LIGO SURF Progress Report 1
Homodyne Detector Characterization

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The project of characterizing homodyne detectors is an effort to investigate a potential improvement or replacement to the LIGO interferometer's signal readout method. The current LIGO setup makes use of a homodyne detection scheme involving DC readout (DCR). In DCR, a length offset is maintained between the interferometer's X and Y arms, leading to a static local oscillator (LO) field at the anti-symmetric (AS) port. A photodiode is placed at the AS port to monitor the power of the signal. As shown by Evans [1],

$$P_{AS} = \bar{P}_{AS} + 2\mathcal{R}e(\bar{A}_{DC}(A_{GW} + \varepsilon\bar{A}_{DC})^*) \tag{1}$$

where P_{AS} is the power at the dark port, A_{DC} is the LO field, A_{GW} is the field caused by the gravitational wave, ε is any noise present on the LO, and $\bar{P}_{AS} = \bar{A}_{DC}^2$. As can be seen in this equation, there is no variation in the relative phase between the GW and LO signals. It is fixed because the two signals co-propagate. However, the gravitational wave component of the power, the second term on the right-hand side, is overshadowed by the average power of the LO field, $\bar{P}_{AS}$, and variations in LO noise can look deceptively akin to power variations due to GW.

In balanced homodyne readout (BHR), the LO is picked off from the carrier beam, and later interfered with the AS field on a beam splitter. The two signals coming from the beam splitter are detected with photodiodes and subtracted. The power difference in the photodiodes reveals the GW signal [1].

$$P_A - P_B = 2\mathcal{R}e\left(e^{i\phi}\bar{A}_{PO}A_{GW}^*\right) \tag{2}$$

where $P_A - P_B$ is the difference in power between the two photodiodes, A_{PO} is the picked-off LO field, and ϕ is the phase difference between the GW and LO fields. The appearance of ϕ indicates that, in BHR, the LO phase must be known and controlled in order to detect a GW. However, the ε term has vanished in the subtraction, showing that all signal noise should cancel, in principle. Also, since the two photodiode signals have the same average power, $\bar{P}_{AS}$ is subtracted out, and no longer overshadows the GW signal in the readout.

The current experiment is centered on characterizing the noise involved in a small-scale BHR detector. To reduce the amount of noise entering the BHD, and intensity stabilization servo (ISS) was constructed.

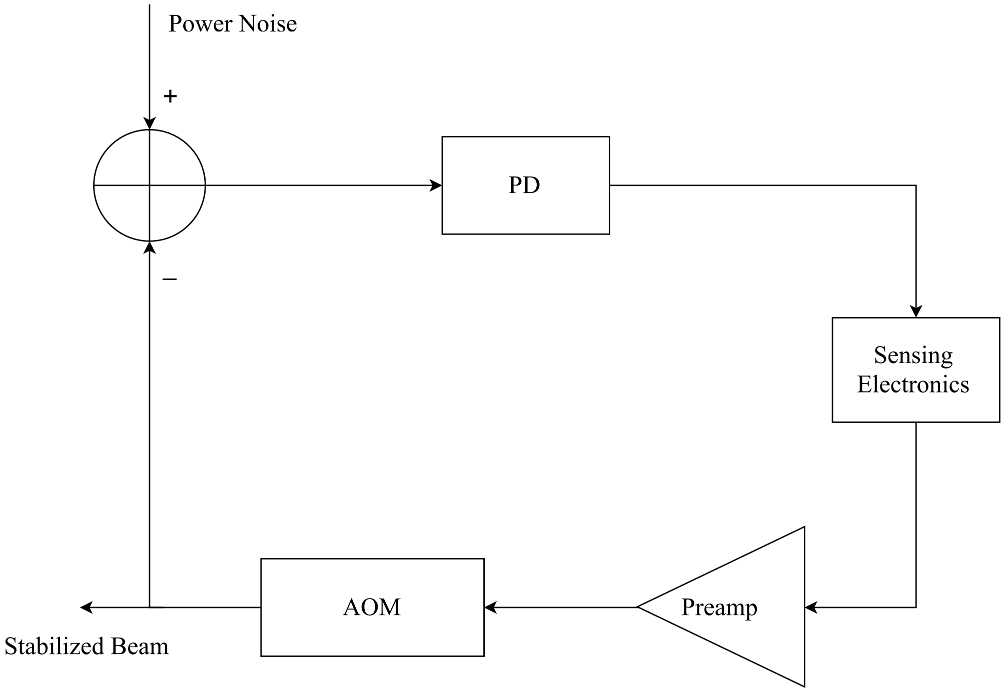

Figure 1 ISS block diagram

In the ISS, the acousto-optic modulator (AOM) diverts an amount of laser power that is proportional to its supplied voltage, and the SR560 preamplifier is set to apply a gain of 500. The sensing electronics are a series of three RC circuit filters that implement a transfer function with a cutoff frequency at 500 Hz, with $^{1}/_{f^3}$ decay. The servo loop photodiode (PD) has a quantum efficiency 55%, which leads to an output current of 0.47 $^{A}/_{W}$. A transimpedance amplifier is implemented at the PD readout that effects a 300 $^{V}/_{A}$ gain, and a capacitor creates a 53 kHz pole. A Bode plot of the total ISS transfer function can be seen in Figure 2.

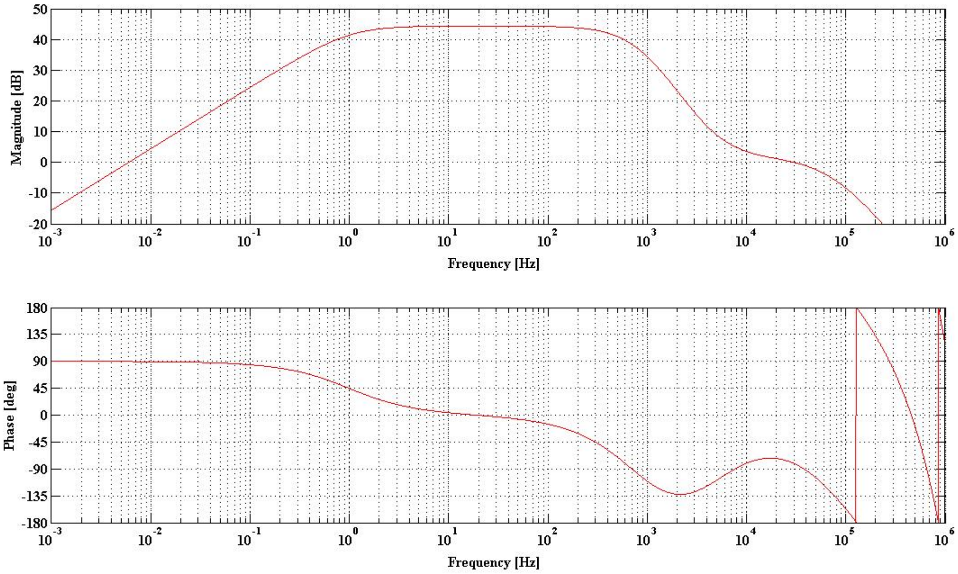

Figure 2 Bode plot of the AOM ISS open loop gain

To model the expected suppression from the ISS, a free-running (no ISS) amplitude spectrum was recorded, and used as an input to the transfer function. Figure 3 shows the input free-running relative power noise (RPN), and the predicted suppression expected from the ISS.

Amplitude spectra were collected for the in-loop photodiode (ILPD) as well as an additional out-of-loop photodiode (OLPD), picked off with a 50/50 beam splitter, with the ISS running. To characterize other noise sources, spectra were collected with the laser off (dark), and with the SR785 spectrum analyzer disconnected from the ISS entirely, displaying the noise of the analyzer itself. Another important noise source is the shot noise associated with the current through the PDs. With the current at 4.5 mA, the shot noise works out to be $8.4 * 10^{-9} \frac{1}{\sqrt{Hz}}$. The spectra of the noise sources of interest can be seen in Figure 4.

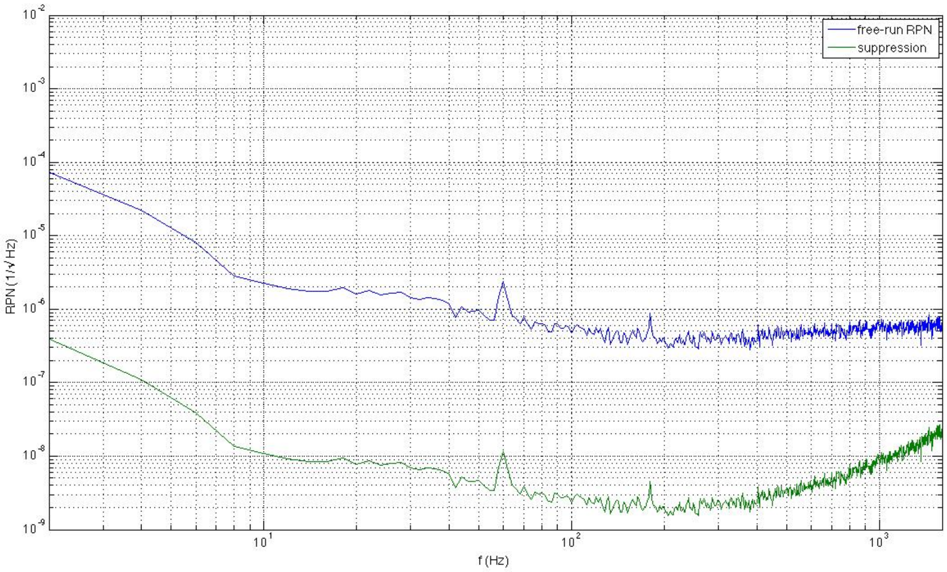

Figure 3 Predicted noise suppression of the ISS

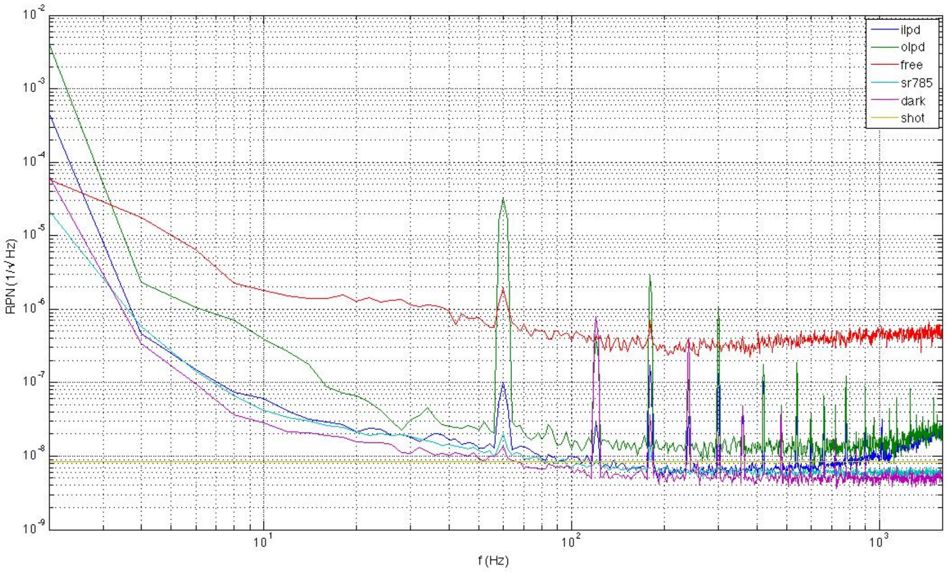

Figure 4 Noise characteristics of the ISS

Power supply harmonics of 60 Hz stand prominently in the noise spectrum. Comparing the free-running noise and the OLPD noise reveals that the ISS greatly suppresses the laser's power noise, although not to the levels predicted in Figure 3. Since there is no way for the shot noise to be suppressed, the OLPD noise cannot possibly descend below the shot noise floor at $8.4 * 10^{-9} \frac{1}{\sqrt{Hz}}$. The fact that the OLPD noise sits a factor of $\sqrt{2}$ higher than the shot noise floor is an artifact of the OLPD accounting for the current through itself as well as the ILPD. This factor of $\sqrt{2}$ indicates that the ISS noise suppression is shot noise limited. As can be seen in Figure 4, the ILPD is artificially suppressed and appears to be below the shot noise floor, which is what gives rise to the need for an OLPD. The dark noise and SR785 noise also descend below the shot noise floor past ~70 Hz and are not measurable with the laser on.

The beam, stabilized by the ISS, enters the BHR arrangement. The setup involves four highly reflective mirrors (HR), a partially transmitting mirror, a piezo-controlled mirror, a non-polarizing 50/50 beam splitter and a photodiode electronics board, on which two photodiodes are wired for current subtraction (Figure 5). The beam from the piezo-controlled mirror will be used as the local oscillator from Evans' equations, and the dashed line will be the signal field [1].

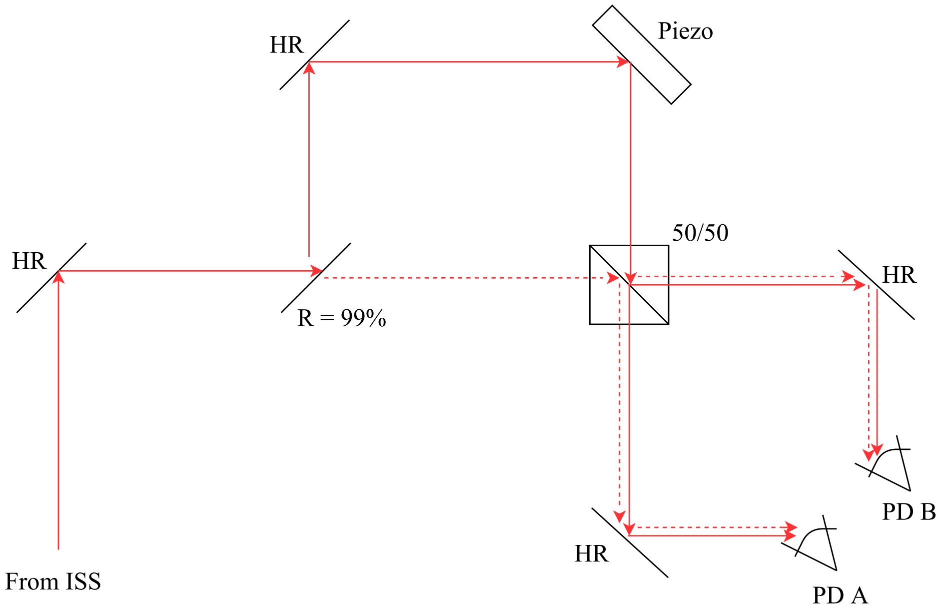

Figure 5 Diagram of BHR readout scheme

Currently, noise analysis has only been performed with signal field blocked by a beam dump, which is akin to the current LIGO DCR scheme. After aligning the two signals to the photodiodes, their output voltages were read and noise spectra were collected. The output voltages were not exactly the same, which yielded a non-zero current subtraction in the BHR circuit. From the voltages read, it was deduced that the shot noise of the BHR current was $1.3 * 10^{-8} \frac{1}{\sqrt{Hz}}$. In principle, all noise but the shot noise should be canceled in the current subtraction. Figure 6 shows the noise spectra of the incoming beam (OLPD), the difference current output (DC) and the shot noise floor.

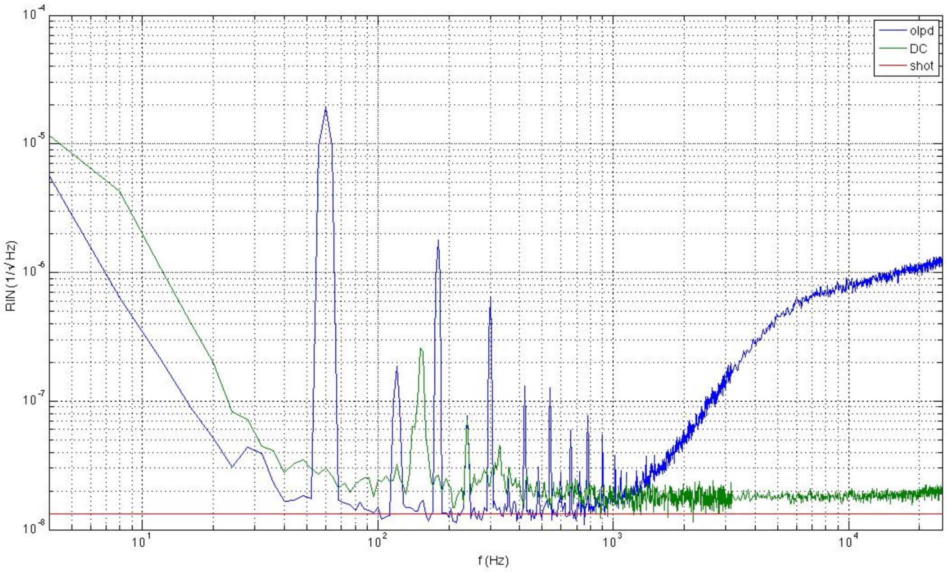

Figure 6 Noise in balanced homodyne readout

Comparing the OLPD noise to the DC noise, it can be seen that the current subtraction in the PD circuit cancels noise quite well. The shelf at the lower frequencies can be attributed to room noise, such as air currents lightly forcing the mirrors, or dust particles drifting through a certain part of the beam. In the higher frequencies, above ~2 kHz, the ISS offers little noise suppression, but there is no noticeable increase in DC noise as this suppression rolls off. This may suggest that the ISS is unnecessary for power stabilization. Also, the large 60 Hz harmonics are greatly cancelled in the DC signal.

Although the BHR circuit seems to be successful in cancelling large amounts of noise, the distribution shown in Figure 6 has some unexpected features. The DC noise is a factor of ~$\sqrt{2}$ higher than the shot noise, and therefore a factor of ~$\sqrt{2}$ higher than expected. Also, there is a prominent noise peak of about $2.5 * 10^{-7} \frac{1}{\sqrt{Hz}}$ at about 150 Hz. Among the current tasks at hand are determining why the DC noise is not level with the shot noise, bringing the DC noise to the shot noise floor, and finding and quieting the source of the 150 Hz spike. Along with reducing the noise in the BHR difference current, future efforts will be directed toward locking the homodyne phase in Eq. 2, and measure the noise couplings.

References

[1] Matthew Evans, Peter Frischel, and Valery Frolov. *Balanced Homodyne Readout for Quantum Limited Gravitational Wave Detectors*. LIGO Laboratory, Massachusetts Institute of Technology, Cambridge. 2013.