
Insights into High-Speed Intensified UV/Vis Spectroscopy

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Introduction. We build upon our foundation of high-speed spectroscopy[1] and pose a new question: what if the light from your event comes at such a premium that it becomes hard, if not impossible, to distinguish signal from noise? Take for example fluorescence – such photoluminescent events emit isotropically from the source and carry away a substantial amount of optical power. For the sliver of the arc angle subtended by the numerical aperture of your optics, perhaps the conspiracy of matter down in the dark can overpower your signal, drowning it in a sea of background noise and random photons. To address this concern, we introduce the image intensifier to our setup.

When should we use an image intensifier? While a standard CMOS sensor can convert light into electrons via the photoelectric effect, there is no additional processing to the generated photoelectrons which would cause it to appear any different from any other electron. This is why, at very low light levels, actual signal is hard to distinguish from noise since a generated photoelectron is read the same as a stray electron comprising the dark noise. An image intensifier, however, compensates for this by accelerating and multiplying any generated photoelectrons such that when it strikes a phosphor screen at the end, the result is a bright, visible image which can be captured by the camera.[2] Thus, you strongly increase the signal-to-noise ratio (SNR) of your system by adding a strong preference to the generated photoelectrons. The SNR quantity is key to understanding when you should use the image intensifier.

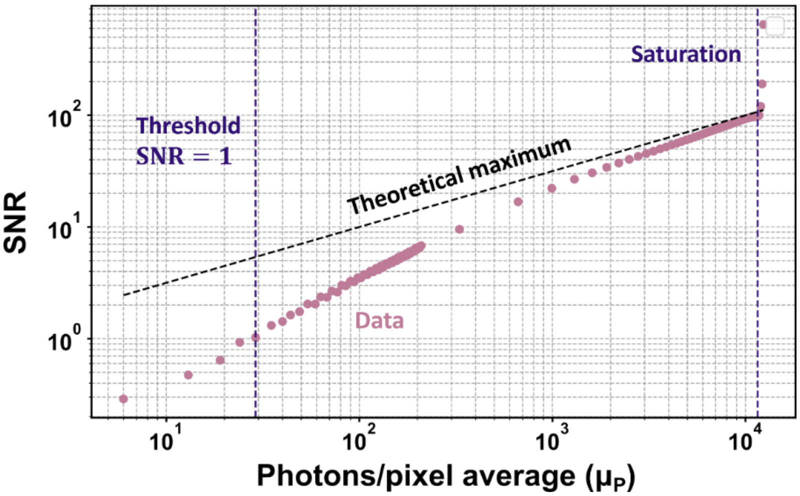

Figure 1 *– SNR plot for the T4040. Shown are the Threshold SNR (represented by the purple dashed line to the left when the necessary amount of irradiation crosses the SNR=1 line), Theoretical Maximum (represented by the black dashed line as determined by the function* $SNR = \sqrt{\mu_p}$ *), and Saturation (represented by the purple dashed line to the right when the irradiation saturates the pixel).*

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[1] Matthew Vayner, Introduction to High-Speed UV/VIS Spectroscopy, Vision Research, 2024. LINK

[2] Visit the Axiom Optics for more info: https://www.axiomoptics.com/products/hicatt-high-speed-intensifier/

Please refer to Figure 1, the SNR plot from our EMVA 1288 spec for the T4040. Notice the line labeled "threshold SNR" – this is the absolute minimum amount of photons per pixel per exposure time needed in order to distinguish signal from noise. For the T4040, this value is 28.4 photons per pixel per exposure time. You should consider using an image intensifier when the irradiance from your source is near or below this value.

Let's consider an example: your source emits 30 mW of optical power and you want to determine the irradiance in photons per pixel per exposure time. Here are our assumptions:

(a) The source emits light isotropically as determined by the inverse square law.
(b) The camera is placed 100 mm from the source.
(c) We use a 4 MPx camera with sensor size 23.7 mm x 15.4 mm (2560 x 1664).
(d) Our exposure time is 1 us.
(e) Let's assume this is monochromatic at 532 nm such that the energy per photon is

$$E_{photon} = \frac{h\,c}{532\text{ nm}} = 3.73 \times 10^{-19}\text{ J } (2.33\text{ eV})$$

where h is Planck's constant and c is the speed of light in vacuum.

By (a) – (c), the fraction of optical power even reaching an individual pixel assuming perfect efficiency is:

$$f = \frac{A_{sensor}}{Res} / A_{sphere} = \frac{23.7\text{ mm} \times 15.4\text{ mm}}{2560 \times 1664} / (4\pi(100\text{ mm})^2) = 6.82 \times 10^{-10}$$

and

$$P_{pixel} = f\,P_{total} = (6.82 \times 10^{-10}) \times (0.03\text{ W}) = 2.05 \times 10^{-11}\text{ W}$$

By (d), the energy incident on the pixel per exposure time is:

$$E_{pixel} = P_{pixel} \times t = (2.05 \times 10^{-11}\text{ W}) \times (10^{-6}\text{ s}) = 2.05 \times 10^{-17}\text{ J}$$

And by (e), the number of photons incident on the pixel per exposure time is:

$$N_{photons} = \frac{E_{pixel}}{E_{photon}} = \frac{2.05 \times 10^{-17}\text{ J}}{3.73 \times 10^{-19}\text{ J}} = 54.88\text{ photons}$$

And the amount of photons incident per pixel per exposure time is roughly 54.88 photons, which is above the threshold for the T4040. While this serves as an excellent back-of-the-envelope calculation for our irradiation and SNR, it consists of several assumptions that might not be realistic for our system. Generally, around the same order of magnitude of the irradiation threshold (especially for spectroscopic systems which intrinsically contain loss), it behooves the user to consider the image intensifier such that you can greatly improve the SNR for very low light scenarios.

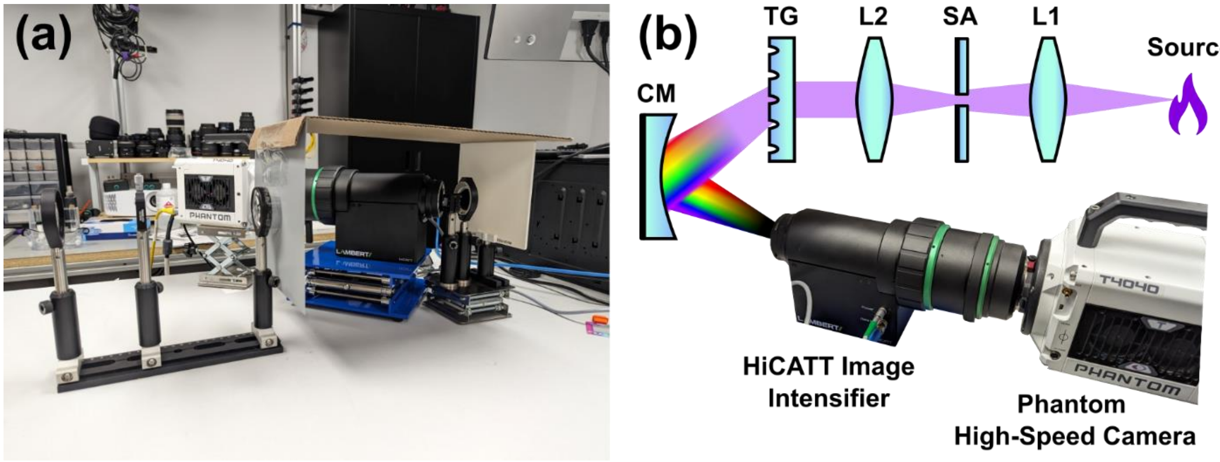

Figure 2 *– The setup. (a) Photograph of the setup featuring the HiCATT Ultra High Speed Intensifier and the T4040 camera. The diffraction grating and concave mirror are enclosed during the final setup to avoid any stray light from entering the image intensifier. (b) Diagram of the full setup. L1: Ø2" f=100mm bi-convex lens, SA: slit aperture, L2: Ø2" f=150mm bi-convex lens, TG: transmission grating 600 grooves/mm, CM: concave mirror f=100mm*

Hardware Configuration. Figure 2(a) features a photograph of the setup with the HiCATT Ultra High-Speed Intensifier and the T4040 camera while in Figure 2(b) we provide a diagram for the spectroscopic setup. The techniques of the preceding paper on spectroscopic imaging still apply – the only difference is the addition of the image intensifier. For a more detailed discussion of wavelength calibration and interpretation of the images, please refer to that paper.

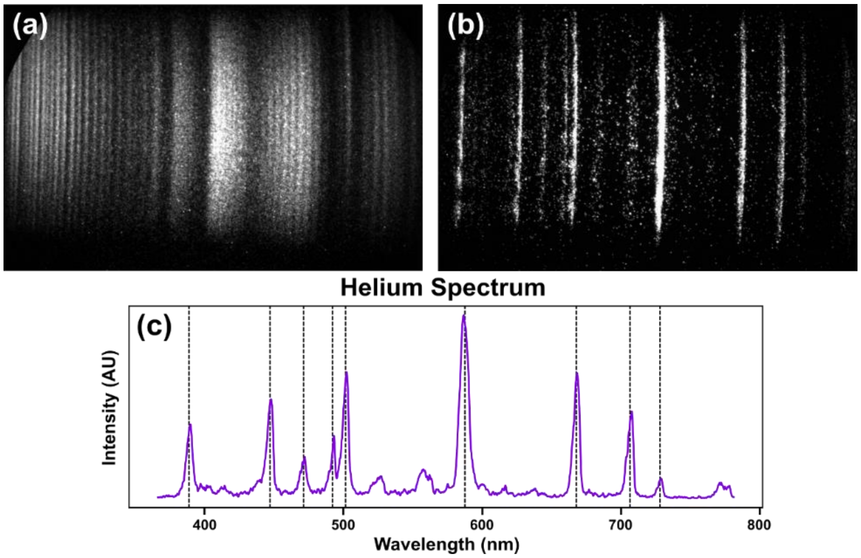

Figure 3 *– Spectral data obtained using the image intensifier. (a) Spectrum of diatomic nitrogen at 1 us exposure time. (b) Spectrum of helium at 1 us exposure time. (c) Plotted helium spectrum with pixel position to wavelength mapping. Spectral lines at pixel position x=498 (447 nm) and pixel position x=2101 (706 nm) were chosen as fixed for the linear fit – all other dashed black lines are plotted manually from the accepted values for the helium spectral lines to demonstrate the accuracy of the fit.*

Calibration. Figure 3 shows two images of the (a) nitrogen spectrum and (b) helium spectrum taken with the HiCATT Image Intensifier attached to the Phantom T4040 at 1 us exposure. The striking feature of each image produced through the image intensifier is the enhanced stochastic noise present, called *shot noise*. Shot noise is a limitation of the laws of physics – notice in Figure 1 that there is an upper limit called "theoretical maximum" which scales as the square root of the irradiation. The image intensifier gets you extraordinarily close to that theoretical maximum but there is only so much you can do with such little light. Consider Figure 4 with simulated irradiation increasing from the top left to the bottom right for a theoretically perfect camera. When the irradiation is too small, a signal cannot be distinguished at all – as we slowly tune the irradiation to larger values, the image becomes less and less noisy.

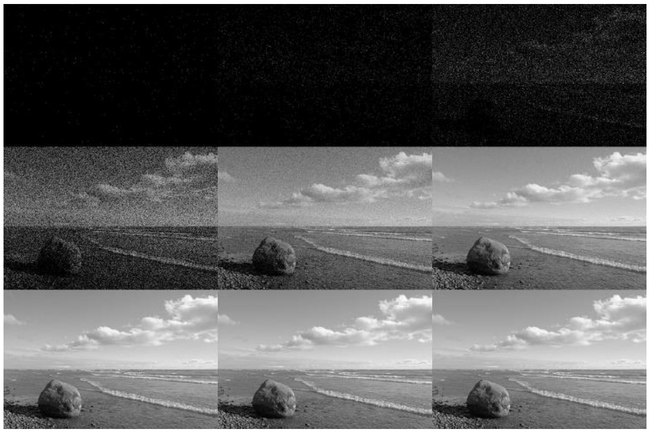

Figure 4 *– A photon noise simulation. Top row, from left to right: 0.001, 0.01, 0.1 photons/pixel/exposure time; middle row, from left to right: 1, 10, 100 photons/pixel/exposure time; bottom row, from left to right: 1,000, 10,000 and 100,000 photons/pixel/exposure time. Note the rapid increase in quality past 10 photons/pixel/exposure time. Image by Mdf licensed under CC BY-SA 3.0.*

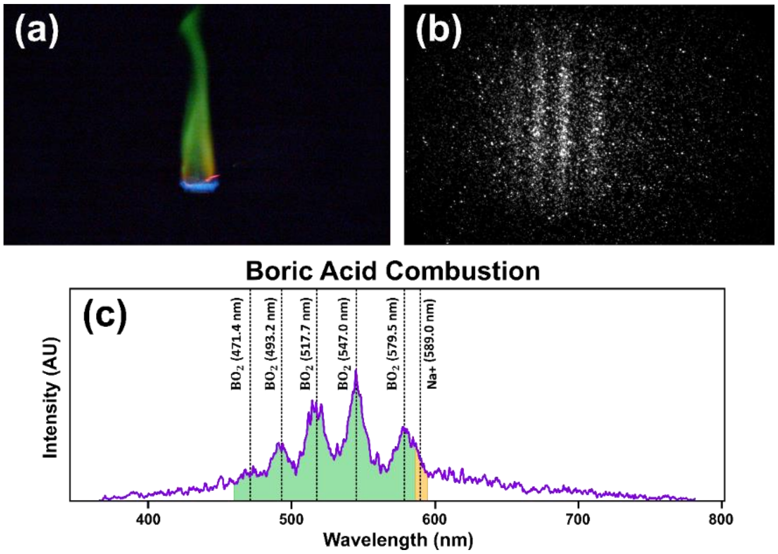

Figure 5 *– Boric acid combustion. (a) Photograph of the steady-state flame. The orange filament weaving through the green flame is caused by sodium, a common lab contaminant. (b) The spectral image of the flame at 1 us exposure with prominent shot noise. (c) The plotted spectrum throughout the visible range. The dashed black lines are the accepted values for spectral peaks of BO_2 and are plotted manually to demonstrate the strong agreement between our calibration and a real measurement.*

Example data set. When boric acid combusts, it emits remarkable viridescent light as shown in Figure 5(a). However, the light emitted from this process is faint with the spectral energies spread out and broadened throughout the 470-590 nm range. Figure 5(b) demonstrates that this is still not an issue for our setup even with such prominent shot noise that's significantly more prominent than the steady-state atomic excitations in the previous section. We plot the spectrum in Figure 5(c) with the accompanying accepted values for the intermediary BO_2 molecule representing the combustion of boric acid.