# Quantum position measurement of a shadow: beating the classical limit

**Ermes Toninelli[1], Matthew P. Edgar[1], Paul-Antoine Moreau[1], Graham M. Gibson[1], Giles D. Hammond[1], Miles J. Padgett[1].**

[1]*SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, UK*
*Author email address: e.toninelli.1@research.gla.ac.uk*

**Abstract:** The precision with which the position of a shadow can be measured is classically limited by shot-noise. We achieve sub-shot-noise position sensitivity by jointly detecting correlated photons with a simple split-detector scheme.

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## 1. Introduction

The relative displacement of an object can be optically measured by determining the position of its shadow, as in the case of microelectromechanical gravimeters [1]. The precision of this measurement ultimately depends on the ability to precisely count the photons on either side of the shadow. However, even in the case of a perfect and noiseless detector, the Poissonian nature of the photon-number fluctuations associated with the employed light source poses a limit to the attainable position sensitivity: shot-noise is the ultimate limit to schemes that attempt to optically determine the position of an object [**?**]. There are a series of strategies that can be used to suppress the error associated to photon-number fluctuations. An approach that is less technically involved than schemes based on squeezed states and homodyne detection is the use of intensity correlated beams produced from spontaneous parametric downconversion (SPDC) [**?**, 3]. These experiments exploit the quantum correlations between downconverted photons, for which in the degenerate case, a pair of signal and idler photons are produced from a twice as energetic pump photon. The downconverted photon-pairs are found to be position correlated where they originate in the crystal (i.e. in the image plane of the crystal), and are found to be position anticorrelated in the far-field of the crystal.

## 2. Experiment

The noise associated to the position measurement of a shadow was reduced below the shot-noise limit, using correlated photons that were detected by an electron-multiplying CCD (EMCCD) camera. The employed experimental setup is shown in Figure 1 (a). By introducing a neutral density filter either before or after the crystal the spatial character of the source was switched from correlated to uncorrelated.

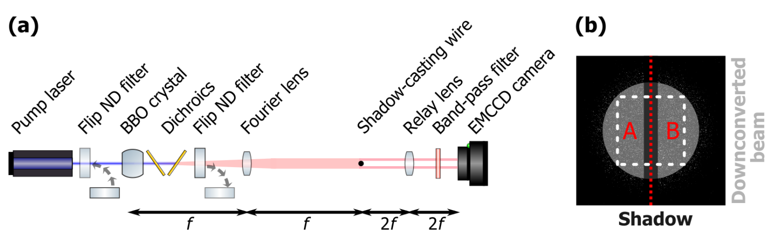


Fig. 1. **(a) Experimental setup.** A 355*nm* pumped non-linear crystal (Beta Barium Borate, type-I) produces 710*nm* correlated photons, which are intercepted by a shadow-casting wire, placed in the Fourier plane of the crystal. The shadow of the wire is re-imaged onto the camera, here employed as a split-detector; **(b) Schematic of a typical frame from the EMCCD camera.** The EMCCD camera is employed as a split-detector returning two signals A and B, which correspond to the total number of photons detected over the two halves of a central region of interest. Relative displacements of the shadow from its central position cause signals A and B to change.

## 3. Results and conclusions

The signals of the two halves of the detector (A and B) shown in Figure 1 (b) were subtracted to return the position of the shadow. The noise associated to the position measurement of the shadow was calculated using the degree of correlation [4], which is defined as the normalised variance of the residual difference of the detected photons over the two halves of the split-detector $Var(A-B)/<N>$, where $N = A + B$ is the total number of detected photons in a frame and $<>$ indicates a temporally averaged value obtained from a statistically significant number of recorded frames.

We experimentally demonstrated a maximum noise suppression in the estimation of the position of a shadow of $\approx 18\%$ with respect to the experimental measurement, corresponding to a noise suppression that is $\approx 11\%$ better than the theoretical shot-noise limit. This amount was found to be dependent on the total quantum efficiency of our system. Our approach to quantum-enhanced position measurement effectively addresses the EMCCD as a split-detector, paving the way to real-world applications of quantum-enhanced position measurement, for which less expensive detectors, such as high-responsivity/low-noise split-photodiodes, are sought to enable wide-spread use [1].

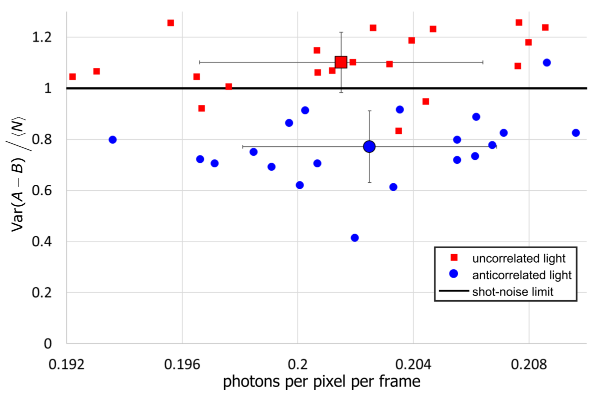


Fig. 2. **Noise suppression in the position measurement of a shadow.** The normalised variance of the residual difference of the detected photons was recorded at the optimal detection light-level of $\approx 0.2$ photons per pixel per frame. Our scheme allows to suppress noise both with respect to uncorrelated light (red squares) and the shot-noise limit (black solid line).

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