LIGO SURF Progress Report 2
Homodyne Detector Characterization

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In order to improve the measurements of the balanced homodyne readout scheme (BHR), recent efforts have focused on the stabilization of the homodyne phase, and isolation of the experimental apparatus. A significant advancement has been the implementation of a piezo-electric mirror as a method of controlling the phase between the local oscillator (LO) and signal paths. In addition, an enclosure was constructed and installed to shield the detector from seismic and acoustic noise.

With the addition of the piezo-controlled mirror into the LO path, it is important to understand how the difference voltage readout responds to phase noise. An expression for the noise variance in the difference current readout of a BHR scheme has been shown by Steinlechner, et al. [**1**]

$$\delta i_-^2 = 4P_{LO}\delta X^2_{-\phi,\sigma} + 4P_\sigma \delta X^2_{\phi,LO}, \tag{1}$$

where δi_- is the noise variance in the difference current, P_{LO} is the power in the local oscillator path, P_σ is the power in the signal path, ϕ is the phase between the two fields due to difference in length between the LO and signal paths, and $X_{\theta,A} = X_{1,A}\cos\theta + X_{2,A}\sin\theta$. It can be seen that noise in the LO field is scaled by the power in the signal field, and vice versa. If the BHR scheme is operated at $\phi = 90°$, then the noise variance in the difference current is dependent on noise in the phase quadrature of the two fields.

$$\delta i_-^2 = -4P_{LO}\delta X^2_{2,\sigma} + 4P_\sigma \delta X^2_{2,LO}. \tag{2}$$

Although the power in the signal field is much smaller than the power in the LO field (2 μW compared to 3 mW), with the injection of phase noise into the LO path by the piezo mirror, the second term in Eq. (2) dominates the noise variance.

$$\delta i_{-} \approx 2\sqrt{P_{\sigma}}\delta X_{2,LO}. \tag{3}$$

In Eq. (3), $\delta X_{2,LO}$ is a small change in phase in the LO path ($\delta\phi$), scaled by the LO field strength.

$$\delta i_{-} \approx 2\sqrt{P_{\sigma}}\sqrt{P_{LO}}\delta\phi\frac{\lambda e\eta}{hc}. \tag{4}$$

This expression includes a necessary conversion factor to achieve units of current, where η is the quantum efficiency of the photodiodes. Finally, an expression can be obtained that shows the phase noise response of the BHR difference voltage readout.

$$\frac{\delta V_{-}}{\delta\phi} \approx \frac{2\lambda e\eta R}{hc}\sqrt{P_{\sigma}P_{LO}}, \tag{5}$$

where R is the amplification resistance of the difference current, in this case 10 $k\Omega$. Figure (1) shows the theoretical phase noise transfer function, with and without an ND filter in the signal path, as well as measured curves.

Note that both of the theoretical curves were calculated for a $\phi = 90°$ homodyne phase. The power in the LO field was 3 mW, and an ND filter was used to attenuate the signal field power from 176 μW to 2 μW. Although there is a discrepancy between the theoretical transfer functions and the measured transfer functions in the phase quadrature ($\phi = 90°$), notice that the offset between theory and measurement goes unchanged after the application of the ND filter. A future goal is to obtain measurements over a larger range of frequencies, but this is, in practice, limited by the difficult task of controlling the homodyne phase while applying phase noise excitation. The slow drift away from the theory curves is possibly due to the homodyne phase drifting during the collection of data.

If instead, $\phi = 0°$ was chosen as the operating point, Eq. (1) reduces to show a noise variance dependent on noise in the amplitude quadrature.

$$\delta i_{-}^{2} = 4P_{LO}\delta X_{1,\sigma}^{2} + 4P_{\sigma}\delta X_{1,LO}^{2}. \tag{6}$$

In principle, the output current while operating in the amplitude quadrature ($\phi = 0°$), is insensitive to phase noise in either field. Rather, Eq.(6) suggests that any noise observed in the output current while exciting phase noise must be attributed to amplitude noise. A measurement of the phase noise transfer function in the amplitude quadrature collected on July 28, 2015, the blue line in Fig. (1), showed the expected result. The magnitude sits roughly four decades below the curve in the phase quadrature, and the coherence is low, indicating that the difference voltage

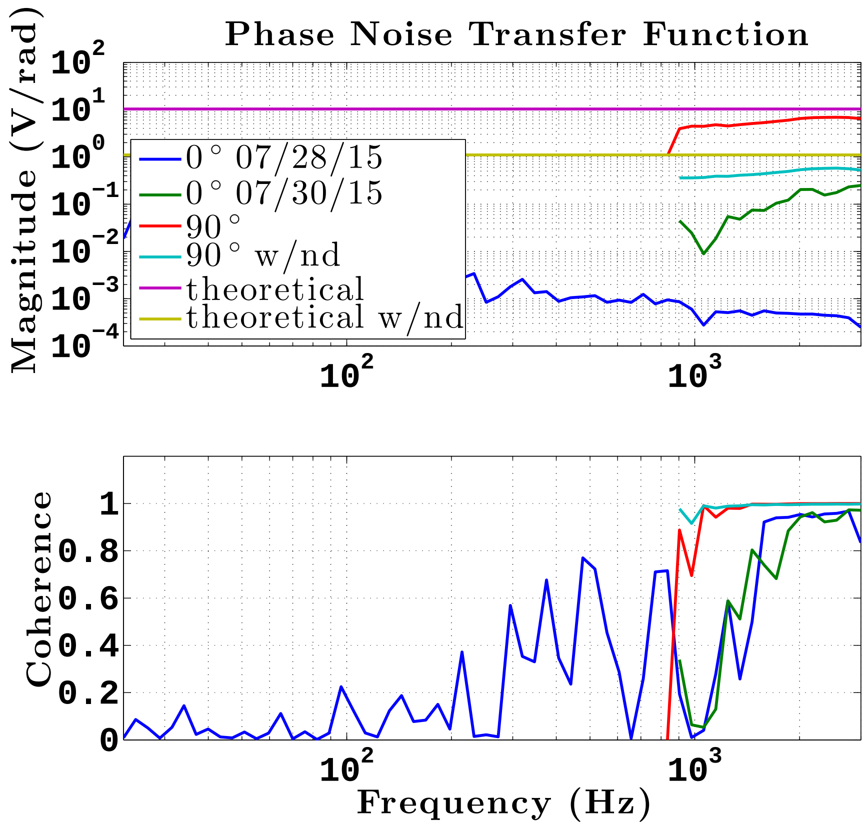

Figure 1: Phase noise transfer function in BHD with coherence.

output is strongly independent of the phase noise input. However, a similar measurement collected two days later shows a response magnitude decades higher. It is possible that there is some undiscovered source of scattering that couples phase noise into the amplitude quadrature during the modulation.

To investigate the influence of power noise in the BHR scheme, we can look at the RIN transfer function associated with the difference current. As derived by Steinlechner, et al.[**1**],

$$i_A \propto \frac{1}{2}(P_{LO} + P_\sigma + 2\sqrt{P_{LO}}\sqrt{P_\sigma}\cos\phi) \tag{7}$$

$$i_B \propto \frac{1}{2}(P_{LO} + P_\sigma - 2\sqrt{P_{LO}}\sqrt{P_\sigma}\cos\phi), \tag{8}$$

or more exactly,

$$i_A = \frac{1}{2}(P_{LO} + P_\sigma + 2\sqrt{P_{LO}}\sqrt{P_\sigma}\cos\phi)\frac{\eta_A e}{h\nu} \tag{9}$$

$$i_B = \frac{1}{2}(P_{LO} + P_\sigma - 2\sqrt{P_{LO}}\sqrt{P_\sigma}\cos\phi)\frac{\eta_B e}{h\nu}. \tag{10}$$

Then the difference current is

$$i_- = i_B - i_A, \tag{11}$$

and

$$RIN_{i_-} = \frac{2i_-}{i_A + i_B}. \tag{12}$$

To predict the ASD associated with the free-running power noise, we can simply multiply the measured noise by the RIN transfer function and convert to $\frac{V}{\sqrt{Hz}}$.

$$ASD = RIN_{free} RIN_{i\_} iR. \tag{13}$$

The unsuppressed power noise and the predicted noise cancellation at $\phi = 90°$ can be seen in Figure (2) as the blue curve and green curve, respectively.

The BHR scheme is very good at cancelling power noise, as evidenced by the fact that the 90° homodyne phase curve sits well beneath the shot noise floor. The frequency noise curve is extrapolated from a noise coupling measurement of $6.8 \times 10^{-6}\ \frac{V}{Hz}$ taken when the NRPO frequency was modulated at 8 kHz, and combined with the laser's noise curve, which is roughly $\frac{10^4}{f}\ \frac{Hz}{\sqrt{Hz}}$. In order to filter electronics noise between the the piezo mirror driver and the analog-to-digital interface with the computer system, a 1 $M\Omega$ resistor was added to the output of the piezo driver. The piezo mirror has a capacitance of 450 nF, which, with the resistor, creates a pole at 0.3 Hz. The noise spectra of the piezo driver and digital-to-analog (D2A) electronics were observed. The driver itself had s flat noise curve of 500 $\frac{nV}{\sqrt{Hz}}$. The digital-to-analog card dominates the electronics noise with a flat curve of 2 $\frac{\mu V}{\sqrt{Hz}}$ after the gain of the piezo driver. The D2A curve was filtered with the 0.3 Hz piezo pole, and passed through the phase noise transfer function from Fig. (1) to yield the magenta curve in Fig. (2). With no laser coming into the BHR scheme, that is, no LO and no signal fields, an ASD similar to the yellow curve was observed.

The black curve in Fig.(2) is the current standing of the noise performance of the BHR scheme. The ultimate goal, of course, is to reach the shot noise floor at all frequencies. This data was collected after the whole detector setup had been elevated by silicon rubber feet, and enclosed in a box made of aluminum and foam, both in an effort to isolate the setup from seismic and acoustic noise. However, the peak around 30 Hz is likely caused by the laboratory air conditioning, so perhaps there is

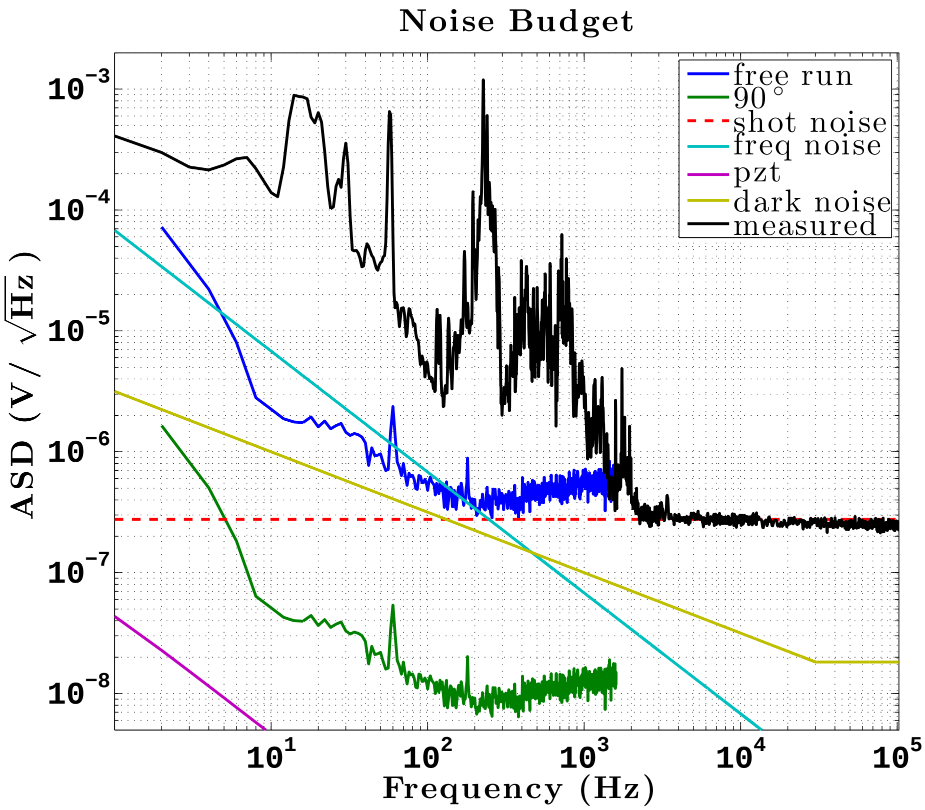

Figure 2: BHR noise budget with ND filter.

more work to be done in isolating the detector. By comparing the blue and black curves, it is evident that other noise sources have been introduced in the BHR setup. A likely culprit is scattering off of some of the optics in use that has, thus far, gone undetected.

Future efforts in improving the performance of the BHR setup will be directed toward moving the noise curve to the shot noise floor at lower frequencies. In order to do this we will have to ensure that any scattering is being dumped, isolate the laser beam if necessary, take a measurement of the amplitude modulation transfer function and understand its nature in theory, and use RF modulation to lock the homodyne phase more securely.

References

[1] S. Steinlechner, B. Barr, A. Bell, S. Danilishin, A. Gläfke, C. Gräf, J. Hennig, E. A. Houston, S. Huttner, S. Leavey, D. Pascucci, B. Sorazu, A. Spencer, K. Strain, J. Wright, S. Hild. *Local-Oscillator Noise Coupling in Balanced Homodyne Readout for Advanced Gravitational Wave Detectors*. SUPA, School of Physics and Astronomy, The University of Glasgow, Glasgow, UK.