Impact of non-stationary events on low frequency homodyne detection

Sheon Chua[1*], Kirk McKenzie[1], Ben C Buchler[2] and David E McClelland[1]

[1] Centre for Gravitational Physics, Australian National University
[2] Quantum Optics Group, Australian National University

E-mail: *sheon.chua@anu.edu.au

Abstract. We present an experimental investigation into non-stationary events that occur in a homodyne detection system. The importance of non-stationary events is that it is a possible mechanism preventing shot-noise-limited homodyne detection at low frequencies, a necessary condition that needs to be *routinely* fulfilled in order to detect squeezed states at these frequencies. These non-stationary events are thought to arise due to airborne dust passing through the laser beam paths. We show that these non-stationary events which occur in our laboratory environment can be minimised by placing the experiment in an airtight enclosure. Isolation against non-stationary events achieved improvement of the colour of the noise spectrum by 3dB at 10Hz towards a flat shot noise spectrum and improvement in the noise distribution of the signal towards a Gaussian distribution.

1. Introduction

Squeezed states of light can be applied to enhance the quantum-noise-limited sensitivity in long baseline interferometric gravitational-wave detectors [1, 2, 3, 4], however, to be applicable to these detectors, squeezing must be routinely producible at Fourier frequencies across the audio gravitational-wave detection band (10 Hz to 10 kHz). Producing such squeezed states has necessitated new techniques of generation [5], control [6] and detection. Construction of a quantum-noise-limited balanced homodyne detection system at these low frequencies has proven to be difficult [7] due to a host of noise sources generally not seen at rf frequencies. Examples of these noise sources included scattered light [8], beam jitter [7], and sources of non-stationary noise. Scattered light was recently determined by Vahlbruch *et. al* [8] to be the low frequency limiting noise source of their homodyne detector. Taking measures to reduce the amount of scattered light allowed shot noise limited detection down to 1Hz.

In this paper we present an experimental characterisation of non-stationary noise in a balanced homodyne detector. The mechanism thought to be driving the non-stationary feature of the photocurrent was airborne dust particles, passing though the laser beam paths in the two homodyne detector arms. This mechanism scatters light out of the laser beams in an uncorrelated manner, causing impulse signals to the difference photocurrent. To demonstrate this noise source, and how it can be minimised, we analyse the photocurrent of the balanced homodyne detector recorded under two different environmental conditions: Firstly, open to the laboratory environment, and secondly, enclosed in a sealed perspex box after waiting for the dust to settle. The results from these two measurements demonstrate that excess noise with

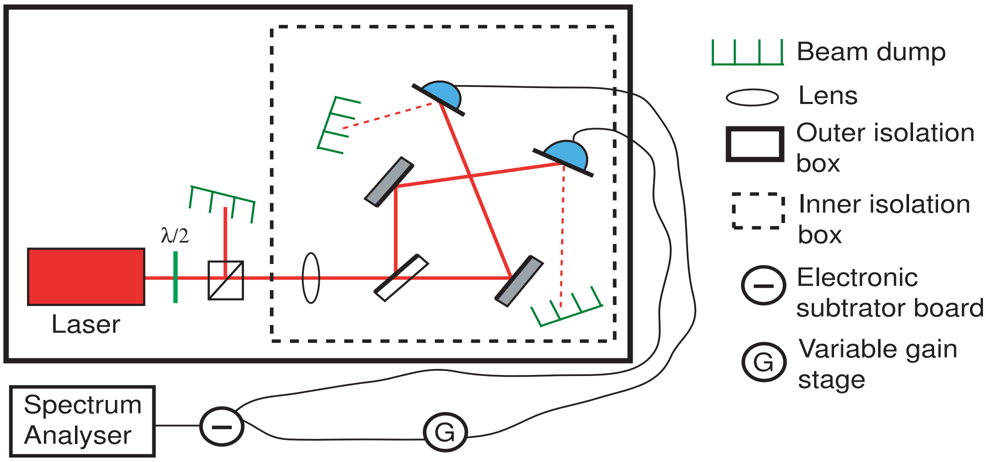

Figure 1. Experimental schematic, showing key optical components and positioning of isolation boxes.

a non-stationary nature is seen when the experiment is open to the laboratory environment, and that this noise is greatly reduced in the enclosed experiment. Even though non-stationary noise is greatly reduced in the closed experiment, excess noise still remains at low frequencies preventing a shot noise limited measurement at frequencies below a few hundred Hertz.

The paper is set out as follows: The experimental setup and procedure are described in section 2 and the results are presented and analysed in section 3.

2. The experiment

A schematic of the experimental setup to characterise this noise is shown figure 1. The 700mW Nd:YAG laser (Lightwave Model 126) operating at 1064nm was attenuated to provide a local oscillator field with power of 400μW. The balanced homodyne detector consisted of a 50:50 beamsplitter and steering mirrors to guide the beams in each homodyne detector arm to the photodetectors, which were built around ETX500 InGaAs photodiodes. The detector was balanced with a variable gain stage before the electronic subtracter board to a level of 65dB common mode rejection. Beam dumps were strategically placed to counter stray reflections, particularly from the photodiodes, and stray light. The entire experiment was enclosed in a sealed black perspex box to reduce air currents and external stray light. A second, smaller black perspex box enclosed just the homodyne detector, to isolate it from scattered light from the beam-dumps upstream.

To investigate if airborne dust was a cause of non-stationary noise two sets of measurements of the homodyne photocurrent were taken and compared. Measurements were taken with the lids of both boxes open so the experiment was exposed to the laboratory environment. These were compared with measurements taken with the boxes closed and then left for two days so the dust particles could settle. For the purposes of the rest of this paper, the 'enclosure' is defined as both isolation boxes. For both sets of measurements the laboratory lights were switched off, thus making the presence of air currents and airborne particles the only changed experimental condition.

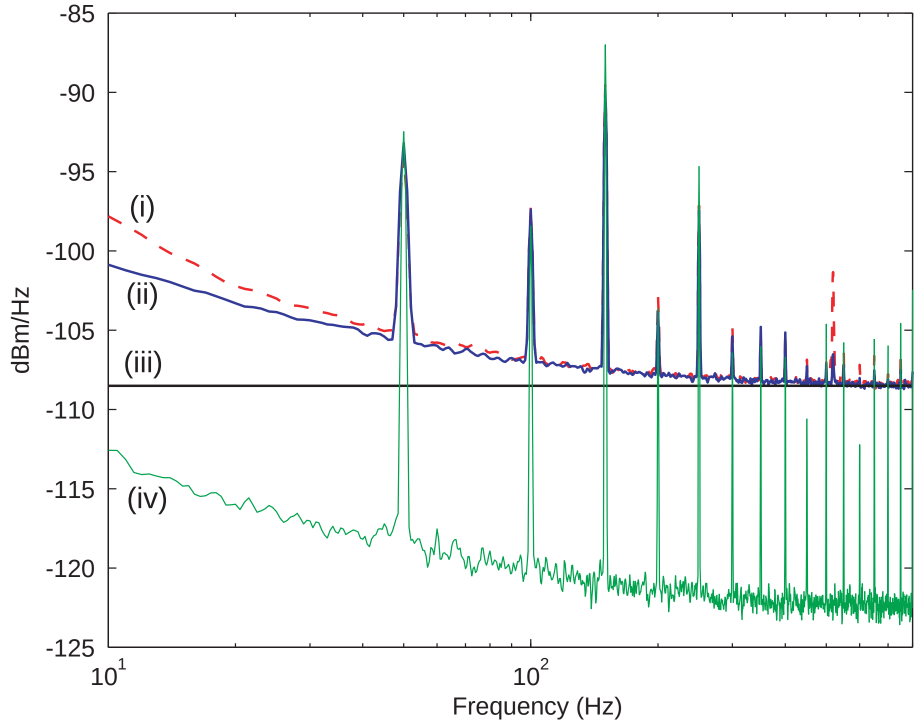

Figure 2. Homodyne detector spectra for (i) enclosure open, (ii) enclosure closed, (iii) calculated shot noise limit, and (iv) electronic noise

3. Results and Analysis

3.1. Noise Colour

In each set of measurements 100 spectra were were recorded on a signal analyzer (Stanford Research System SR785), each with 20 Root-Mean-Square (RMS) averages. Figure 2 shows the spectrum of the measurement with the enclosure open, curve (i), and closed, curve (ii). These curves are the average of the 100 spectra taken in each experimental run.

At low frequencies gradual increase in noise power relative to the calculated shot noise limit (curve (iii)) is present in the spectra from both the open and closed experiments. The spectrum taken with the enclosure open to the laboratory environment show 3dB of excess noise at 10Hz relative to the spectrum taken with the enclosure closed. This excess noise is thought to be due to non-stationary events. The peaks at 50Hz and harmonics are due to pickup from mains electricity and can be seen in the spectrum of the electronic noise of the homodyne detector, curve (iv).

3.2. Noise Distribution

The statistics of the noise power can be used to determine if the signals have a stationary or non-stationary characteristic. We compare the distribution of the noise power of the 100 spectra taken in the two experimental conditions to the predicted distribution for a photocurrent of a shot noise limited beam to determine if the noise was stationary.

The noise characteristics for a shot noise limited signal with appropriately large sample size follow a Gaussian distribution [9]. A spectrum analyser measures the voltage envelope of the input signal. The noise characteristics of the voltage envelope of a shot-noise-limited signal follow a Rayleigh distribution [10].

The affect of the RMS-averaging can be accounted for by utilising known relationships

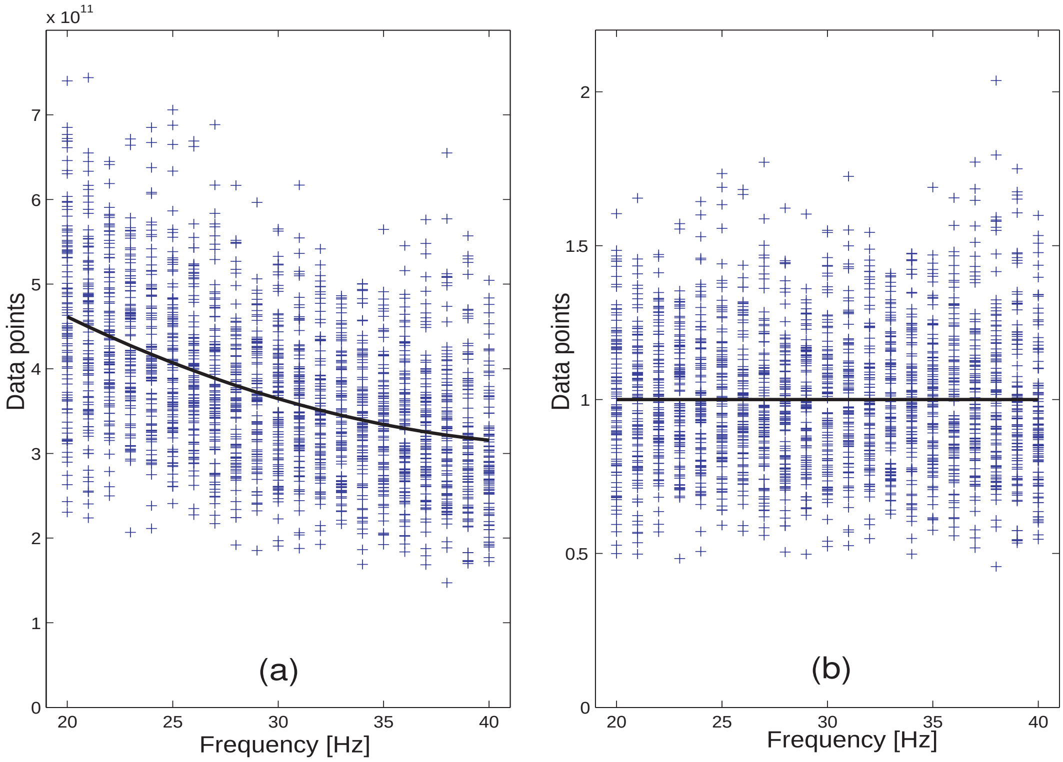

Figure 3. Data whitening process with (a) raw data with polynomial fit to 1Hz-bin averages and (b) data normalised to polynomial fit (data with noise colour removed).

between statistical distributions, namely that a summation of Rayleigh-square distributed variates follow a Gamma distribution [11]. Therefore, an assessment of the Gaussian nature of the noise signal can be made with an assessment of how well the distribution of the measured noise follow a Gamma distribution.

We make comparisons of the distribution of data from the open and closed experiments in two frequency bands: 20-40Hz and 760-790Hz. These particular frequency bands were chosen because the lower frequency window is well within the excess noise region (thought to be due to non-stationary noise), the higher frequency window is well outside the excess noise region, and both bands do not coincide with electrical mains harmonics.

Before plotting histograms of the four data sets the following process was applied to each set of the data to remove the influence of noise colour:

- The average of each 1-Hz frequency bin of the spectra was calculated
- A polynomial fit was applied to the bin averages.
- The data was then normalised to the polynomial fit

The result of the the mean-normalising process is explicitly shown in figure 3. Figure 3 (a) shows the raw data and polynomial fit, and figure 3 (b) shows the whitened data.

After whitening, the data points were collated and plotted in histograms, shown in figure 4 (a)-(d). A Gamma distribution model was fitted to the 760-790Hz data taken in the closed experiment (figure 4 (c)) using the Matlab distribution fitting tool. The 760-790Hz-closed-run data was expected to be an appropriate proxy for a shot-noise-limited signal. This is due to the data band being well outside the excess noise region and within the closed enclosure

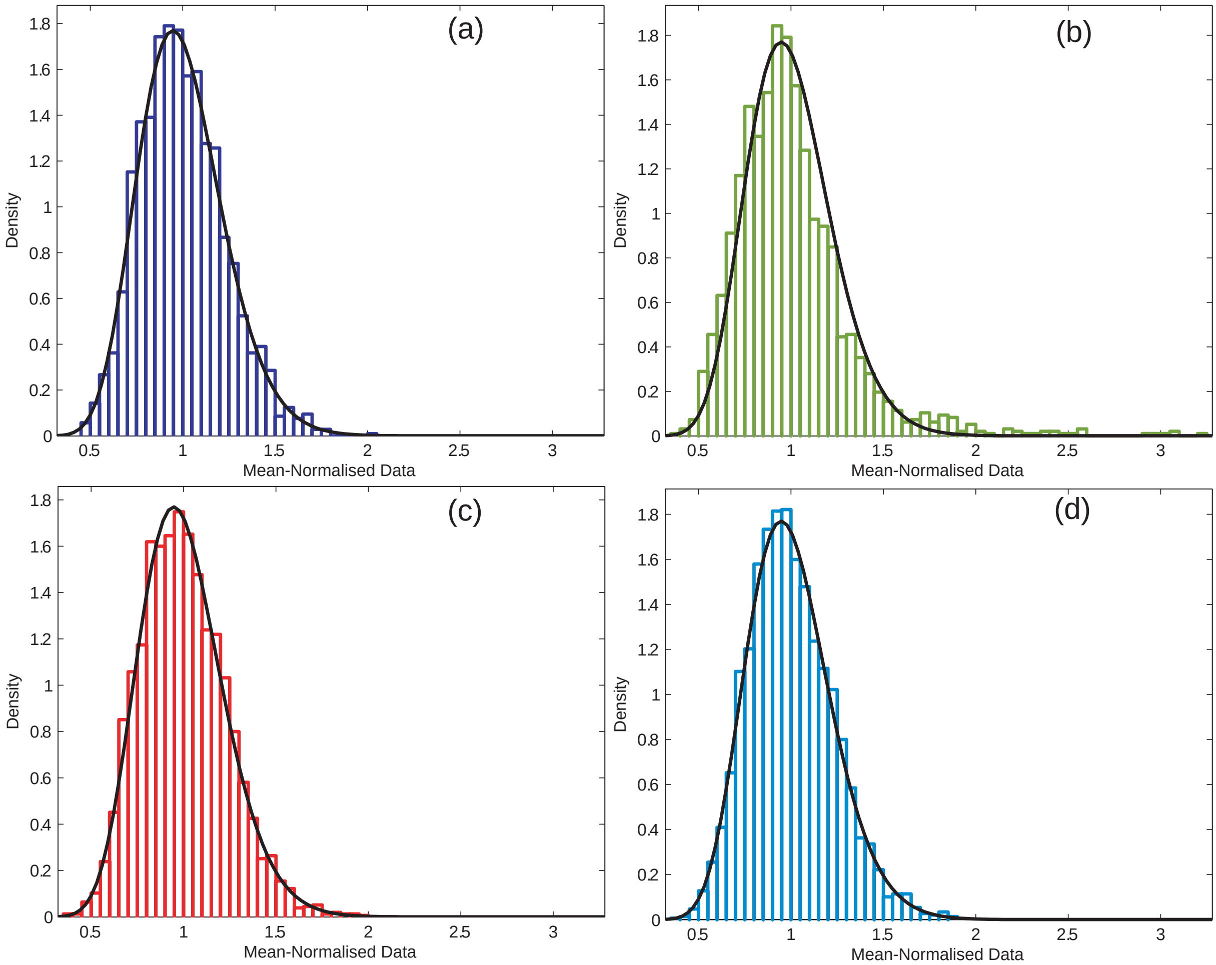

Figure 4. Histograms of mean-normalised data with (a) closed enclosure 20-40Hz, (b) open enclosure 20-40Hz, (c) closed enclosure 760-790Hz and (d) open enclosure 760-790Hz. Gamma model fit paramters as determined by a fit to (c): $\mu = 1.00$, $\sigma = 0.053$, shape parameter $a = 18.8$, scale parameter $b = 0.053$

environment. This Gamma distribution model was plotted in all of the figures to compare the data distributions.

Three key features between the data sets and the Gamma distribution model are highlighted in figure 4. Firstly, there is close agreement between the Gamma distribution model and histograms of both the 20-40Hz closed run data and the 760-790Hz open run data. Secondly, the distribution of the 20-40Hz open run data and the Gamma distribution model significantly differ, with a shift in the bulk of the density to the left and the presence of an excess of points in the upper tail. This excess of points is further exemplified by an analysis of the skewness moments of the histograms and the Gamma distribution model, which are summarised in table 1. The distinctly larger positive value for the skewness of the 20-40Hz open run data indicates the presence of a greater proportion of points in the upper tail (relative to the Gamma distribution model and other data bands).

Table 1. Skewness of data histograms and GD model

Case	Skewness
Gamma Model	0.46 ± 0.01
20 - 40Hz Closed	0.45 ± 0.01
20 - 40Hz Open	0.57 ± 0.01
760 - 790Hz Closed	0.46 ± 0.01
760 - 790Hz Open	0.46 ± 0.01

Thirdly, a comparison between the two sets of data in the 20-40Hz band shows that the presence of the enclosure greatly improved the density towards a Gamma distribution. With an improvement towards a Gamma distribution with a closed enclosure, the noise characteristics of the signal have improved towards a Gaussian distribution, and therefore the impact of non-stationary events on the Gaussian nature of the noise distribution has both been identified and minimised.

4. Conclusion

The observation of squeezed states at low frequencies is reliant on a shot noise limited homodyne system. The presence of an enclosure to counter the impact of non-stationary events thought to be due to airborne dust was effective, with an improvement of both colour of the noise spectrum and the Gaussian nature of the noise having been demonstrated. An expansion of the investigation to include known measures against other possible noise sources (such as beam pointing) is recommended, to further progress towards obtaining a low frequency shot-noise limited homodyne detector.

Acknowledgements

The authors would like to thank Henning Vahlbruch for useful discussions. We acknowledge the financial support from the Australian Research Council.

References

[1] Caves C 1981 *Phys Rev.* D **23** 1693
[2] Kimble H J, Levin Y, Matsko A B, Thorne K S and Vyatchanin S P 2002 *Phys. Rev.* D **65** 022002
[3] Harms J, Chen Y, Chelkowski S, Franzen A, Vahlbruch A Danzmann K and Schnabel R 2003 *Phys. Rev.* D **68** 042001
[4] Buonanno A and Chen Y 2004 *Phys. Rev.* D **69** 102004
[5] McKenzie K, Grosse N, Bowen W P, Whitcomb S E, Gray M B, McClelland D E and Lam P K 2004, *Phys. Rev. Lett.* **93** 161105
[6] Vahlbruch H, Chelkowski S, Hage B, Franzen A , Danzmann K, and Schnabel R, 2006 *Phys. Rev. Lett.* **97** 011101
[7] McKenzie K, Gray M, Lam P K and McClelland D E 2007 *Appl. Opt.* **46** 3389-95
[8] Vahlbruch H, Chelkowski S, Danzmann K and Schnabel R *New J. Phys.* **9** 371
[9] Walls D F and Milburn G J 1994 *Quantum Optics* (Berlin: Springer-Verlag)
[10] Agilent Application Note 1303 (AN 1303) *Spectrum Analyzer Measurements and Noise*
[11] Krishnamoorthy K 2006 *Handbook of Statistical Distributions with Applications* (Boca Raton:Chapman and Hall/CRC Press)