(\hat{x}_{shot1})|^2 + |\mathcal{F}(\hat{x}_{bunching})|^2 \quad (2)$$

However, the Cross Spectral Density (CSD) will average down to just the photon bunching signal. Per the definition of the CSD,

$$\begin{aligned} CSD[\hat{x}_1, \hat{x}_2] &= \mathcal{F}(\hat{x}_1)\mathcal{F}^*(\hat{x}_2) \\ &= \mathcal{F}(\hat{x}_{shot1})\mathcal{F}^*(\hat{x}_{shot2}) \\ &\quad + \mathcal{F}(\hat{x}_{shot1})\mathcal{F}^*(\hat{x}_{bunching}) \\ &\quad + \mathcal{F}(\hat{x}_{bunching})\mathcal{F}^*(\hat{x}_{shot2}) \\ &\quad + \mathcal{F}(\hat{x}_{bunching})\mathcal{F}^*(\hat{x}_{bunching}) \end{aligned}$$

The shot noise is uncorrelated between detectors, so the first term in the summation may be disregarded. Shot noise and bunching are independent processes, so their covariance is also zero. This only leaves the covarying bunching term left.

$$CSD[\hat{x}_1, \hat{x}_2] = \mathcal{F}(\hat{x}_{bunching})\mathcal{F}^*(\hat{x}_{bunching}) = |\mathcal{F}(\hat{x}_{bunching})|^2 \quad (3)$$

Given enough time, the CSD will average down to simply the photon bunching signal. This reveals the power of this technique, using the CSD a measurement can probe below the quantum shot noise limit.

3.3 HBT Configuration

3.3.1 Imaging system model

The HBT setup will see higher power if the FROSTI aperture is imaged onto the photodetector. This means it is necessary to perform some theoretical calculations before purchasing parts for the experimental setup. These calculations will narrow down the options available commercially from Thorlabs and Edmund Optics. As the beamsplitter does not influence the imaging, a simplified view of one arm is used. A simple cascaded imaging system of equations is applied.

$$\frac{1}{z'_1} = \frac{1}{z_1} + \frac{1}{f_1} \quad (4)$$

$$\frac{1}{z'_2} = \frac{1}{z_2} + \frac{1}{f_2} \quad (5)$$

$$m = m_1 m_2 = \frac{z'_1 z'_2}{z_1 z_2} \quad (6)$$

$$t = z'_1 - z_2 \quad (7)$$

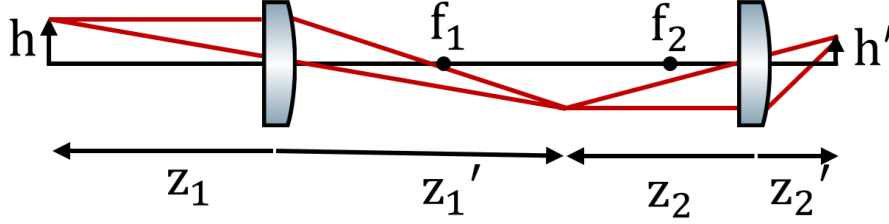


Figure 9: Diagram of the imaging system

3.3.2 System constraints

This means the system magnification is constrained by the FROSTI aperture size (object height) and the photodetector area (image height). To get the aperture size, the FROSTI opening was measured both in lab and using the CAD model. A Thorlabs PDAVJ5 photodetector is available in the lab, which has an effective detector area of 1 mm^2 and wavelength range of $3 - 5 \mu\text{m}$. The system magnification must then be $m = -\frac{1}{22}$.

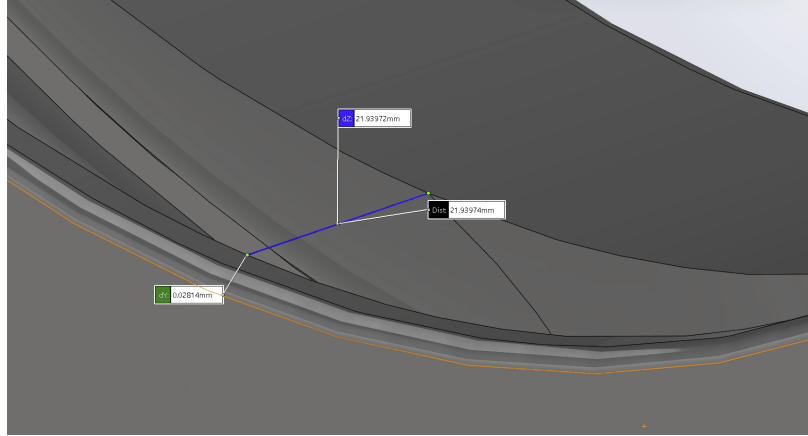


Figure 10: FROSTI aperture opening in Solidworks.

Other constraints are the distances at the extremes of the HBT setup. First, the lens which captures the radiation from FROSTI must be 3-5 mm from the aperture opening. Second, the lens which focuses the light onto the PD must be $< 1''$. Finally, the beamsplitter will be positioned at the focus of the first lens as to direct all of the light without cropping the aperture. This means the focal length of L1 must be less than the separation distance between the two lenses.

If possible, this experiment should be mounted onto a single, small, breadboard which can fit into the laboratory cabinet. In this way, when FROSTI needs more RIN measurements, the system designed in this report can be quickly mounted in front of the FROSTI and perform the measurement. Additionally, the setup can be used for future upgrades to FROSTI. The design of this HBT apparatus should be small, modular, and quickly reusable. For this reason, the system thickness, t , is a major design parameter and should be less than $35''$ (dimension of cabinet).

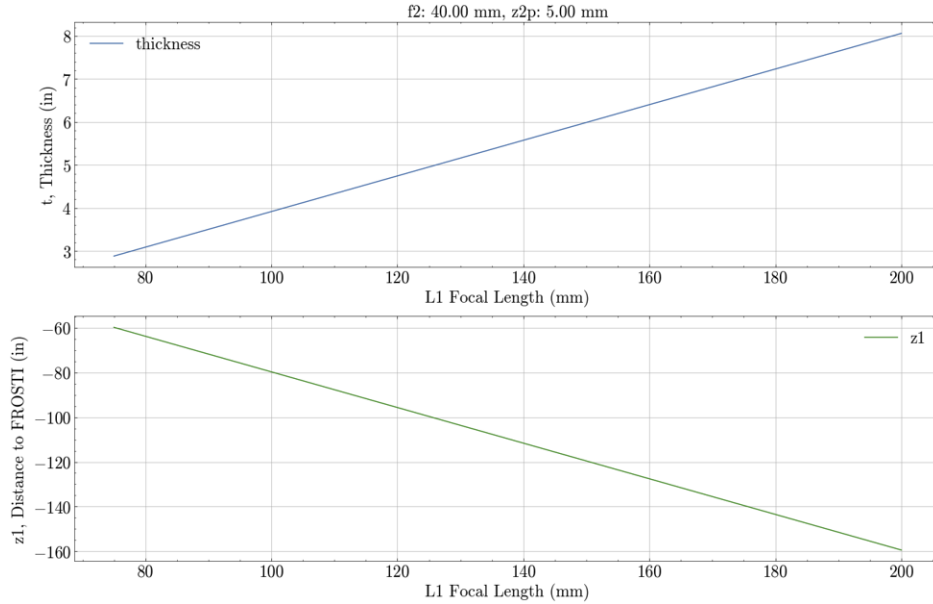
z_1	z_1'	z_2	z_2'	t	f_1	f_2
-5 mm	Free	Free	<1"	< 35"	Free	Free

Table 1: Fixed and free variables in the system

- Fits inside the laboratory cabinet, $t < 35''$
- Beam splitter is placed at the focus of L1, $f_1 < t$
- Lens 1 placed 3-5 mm from FROSTI opening, $z_1 = [-5, -3]$ mm
- Lens 2 placed < 1" in front of the photodetector, $z_2' < 1''$

3.3.3 Focal lengths and thickness

After reading the catalogs from Thorlabs and Edmund Optics, an initial list of parts were compiled. The available focal lengths were between 40 and 500 mm. We want to use a fast lens near the photodetector, so f_2 was set to be 40mm. f_1 was considered a free variable, and computed for the range of 40 to 500 mm. These were passed to Eq. 4-7, where t - f_1 and z_1 - f_1 plots were generated.

**Figure 11:** t - f_1 and z_1 - f_1 plots for $f_2=40$ mm.

At $f_1 = 40$ mm, the system thickness is between 3 and 8", which is compatible with system requirements. Unfortunately, the z_1 distance must be at a minimum 60". This is unreasonably far from the FROSTI radiation source.

Many other configurations were computed and all reached the same conclusion. *There is no imaging system which uses $f_2 = 40$ mm that can fit within the laboratory cabinet.* With this

undesirable result, we chose to hold off on purchasing the first lens. Instead, A single 40 mm lens will be placed before each PD. The HBT apparatus will be initially built with no lens to capture the FROSTI radiation, instead the beam splitter will be placed 5 mm from the opening and direct radiation to the lenses before the PDs. We can treat the light rays as quasi-collimated as they exit FROSTI, we may be able to focus enough power onto the PDs using only one plano-convex lens. After measuring the power captured this way, we may upgrade later by purchasing a lens to place at the FROSTI.

One 40 mm plano convex lens will be placed in front of the photodetectors. After measuring the power, another lens may be purchased to place in front of the FROSTI.

3.3.4 Substrate type and coating

The Thorlabs PDAVJ5 photodetector used for this project is optimized for the $3 - 5\mu\text{m}$ range. Any optics used should also be optimized for these wavelengths as well. Therefore, calcium fluoride, CaF_2 substrate was selected for its high transitivity between 1 and 8 microns. Zinc Selenide optics are the traditional choice for Mid-IR experiments, but CaF_2 actually provides more transmission at the 3-5 micron range we are working in. Also, CaF_2 beamsplitters have more equal reflection and transmission spectrums, so we can get equal 50/50 power in both arms.

Finally, the lenses should have an anti-reflection coating for $3 - 5\mu\text{m}$ to remove unwanted reflections from propagating in the system.

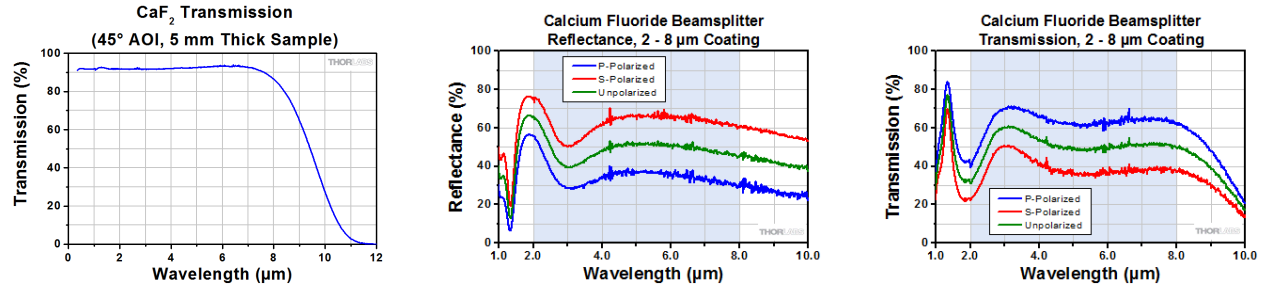


Figure 12: Properties of Thorlabs BSW510 CaF_2 beam splitter. Left: Overall substrate transmission, Center: Coating reflectance, Right: Coating transmission [15]

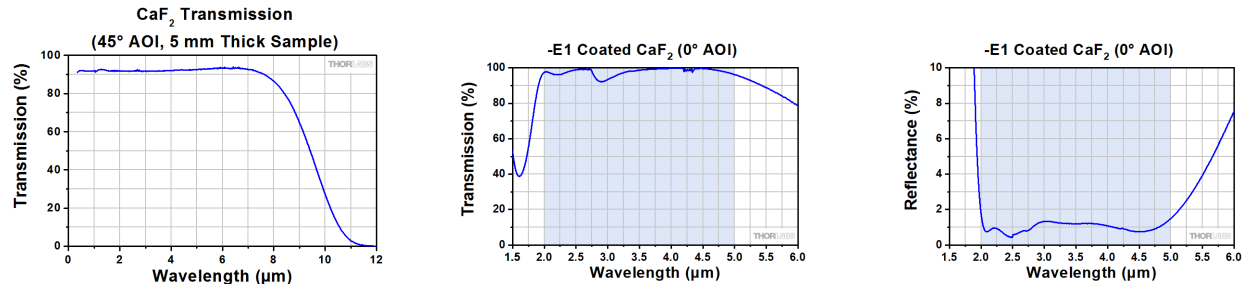


Figure 13: Properties of Thorlabs LA5370-E1 CaF_2 plano-convex lens. Anti-reflection coating on the shaded region. Left: Transmission, Right: Reflectance. [16]

The beamsplitter and lenses will both use a CaF_2 substrate. The beamsplitter will be coated for $2 - 8\mu\text{m}$ and the lenses will be coated from $2 - 5\mu\text{m}$.

3.3.5 Ordered parts

From the discussion above, final selections on the parts list were made and purchased from Thorlabs. With these parts in hand, assembly of the apparatus can begin and measurements will follow. The next report should highlight power measurements of the system and any upgrades to the focusing lenses if they come.

Manufacturer	Name	ID	Cost	Quantity
Thorlabs	Ø1" CaF_2 Plate Beamsplitter	BSW510	\$363.52	1
Thorlabs	Ø1" CaF_2 Plano-Convex Lens	LA5370-E1	\$227.52	2
Thorlabs	Aluminum Breadboard 8"x8"x1/2"	MB8	\$91.59	1

Table 2: Parts ordered to built HBT setup

A Solidworks model is under development for future reference. It will include all of the optics discussed above, along with their mounts and precise placements. As stated above, the immediate next step is to measure the power received on the photodiodes using a single-lens system.

4 Experiment Design & Assembly

This optical testbed is intended to characterize prototypes of FROSTI constructed for both A+ and A# LIGO upgrades. After this testbed is used on the A+ prototype, it will be stored until another iteration of FROSTI is built. When a new version of FROSTI is ready, this optical testbed will be reused in the same configuration. For this reason, it is desirable that this measurement tool is both compact and easily reusable. This also means that the testbed will be stored and reused several times and a smaller footprint would be convenient to this end.

Another design consideration arises from the measurement technique itself. The relative intensity noise measurement benefits from maximizing the power delivered to the photodiodes. With increased power on the photodetectors, a smaller gain can be used while maintaining a reasonable SNR. This lowers the electronic noise, allowing the cross-spectral density to average down to any correlated noise in a shorter integration time. For this reason, another constraint is placed on the experiment design. The experiment is designed to capture as much radiation as possible. Therefore, the beamsplitter at the edge of the breadboard should be as close as possible to FROSTI's aperture opening. Additionally, more power can be acquired by placing the focusing lenses as close to the beamsplitter as possible, to minimize any losses originating from beam divergence after splitting into two arms.

These considerations culminate in three primary design considerations:

- R.01: The breadboard area must be smaller than the laboratory cabinet dimensions, 12" W X 35" L.

- R.02: The optics should sit comfortably inside the breadboard, leaving roughly 1 inch of clearance.
- R.03: The beamsplitter should be placed as close as possible to FROSTI's aperture opening.

CAD models were developed in order to iterate on the placement of optics onto the breadboard. After the first iteration, it was found that the corner of the breadboard was limiting the distance at which the beamsplitter could be placed relative to the aperture. To mitigate this, a 1.5"x1.5" corner was cut off of the breadboard. The traditional post holders were changed to a railsetup. Each optic was mounted to the post which runs parallel to the breadboard using a right angle mount. This telescoping mount mechanism allowed the beamsplitter to extend slightly off the breadboard and into the FROSTI aperture. With this refined experiment design, the beamsplitter is able to the maximum radiation <10 mm from the aperture opening.

The experiment was mounted to FROSTI's horizontal axis, directly in front of the 8th heating element. It is secured to the table using "feet" consisting of a 4" optical post holder, and two 3" optical posts connected to another 2" optical post. Note: another mounting leg was added later, with additional weights on the top platform for stability as well (See 5.1).

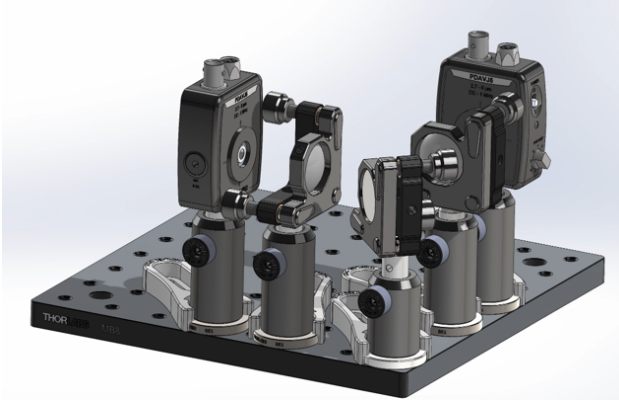


Figure 14: First iteration of CAD model

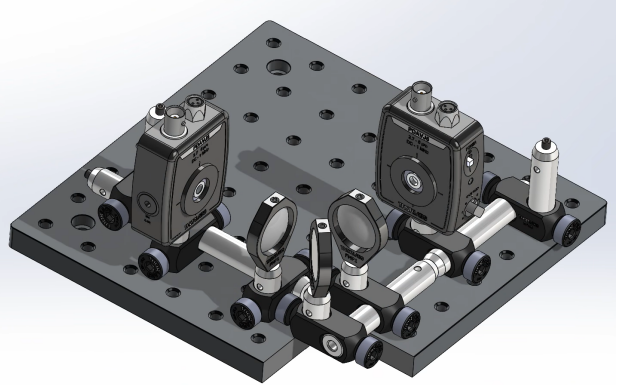


Figure 15: Notched design intended to extend beam splitter into FROSTI's aperture

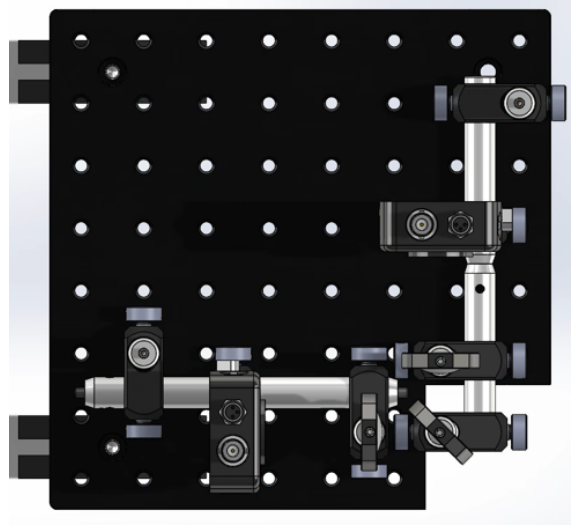
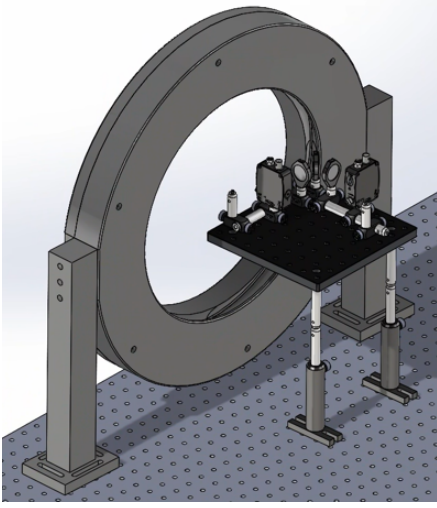


Figure 16: HBT apparatus and FROSTI **Figure 17:** Top down view of breadboard, highlighting the telescoping mount

4.1 Assembly & Alignment

An image of the assembled Hanbury-Brown-Twiss apparatus can be seen in Figure 18. The FROSTI was transferred to an ISO Class 5 clean room and secured to the optical table. The Hanbury-Brown-Twiss apparatus sits at the aperture opening at the height of the horizontal axis. FROSTI's radiation is not emitted perpendicular to the annular ring, rather at some deviation angle. For this reason, the whole breadboard was mounted to meet this angle and capture more radiation. The beamsplitter and lenses are aligned to achieve equal power on both arms. Relative alignment of $\pm 10 \text{ mV}$ was obtained.

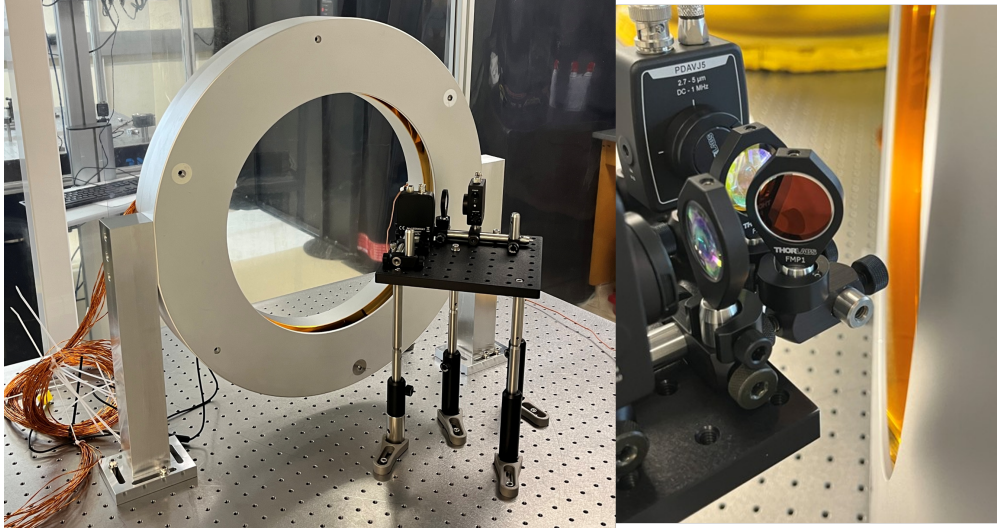


Figure 18: Assembled Hanbury-Brown-Twiss apparatus mounted at the FROSTI aperture (gold reflective ellipsoid). Mounted at the opening of the eighth heating element on the horizontal axis.

5 Results

5.1 Electrical noise

The first identified source of noise originates from the coupling of 60hz harmonics through the sensing electronics. These originate in the ADC and photodetectors and cannot be removed or filtered out. Shown in dark blue (Figure 19), measurements of the electrical dark noise (FROSTI OFF), show these harmonics persist. Using a 2-DOF χ^2 statistic, $\chi^2 = \frac{S_{12}^2}{S_1 S_2 / N}$, significant peaks in the dark noise were identified. Since these are entirely unrelated to FROSTI's radiation, frequency bands which these peaks exist are rejected from the data. With a 99.7% confidence threshold, significant peaks that exceeded this threshold in both the FROSTI on data and the dark noise were removed from the 'on' dataset. This electrical noise veto rejection must be done for all data acquired.

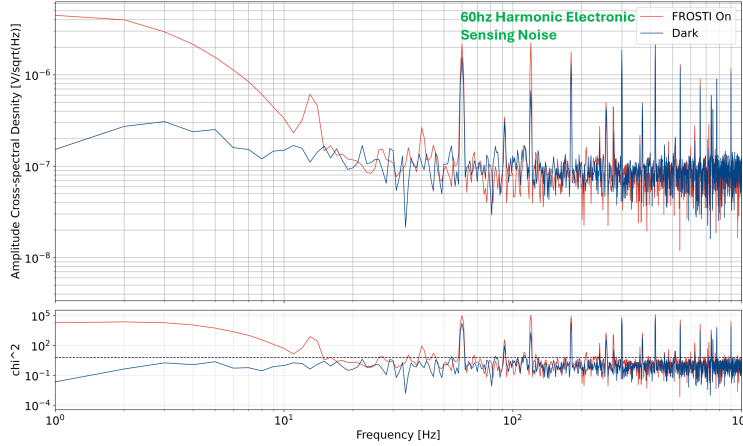


Figure 19: Amplitude Cross Spectral Density with 60hz harmonic electrical noise

5.2 Mechanical Noise

With the spectrum significantly cleaned up after to electrical noise veto rejection, a few individual features are still present. These are noise sources which originate elsewhere that are not related to acquisition. One such noise source, mechanical resonance, appears at 40 Hz. A singular peak which spans a few frequency bins in the spectrum is statistically significant (exceeds χ^2 threshold), and was not found in the dark noise measurement. This noise was identified as mechanical vibrations from the table coupling into the measurement structure through the mounting structure. Additional weights were placed on the platform to change the effective moment of inertia of the platform. By increasing its inertia, the 40 Hz peak reduced in amplitude. A damped peak indicates that is not a technical noise which originates from FROSTI, rather it is mechanical noise coupling from the support platform into the data acquisition.

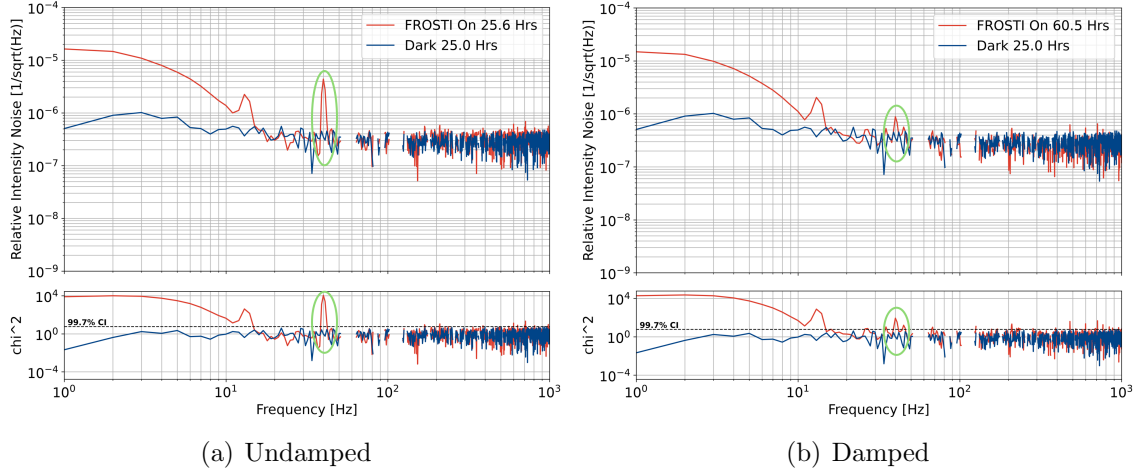


Figure 20: 40 Hz mechanical noise via damping with a change in the platform's inertia

5.3 Measurement of Relative Intensity Noise

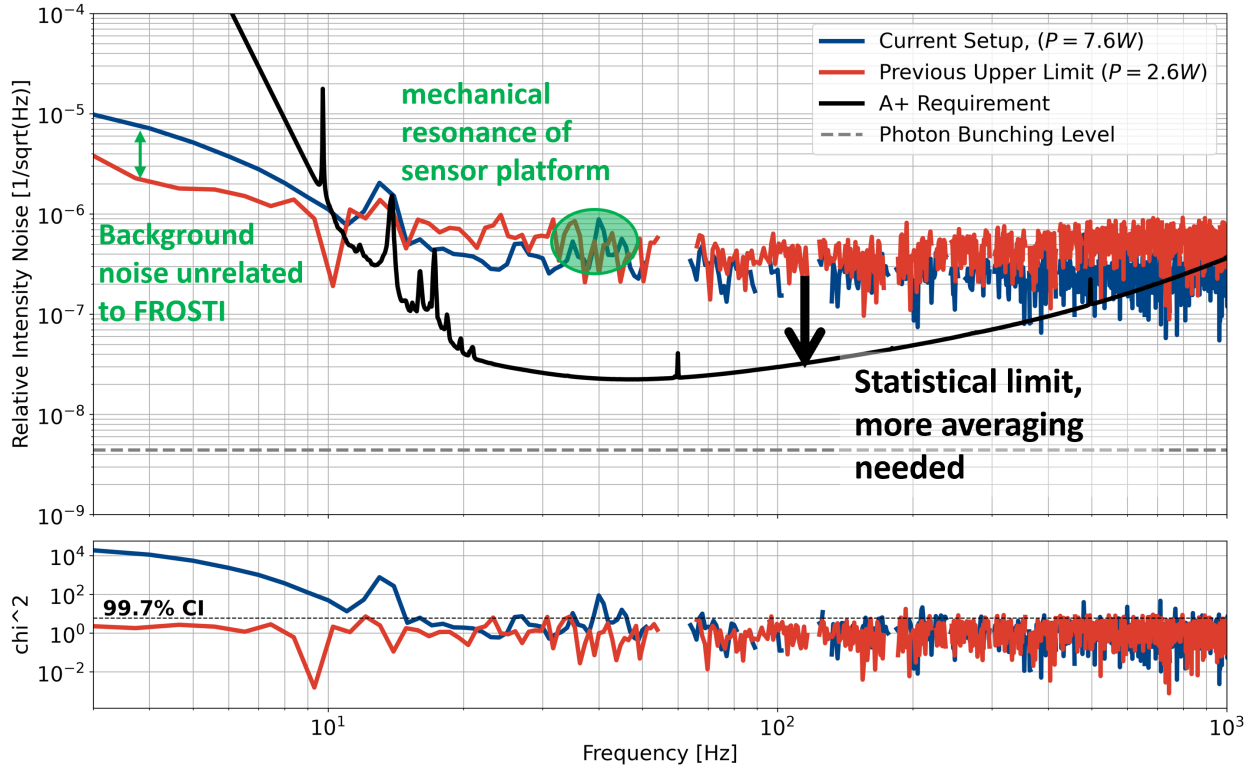


Figure 21: New upper limit placed on the Relative Intensity Noise using the Hanbury-Brown-Twiss apparatus (60 hours)

A new upper limit was placed on FROSTI's Relative Intensity noise in Figure 21. 60 hours of FROSTI on data was integrated and measured using this new setup. The gaps in the spectrum are due to the electrical sensing noise veto. Some mechanical sensing noise can be seen at 40 Hz, which can be reduced by a number of structural upgrades. There is also a higher level of RIN below 10 Hz. Although the source of this is yet to be identified, a previous

upper limit did not contain this feature. Thus, this can be concluded that it is not a noise originating in FROSTI. Work is ongoing to identify and remove this noise coupling. Current hypotheses are investigating backscattering, additional mechanical noise, or ambient light. Regardless, this noise feature is already below LIGO A+ requirements, thereby not limiting the instruments ability to prove that FROSTI meets LIGO's RIN budget.

This new measurement meets or improves on the previous upper limit in the frequency band above 10 Hz. This measurement is statistically limited as the Cross Spectral Density needs significant averaging time to converge on the photon bunching limit. The RMS fluctuations in the arrival rate of thermally emitted photons are larger than shot noise by Eq. 8. For FROSTI, at $T = 491\text{ K}$ and $\lambda = 5.9\mu\text{m}$, this corresponds to 0.69% larger fluctuations in addition to the shot noise [13]. Note that FROSTI's radiation actually contains a broad wavelength band from 3-14 μm , this calculation is meant to provide a prediction of the magnitude of thermal photon bunching. Measuring down to these small fluctuations would prove that FROSTI can operate near its theoretical noise minimum.

$$\frac{\sigma_{thermal}}{\sigma_{shot}} = \sqrt{\frac{e^{h\nu/k_B T}}{e^{h\nu/k_B T} - 1}} \quad (8)$$

$$RIN_{shot} = \sqrt{2h\nu/\bar{P}} \quad (9)$$

$$RIN_{bunching} = RIN_{shot} \sqrt{\frac{e^{h\nu/k_B T}}{e^{h\nu/k_B T} - 1}} \quad (10)$$

A theoretical prediction of the photon bunching level can be computed using Eq. 10. With Eq. 8 computed for $\lambda = 5.9\mu\text{m}$, $T = 491\text{ K}$, and $\bar{P} = 24\mu\text{W}$, the predicted magnitude of thermal photon bunching is $RIN_{bunching} = 4.4 * 10^{-9} 1/\sqrt{\text{Hz}}$ (dashed gray in Figure 21).

6 Next Steps

This new upper limit on the Relative Intensity Noise is just the beginning of a measurement campaign to prove there are no technical noise sources present in FROSTI. More averaging is necessary to allow the CSD more integration time to converge below the A+ requirement. This measurement can also be improved by obtaining more power. The FROSTI operated with an input voltage of 111 V and measured temperature of 491 K. This can be safely increased to deliver more power to the photodiodes. It is also possible to improve the electrical sensing noise. More power will allow the photodetectors to operate at a lower gain factor, which reduces their noise. Although the electrical noise is uncorrelated, and should theoretically be removed from averaging, the variance is quite high. This high initial variance causes the CSD to begin at a much larger value and needs a practically unrealistic integration time to average down to the photon bunching limit. Finally, upgrading the photodetectors would allow a broader wavelength band to be captured. The current photodetectors detect $2.7\ \mu\text{m}$ to $5.0\ \mu\text{m}$, which is outside of FROSTI's peak wavelength in air at approximately $8\ \mu\text{m}$.

7 Conclusion

In this project, a new optical testbed to measure photon bunching within FROSTI's radiation was designed, built, and commissioned. A new upper limit on Relative Intensity Noise (RIN) was placed that meets or improves upon the previous measurement. This study marks the beginning of a measurement campaign to prove that FROSTI can meet LIGO's strict RIN requirements.

Development of future FROSTI prototypes are already underway. Upgrades to LIGO will require integration of newer adaptive optics to meet their design sensitivity. A larger version, designed to correct the 100 kg test masses in A# is currently being designed. This optical testbed was designed to be compact, reusable, and stored easily, such that it will be used to characterize future FROSTI prototypes built for A#. Measurements of small fluctuations in the operating power of FROSTI pave the way for improving the sensitivity of LIGO and further gravitational wave science.

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