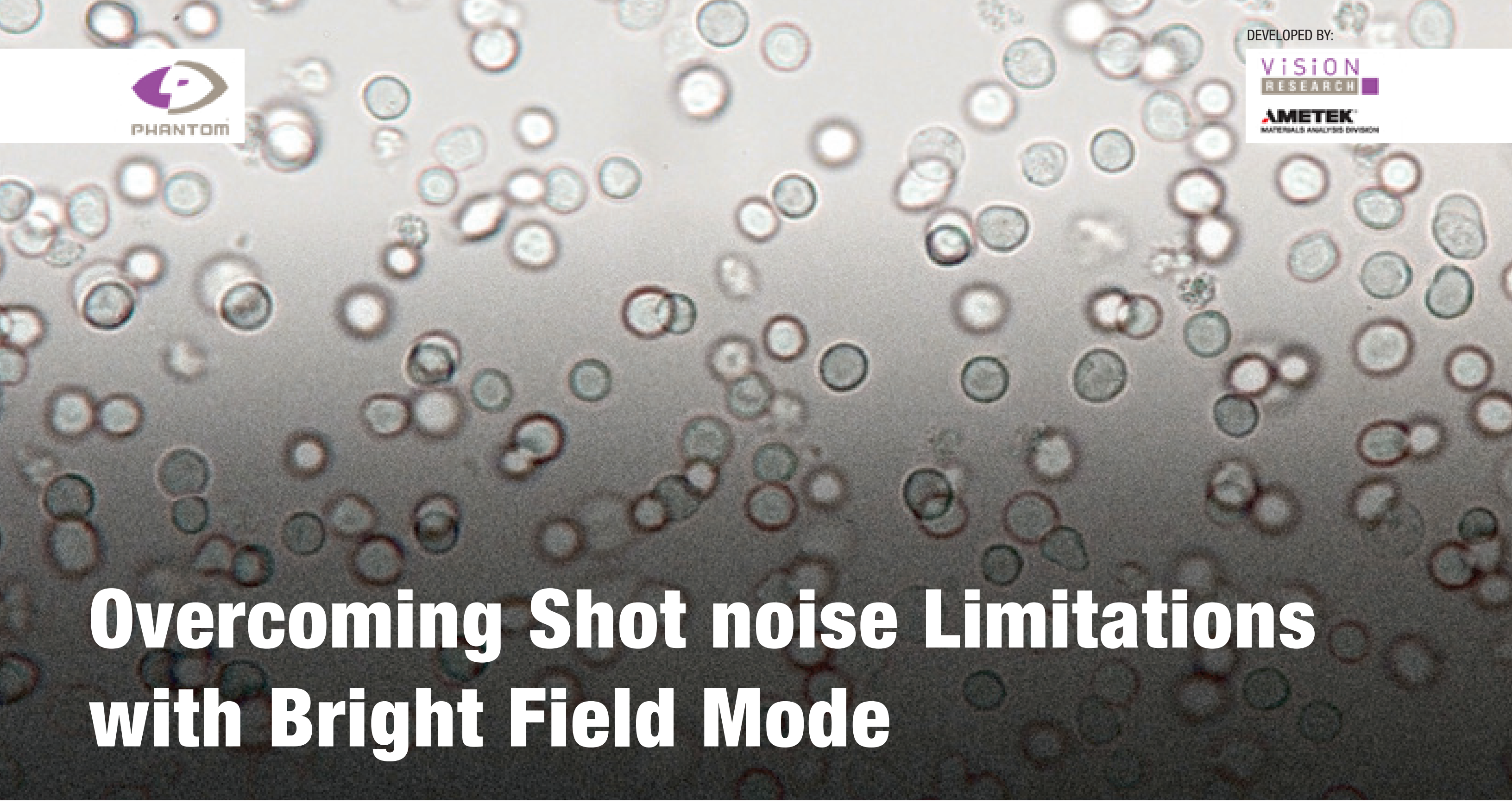

Overcoming Shot noise Limitations with Bright Field Mode

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ABSTRACT. Shot noise is one of many forms of noise inherently found in digital imaging systems that can hinder the clarity of a feature within an image. Trending with the square-root of the signal intensity, Shot noise makes it especially difficult to resolve light-levels (or gray values) of details defined by slight differences in bright areas within an image.

This white paper describes the newly released methodology called **Bright Field (BF) mode** – a new Phantom camera mode designed specifically to reduce the impact of Shot noise, improving image quality by better resolving light-levels in the bright areas of each image. We demonstrate this quantitatively by analyzing image noise in a DSC XYLA chart.

INTRODUCTION. High-speed imaging goes far beyond achieving flagship frame rates – it is also critically important to optimize image *quality* in preparation for motion analysis.

The term 'image quality' can be problematic as its parameters are open ended and difficult to define. It may even mean something different depending on who you ask. For example, if you ask a data scientist they may tell you that it is purely related to the spatial and temporal resolution, while at the same time maintaining a high level of accuracy. If you then ask an artist, the measure of image quality often depends on the style and artistic goal of the individual.

In this report, we define image quality by parameters that include, but are not limited to bit depth (a parameter that defines the highest number of light-levels achievable per pixel), the minimization of artifacts (color interpolation, pixilation, motion blur, etc.), and temporal noise (a statistically random variation in the intensity of a pixel value that changes in time). In this white paper our focus will be on introducing Shot noise, and how the new BF mode can be implemented to mitigate it when using certain high-speed cameras.

NOISE. In digital imaging systems, noise can be generated during data collection, and/or during data transmission.[1,2] Among the different types of noise found in these systems (*e.g.*, thermal noise, fixed pattern noise, etc.)[1], the origin of Shot noise may be the most difficult to understand. This is because Shot noise originates from the quantum nature of electrons,[3] and it can be modeled using the Poisson distribution where Shot noise is related to the signal intensity (N) by $N^{1/2}$. By simply plotting Shot noise versus signal intensity (N), see **Figure 1**, you can see that Shot noise quickly becomes the dominant form of noise in comparison to dark noise, with increasing signal intensities.

Our focus is introducing Shot noise and how the new Bright Field mode can be implemented to mitigate it.

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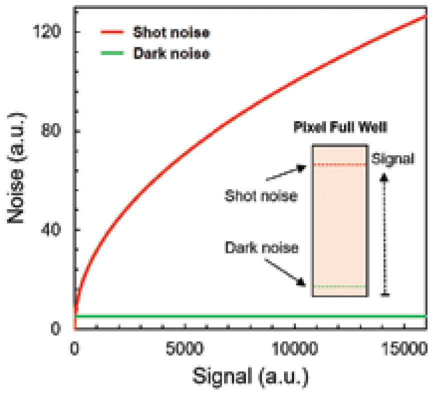

Figure 1: Pixel full well diagram showing where dark Shot noise is dominant. Shot noise trends with the square-root of the signal, and thus is dominant when the full-well is nearly full, and lower when only a fraction of the well is filled.

Accordingly, signal-to-noise ratio (SNR) can be found by simply dividing the signal, N, by the Shot noise, $\sqrt{N}$, which gives $N/\sqrt{N}$, or equivalently, $\sqrt{N}$. Therefore, SNR trends with $\sqrt{N}$, so the more intense the signal, the higher (or better) the SNR. Although the SNR *increases* with signal intensity, it is important to realize the critical fact that it becomes increasingly difficult to *resolve* light levels of those pixels that are increasingly bright. This is because the Shot noise becomes intense enough to span numerous neighboring light levels. To understand this concept, it is helpful to perform and then analyze some simple calculations.

Thought experiment. For a 12-bit image, the theoretical smallest increment you can resolve is $1/2^{12}$ or 2.4×10^{-4}, which in terms of electrons (if full well capacity (FWC) of a pixel is 10k electrons), represents approximately $10k/2^{12}$ or 2.4 electrons. In other words, it only takes ~2.4 electrons to achieve a change from one light level to the next. Therefore, when a pixel is at its brightest (*i.e.*, FWC ~ 10k electrons), the Shot noise is 100 electrons, which corresponds to a variation of up to 41 light-levels! If you have a bright object **within your image** composed of high gray values (*i.e.*, in the 4000 range) with subtle differences between them, it will be nearly impossible to pull them out from the random variation in signal caused by the intense Shot noise.

In contrast, if the FWC is 50k electrons, theoretically it takes 12.2 electrons to go from one light level to another (divide 50k electrons by 2^{12}). If this pixel is at its brightest, then the Shot noise will be equal to $\sqrt{50k}$ or 224 electrons. Therefore, by dividing the Shot noise by the number-of-electrons-per-light-level (*i.e.*, 224 electrons /12.2 electrons), you will find that the noise spans 18 light levels, which is less than half as many as in the case where a FWC of 10k was used. In other words, having a larger FWC will allow the ability to better resolve light levels between bright features within the image.

The important tradeoff to consider is that the benefits of a deeper FWC come at the expense of light sensitivity. Therefore, BF mode is particularly useful for high-speed applications that have bright or translucent objects moving across an intensely lit bright background, see figure 4 as an example. It shows red blood cells flowing through a channel imaged using bright-field microscopy.

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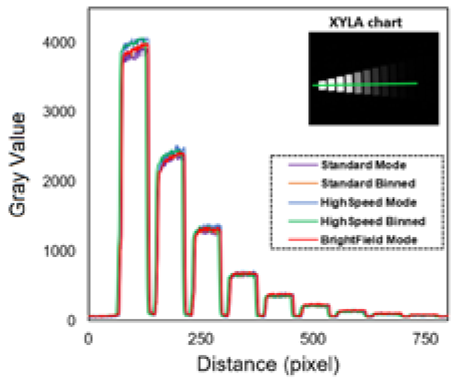

Figure 2: Gray-value plot generated by drawing a line across a XYLA dynamic range test chart and plotting the gray values of each pixel for each Phantom camera mode.

Vision Research developed a 4 Mpx sensor allowing the user to change imaging modes to optimize the camera's performance for the task at hand.

Phantom cameras and Bright Field Mode. While there have been many advances in CMOS sensor technology resulting in a combination of higher resolution, frame rates, sensitivity, dynamic range, and lower readout noise, it is not possible to optimize all these metrics together as increasing one typically comes at the expense of the others. Vision Research developed a 4 Mpx sensor with these tradeoffs in mind, allowing the end user to change imaging modes to optimize the camera's performance for the task at hand. This sensor is now deployed in the Phantom v2640 and v1840 camera models, providing access to the following modes:

- **Standard mode:** Operates with Correlated Double Sampling (CDS) to provide the lowest readout noise (7.2 electrons), and comparatively high dynamic range (64 dB).
- **Standard Binned mode:** Increases sensitivity and frame rate at the expense of lower overall resolution and slightly higher readout noise (11.9 electrons).
- **High Speed (HS) mode:** Operates without CDS to provide higher frame rates at full resolution with higher readout noise (18.8 electrons) and exposure times as low as 142 ns.
- **HS Binned mode:** Provides increased sensitivity, the highest overall frame rates with exposure times down to 142 ns, with the tradeoff of a decreased maximum resolution and higher readout noise (29.7 electrons).
- **Bright Field mode:** Increases FWC of the 4Mpx sensor to mitigate the negative effects of Shot noise, however the image has overall lower light sensitivity.

Quantitative Analysis. To compare Shot noise between the various modes on a Phantom v2640 (Standard, Standard binned, HS, HS binned, and BF mode), a single frame of a DSC XYLA chart was exposed with the intensity of the brightest area just below saturation, see **Figure 2** for an overlay of the five different profiles. By importing the single frame into ImageJ software, drawing a line across the square, and using the 'Plot Profile' function, a gray-scale line plot can be generated. Evident from the overlay is that each mode behaves similarly with respect to the overall profile, but a closer look shows that the noise on each flat peak increases as the peak height increases.

As a model example, by plotting the gray values across the brightest area for the BF and Standard modes, we can directly compare the intensity of the noise, see **Figure 3**. Clearly, BF mode has less noise than Standard mode, permitting the ability to better resolve light levels in the bright regions.

It is important to recall from the "Thought experiment" section that increasing the FWC allows for better resolving light levels in the bright regions because the Shot noise in BF mode, although higher **in terms of electrons** than Standard mode, spans relatively fewer light levels.

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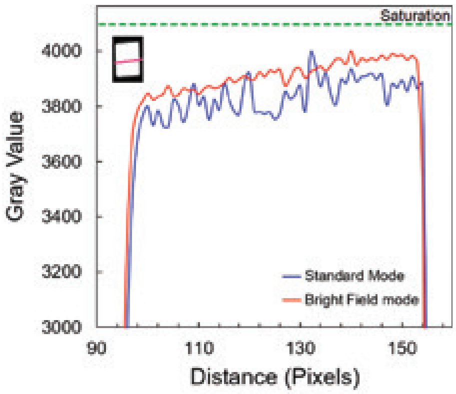

Figure 3: Plot of the gray values in Bright Field mode (red line) and Standard Mode (blue line), derived from imaging the same bright square. Upon inspection, standard Mode is nosier than the Bright Field Mode.

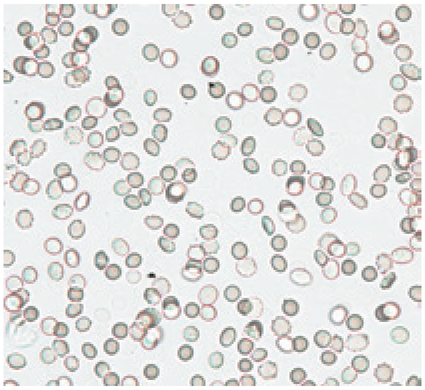

Figure 4: Bright field microscopy example from a flow cytometry experiment

Conclusion. In summary, the newly released BF mode improves image quality for those strongly backlit applications where resolving light-levels is essential for measurements and motion analysis. This can be useful for applications ranging from bright field microscopy (see **figure 4**) to large scale outdoor environments that involve analyzing the motion of bright subjects against a bright sky.

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Image Credit: Title image and Figure 4 courtesy of Dr. Andrew Filby and Dr. Alex Laude, Newcastle University Faculty of Medical Sciences

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