Assessment of cameras for low intensity acquisitions

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Abstract

Three high bit depth cameras were tested to benchmark their performance in low intensity acquisitions: the iXon and the Neo by Andor, and the Manta by Allied Vision. These cameras are regularly used in the Central Laser Facility to probe laser plasma interactions where very low intensity signals are common. The cameras were subjected to progressively lower intensities of light, to assess their read noise floors and dynamic ranges. It was concluded that the Neo and iXon were the least noisy cameras. For single photon situations, the iXon performed best, with a dynamic range of near 15 bits, and a read noise of only 2 counts. For low but above 10 photons per pixel acquisitions, the Neo performed well, with a dynamic range of 13 bits and a read noise of 6 counts. The Manta was found to perform very well, given its size and lack of cooling. If used for small (sub 1s) exposure times and as a single shot device, it had a dynamic range of 12 bits and a read noise floor of 14 counts (at 16 bit scaling).

1 Motivation

Cameras form an integral part of many diagnostic systems employed in high powered Laser systems, acting as detectors for scintillation light, x-rays and for imaging purposes. It is hence important for users to have a clear picture of the performance of these devices, to ensure they are appropriate for the diagnostic systems in which they are fitted. The performance of cameras at low signal levels is especially interesting for many applications; Here noise becomes a significant limiting factor of the level of signal detectable. While specification sheets are often provided to aid with such comparisons, it is always prudent to directly compare the quoted parameters, which is what this report seeks to do. The focus here is the comparison of 3 models of camera: The Andor Neo, the Andor iXon DU-888E-C00-UVB, and the Allied Vision Manta-G235b.

The main objective of this study is to determine the noise levels of the cameras, particularly comparing their read noise and dynamic ranges. However, other parameters such as the absolute and the linearity of response of the cameras were also measured.

2 The Cameras

Three cameras were tested, with different types and quality of sensors:

- **Andor Neo:** This is used in the CLF for low intensity acquisitions. It houses a scientific CMOS sensor.
- **Allied Vision Manta:** As the Neo, this is a CMOS sensor camera, but in a significantly smaller form factor. The sensor is only 12 bits and is the only uncooled camera examined here.
- **ANDOR iXon:** This is an EMCCD camera. This works by applying 'Electron multiplying'(EM) gain. The electrons excited by light are made to move through several steps in a gain register, where through impact ionisation they induce more electrons to enter the conduction band. This multiplies the number of electrons before readout; read noise stays constant while number of electrons increase hugely.

3 Comparison Overview

Table 1 shows the parameters measured for all the different cameras studied. For cameras where different gain settings were used, the recommended gain setting is displayed, along with a different gain setting to illustrate the comparison. For the Manta this was a gain setting of 0, while for the iXon this was an EM gain of 50.

4 Methods

4.1 Determining Read noise and Dynamic Range

To determine their read noise and dynamic range, the sensors were subjected to increasingly lower intensities of light, with their response measured. The method is

	Neo	iXon: EM Gain off	iXon: EM Gain 0	iXon: EM Gain 50	Manta Gain off	Manta Gain 20
Dynamic range (Bits)	13.4	14.8	14.8	14.6	12	9.4
Read Noise (counts)	6	2	2	3	14	95
Counts per optical photon	1	0.2	3	280	2	6
Sensor size (mm)	14.04x16.64	8.2x8.2	<—	<—	11.3x7.123	<—
Pixel size (µm)	6.5	16	<—	<—	5.86	<—
Resolution	2160x2560	512x512	<—	<—	1936x1216	<—

Table 1: Table comparing the atributes of the cameras. Note the Read noise for the Manta is in 16 bit format, where the camera itself houses a 12 bit sensor. The counts outputted are scaled up to 16 bit. All the cameras were tested at 1s exposure, except the iXon, which was tested at 0.01s exposure

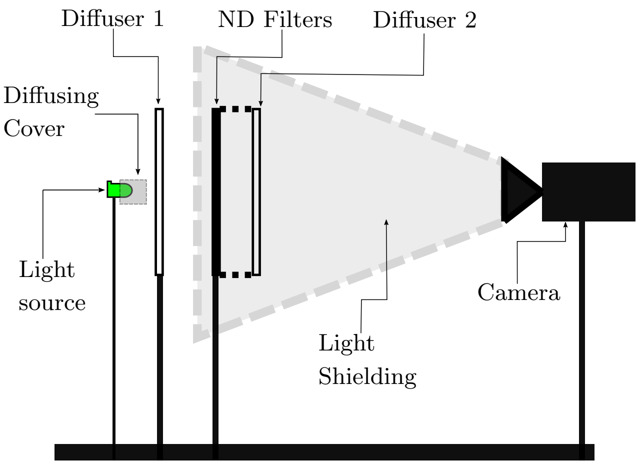

Figure 1: Setup used for determining dynamic range. A $520nm$ LED was used as a light source, with sheets of paper used as diffusers. A light tight tunnel was made with black anodised alluminum.

modified from that used by Rusby[1]. The set-up used is illustrated in Figure 1.

The path between the light source and the camera face was completely shielded in black anodised aluminium, ensuring a light tight set-up. The light source used was a $520nm$ LED, paired with three layers of diffusion (two layers for the iXon to get sufficient counts at the lower exposure time), so that a uniform light profile could be deposited on the sensor. While the profile of the incident light was not entirely uniform across the whole sensor, showing dark corners for example, the analysis was carried out considering the largest area on the camera chip where the light profile was uniform.

Initially, the LED was turned off and a dark frame was taken to determine the mean background level (due to dark currents, read error), by taking 100 frames in complete darkness. With the LED on, a set of 25 readings were taken at each intensity level. The intensity of the light was controlled by introducing neutral density (ND) filters between the light source and the sensor. For all tests except for the iXon an exposure time of 1s was used. The iXon tests were conducted at 0.01s exposure.

The Neo was cooled to $-25°C$ and the iXon to $-40°C$. These reflect the lowest temperature that could be maintained at room temperature in the lab, and the recommended operating temperature of the Neo. The manta had no cooling mechanism built in, and the effects of this are discussed below, but in this case a dynamic background was taken, with 20 dark frames before each intensity tested.

For each intensity, the signal was determined by subtracting the average background per pixel that was measured from the average measured counts per pixel, a procedure commonly followed in experiments. The RMS noise was taken to be the standard deviation of the signal. As each Pixel could have a slightly different sensitivity to light, taking the standard deviation over an extended region of the image would have introduced additional spread. To avoid this, the noise level per pixel was calculated as the standard deviation of the number of counts across the 25 readings for each individual pixel, with the final RMS noise taken as the average standard deviation across all the pixels on the sensor. In this way, differences in pixel response do not contribute to the final standard deviation.

In order to compare the two cameras, an absolute calibration was carried out, linking average counts (in the shot noise dominated regime) to the power flux incident. Using a laser, the same exposure times and ND filters to avoid saturation, a known amount of flux was deposited onto the chip. From this, the power flux corresponding to the average number of counts was calculated.

4.2 Gain Setting

To avoid confusion at this point the three different uses for the word 'Gain' in this report will be defined below.

1. The 'system gain' is the gain of the detector and is defined as the number of electrons required to register 1 count (in analogue digital units, or ADU).
2. The Manta software was equipped with a software solution to control the gain of the camera. The software gain is in a range between 0Db and 40Db, and this setting will be referred to as the 'gain setting'.
3. Finally, the iXon features the mentioned 'Electron multiplication gain', which will be referred to as EM gain.

For a signal level S, the number of counts and their standard deviations are proportional to the gain, i.e., the variance of the readings is proportional to the square of the gain. A graph the number of counts against variance will hence have a gradient equal to the gain. This was done with the dynamic range data for all the cameras.

The gain setting on the manta is related to the system gain as follows: Let the system gain at software gain level 0 be G_{sys} , and the system gain be G at some software gain of G_{set}, then,

$$G_{set} = -20\log_{10}\left(\frac{G}{G_{sys}}\right) \quad (1)$$

The Manta tests were conducted across different Gain levels, so the use of a higher gain setting in a low signal environment may be explored.

5 Results

5.1 Low Light Performance

Here the performance of the cameras is compared, at the gain setting which was determined to be optimal where applicable. The Gain settings are discussed in sections 5.2, 5.3. The linearity of the cameras for lower incident intensities can be seen in Figures 2 and 3. While the signal remains relatively high, the cameras display a linear response to light, as seen in Figure 2. Surprisingly, despite at the lowest gain setting the Manta produces similar counts per photon to the the Neo, which is still more sensitive than the Manta, but are on a comparable scale. This is a strength of the Manta; in the lowest gain setting its dynamic range is essentially the same as its bit depth; the same read noise in electrons translates to fewer counts. The three cameras plotted (Neo, iXon, Manta) have similar responses for a given power flux.

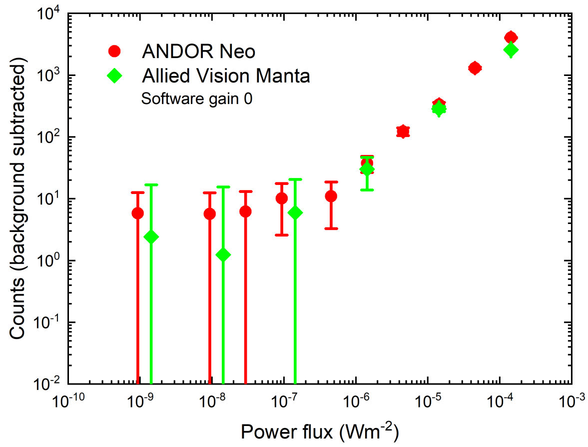

Figure 2: Counts above background recorded for varying power flux levels incident on the chip. Error bars represent the average standard deviation per pixel. The data for the Manta is the raw counts produced from saved files (12 bit scaled up to 16bit)

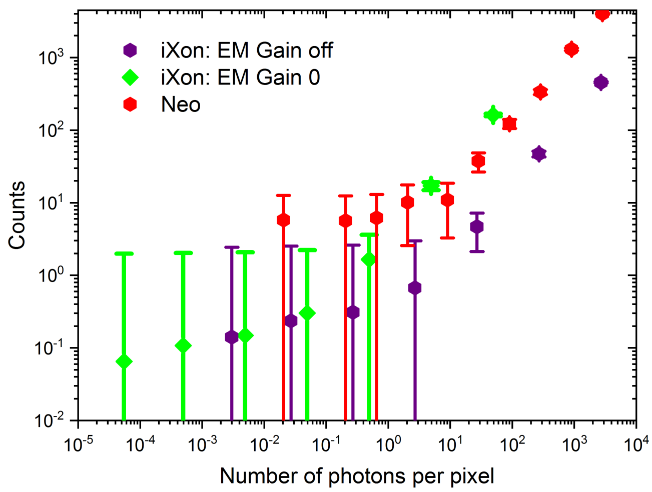

Figure 3: Linearity of Andor iXon (at EM gain 0, EM gain turned off) and Neo compared. The graph is plotted in terms of average photons that arrived per pixel, to compare the different exposure time data.

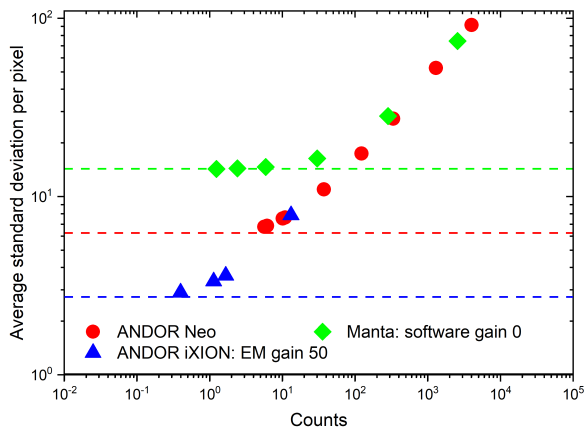

Figure 4: Plot of counts to the average standard deviation per pixel. The noise falls linearly until the noise floor (indicated by the dashed lines) is hit, where it begins to flatten out. The data for the Manta is the raw counts produced from saved files (12 bit scaled up to 16bit)

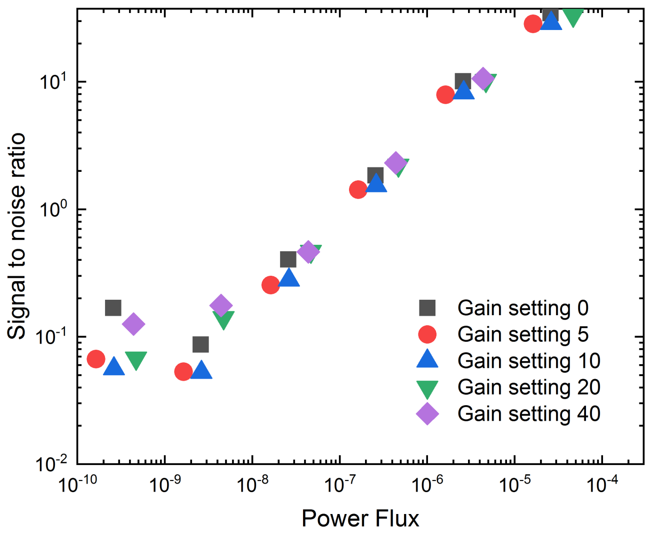

Figure 5: Signal to noise ratio for different gain settings of the Manta. The points lie approximately on the same line, with the gain setting 0 actually slightly higher than the other points for the same power flux

The break in linearity can clearly be seen in the low intensity regime.

The results for the iXon were treated slightly differently, as its sensor with the EMCCD gain on is designed to operate in very low photon incident environments only, and it would not be very useful to compare it to the other cameras in the list for this reason. However, to give some point of comparison, Figure 3 shows the linearity of the iXon and the Neo plotted on the same graph. There are two settings on the iXon which may be mistaken to be equivalent but are in fact not, as can be seen on the graph. With the EM gain turned on but set to 0, the iXon has a similar counts per photon to the Neo, but with it turned off, it is much lower.

The noise as a function of counts is displayed in Figure 4. The noise can be seen scaling linearly with the number of counts initially, while the shot noise still dominates, but as the exposure is reduced, the read noise floor becomes apparent. Here it can clearly be seen that the iXon at EM gain 50 has the lowest read noise followed by the Neo and finally the Manta. The difference in noise between the Neo and the Manta, as well as the iXon and the Neo is a large margin.

In terms of Dynamic range as shown in, Figure 4, the difference between the Manta and Neo is large. The iXon shows much better low signal performance and, as seen in Figure 4, its noise floor is a third that of the Neo. It is limited however in that when the EM gain is turned on, greater than 10 photons per pixel over time damages the sensor. For a good all round camera, the Neo remains the best. The iXon however is the most sensitive at low light.

5.2 *Manta Gain Setting*

For the Manta, both the noise level and the counts increase as the gain is increased. The upper limit of saturation remains constant, and so as the gain is increased, the dynamic rage of the sensor is also decreased. However, in low intensity environments, the dynamic range reduction may not be as important as the signal to noise ratio. If turning up the gain can reduce the read noise, than the loss in dynamic range may be justified. If follows from Equation 1 that the read noise, which stays the same in electrons, will increase by a factor of 10 in counts per increment of 20 dB in gain setting. However, the increase in gain may also have an effect on counts per photon incident, which may change the signal to noise ratio.

The signal to noise ratio for different gain settings is illustrated in Figure 5. The results for each gain setting lie approximately on the same line, with the gain 0 setting showing marginally higher signal to noise.

Based on the data it was concluded that changing the gain setting on the Manta does not in fact improve the image quality: both the read noise and the counts scale up, but the ratio does not change significantly. In fact, as seen in Table 1, while the read noise between gain settings 0 and 20 increases a factor of around 7 for an increment of 20 dB, the counts per photon between gain 0 to gain 20 only increase by a factor of 5, so the signal to noise ratio is slightly worse for the higher gain settings (although not significantly). Based on this it may be concluded that the gain setting on the Manta does little for the image. The reduction of dynamic range is a price not worth paying here.

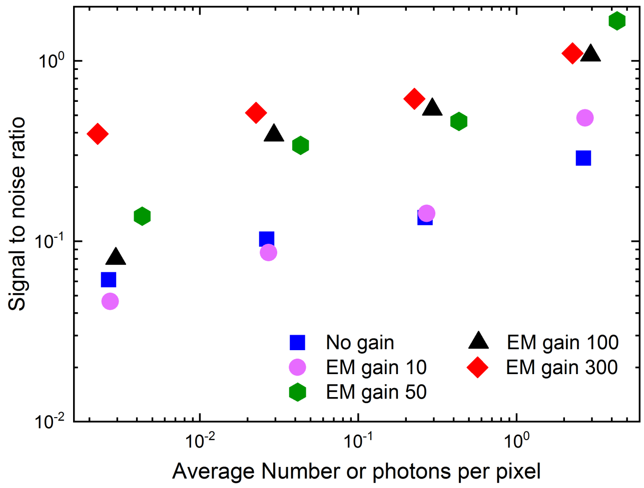

Figure 6: Signal to noise ratio of iXon camera under different gain settings. Signal was taken to be the background subtracted number of counts, noise as the average standard deviation per pixel. For all the tests, the sensor was cooled to $-40°C$, with a vertical shift speed of $0.9\mu s$ for the 'gain off' setting, and $12.9\mu s$ for the gain on readings.

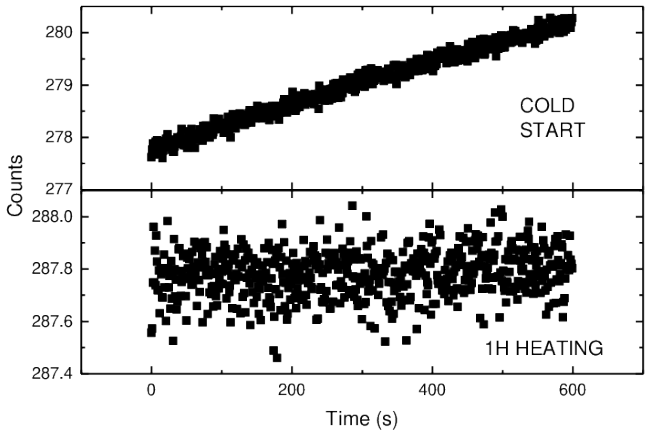

Figure 7: The effect of continuous acquisitions on the background level of the Manta camera. A set of continuous readings were taken for 10 mins with the sensor covered, just after the camera was started up (Cold start) and after 1h video acquisition (1H heating)

5.3 iXon Gain Setting

The EM gain settings of the iXon were investigated. As the Manta, both noise levels and number of counts increase with higher gain, so the signal to noise ratio for different EM gain settings that is plotted in Figure 6. As can be seen, for at EM gain 50, the signal to noise ratio is about 3 times higher than the conventional gain and low gain settings like gain 10. it was concluded that EM gain of 50 is the optimal operating setting. It has significantly higher signal to noise ratio than EM gain 0 for example but raising the EM gain above 50 will lead to a much smaller improvement than that between EM gain 0 and 50.

The read noise was found to be nearly the same for a different gain settings in terms of counts (as is expected with the EMCCD, where the number of electrons is amplified before readout), while the increasing number of counts for the same number of photons makes it a smaller percentage of the signal.

It was found that the conventional gain setting is not in fact equivalent to turning the EM gain on but setting it to 0. The counts per photon drops by 2 orders of magnitude when EM gain is turned off. This setting should be avoided; the read noise is still around 2 counts, so is quite large in terms of photons. In conventional gain settings the Neo is a better camera to use than the iXon.

5.4 Manta temperature effects

The effect of heat build-up across multiple continuous shots can be observed in Figure 7. As can be seen, a steady state is reached once the camera has heated up,

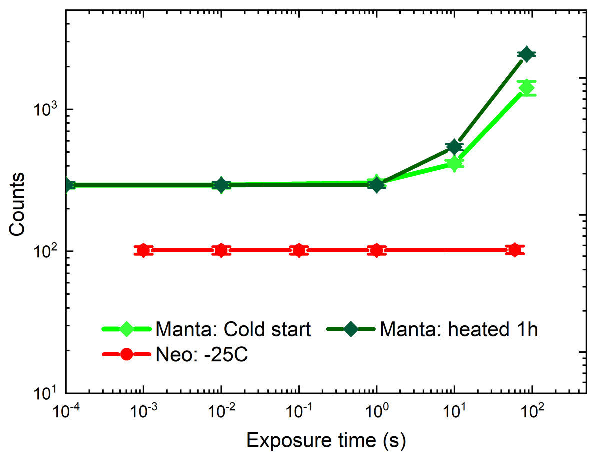

Figure 8: Background count level across exposure times for the Neo, cooled to -25°C and the Manta with a cold start and 1h heating. Error bars represent the average standard deviation per pixel. The number of counts and standard deviations are from the raw, 16 bit files, which is scaled up from 12 bits

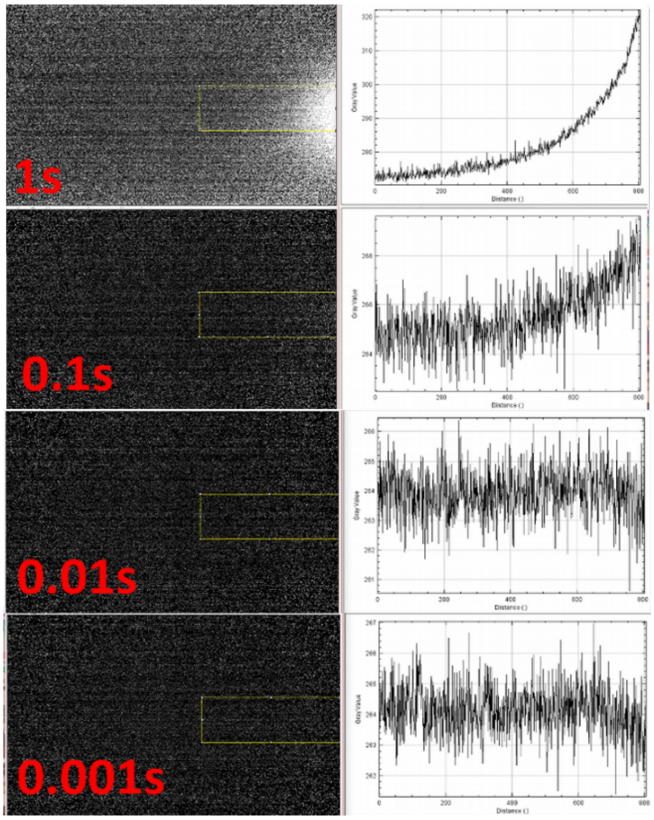

Figure 9: Image output of dark field from Manta at different exposure times

but in the cold start, the background varies at a rate of about 2 counts in 10 minutes. This was taken into consideration when acquiring data with the Manta, and a dynamic background was taken.

Figure 8 shows the relationship between exposure time and background level in a completely dark frame. The actively cooled Neo and iXon maintain a relatively constant noise level across exposure times. This constancy shows the dark current noise, which should increase with time, is much lower than the read noise. The Manta however at greater than 1s exposure, quickly becomes extremely noisy. Without active cooling, heat quickly builds up on the sensor for longer exposure times. It is hence unsuitable for long exposure use.

Another temperature related effect noticed on the Manta is an abnormality in the image which only manifests itself for longer than 1s exposures. A bright localised gradient is seen on the right of the image for exposures greater than 1s. This was observed across multiple Manta units, and is demonstrated in Fig(9).

6 Conclusion

Based on the data it can be seen that the Andor are the best cameras of the three investigated. The iXon is the best camera in terms of low single photon like intensities, but the Neo, definitely noisier than an EMCCD, is still better than the other two by a wide margin, in terms of dynamic range and the lowest noise floor in terms of counts. For critical low intensity acquisitions the Neo and iXon are recommended, with a recommendation of operation at EM gain 50. Their low noise and ability to be programmed makes them by far the best choice. However, the cooling mechanism and physical size, and the need for a custom card and I/O interface certainly make them less flexible as a module to fit into diagnostics, which should be kept in mind.

Finally the Manta is a very versatile camera, with a small form factor and a flexible connector. It is recommended that it should be operated at a gain setting of 0 dB, should not be used with exposure times of greater than 1s and that a dynamic background be taken.

It should also be noted that the cameras studied vary by over a magnitude in cost, but the performance recommendations are based on image acquisition quality only.

APPENDIX I: Form factor and software

Table 2 compares some of the physical attributes of the cameras. One thing to mention is the software.

The Andor cameras were the easiest to use. Every aspect of the cameras is controllable both from the GUI of the provided program, as well as through a custom program. This is written in a proprietary language, but is similar to Visual Basic.

The 'Vimba Viewer' software of the Manta is good, and is able to save files to a specified path with a specified filename. It is stable enough to use. The output files of the software are saved as 8 or 16 bit images. The camera itself of houses a 12 bit sensor, so to utilise its full bit depth the 16 bit image, where the counts are multiplied by a factor of 16, should be used.

7 APPENDIX II: Theory

7.1 Noise sources considered in low intensity regime

Dark currents:

These are due to thermal effects. At a given temperature, due to the Boltzmann distribution of energy, some electrons will have enough energy to become excited to a higher state and be read as counts, independent of amount of light incident. The uncertainty in counts due to this is the dark current noise. This is a thermal dependent process, so in actively cooled cameras is always dominated by other sources of noise [2]).

Shot noise:

The counting of electrons excited by incident photons is a statistical process lending itself to a Poisson distribution. For the same pixel with the same power flux incident in an ensemble system, the number of counts registered will vary about the mean with a standard de-

	Neo	iXon	Manta
Sensor Type	sCMOS	EMCCD	CMOS
Frame rate (fps)	30 (up to 100 burst)	<—	30.1
Connector	Proprietary, serial Requires PCI card installed	<—	Gigabit Ethernet Requires Powered network switch Many can run on same network
Size/shape	Large, but mounting options built in	<—	Very small No mounting, but small enough to be easily clamped in
Comfortable Cooling Temperature	-25	-40	Not cooled
Operate in Vacuum?	No	No	Yes

Table 2: A rundown of the physical attributes of the cameras tested. The cooling temperatures quoted are the minimum temperature that was achieved stably in room temperature loboratory.

viation equal to the root of the mean. This uncertainty is the shot noise [3].

Read noise:

Due to the readout electronics involved, a constant current is always registered in the final acquisition, whose spread is the read noise. This is independent of the signal. [4].

7.2 Dynamic range

Because electron count is an integer quantity, the intensity of light measured is necessarily discrete. The dynamic range is a quantifier of the number of digital increments into which the camera can resolve a continous signal. A 16 bit camera will be able to detect for example 2^{16} or 65536 different levels of intensity between complete darkness and its saturation level. However, for low intensity readings, the noise present acts as a floor for the minimum discernible signal. The dynamic range is the ratio of the largest detectable counts (the maximum bit depth of the camera) and the lowest signal (taken to be the read noise). A larger dynamic range indicates a less noisy sensor, which allows for lower intensities of light to be probed. The benefit of quoting a dynamic range over a read noise is it allows for comparison across cameras of different bit depth and system gains.

The Dynamic range is expresses as a ratio:

$$Dynamic\ Range = \frac{2^{bit\ depth}}{Read\ Noise} \tag{2}$$

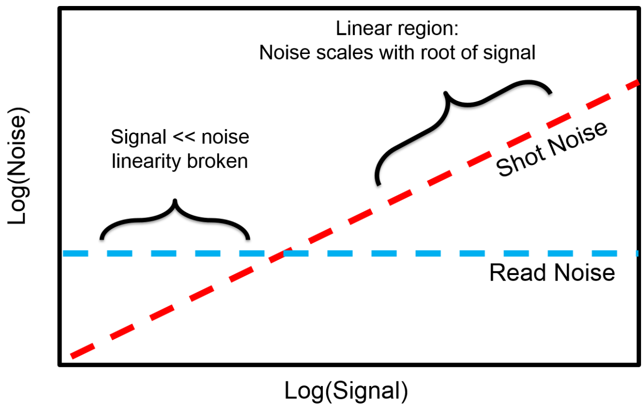

Figure 10: Diagram showing the shot and read noise levels in the low intensity regime

or in terms of bits:

$$Dynamic\ Range_{bits} = \frac{\ln\left(Dynamic\ Range\right)}{\ln 2} \tag{3}$$

While the read noise, which is independent of the signal itself, dominates in the low intensity regime, for higher intensities, the 'shot noise' dominates [5]. On a Log/Log graph, the shot noise appears as a straight line of gradient $\frac{1}{2}$, while the read noise is a constant horizontal line, as seen in Figure 10 .Plotting such a graph allows us to determine the read noise, and hence the dynamic range of the camera sensor.

8 References

[1] Rusby, D. R. *Study of Electron Dynamics and Applications from High-Power Laser-Plasma Interactions*. Ph.D. thesis, University of Strathclyde (2017).

[2] Photometrics. *Dark Current*.

[3] Photometrics. *Signal to Noise Ratio: Photometrics Whitepaper*.

[4] Photometrics. *Read Noise: Photometrics Whitepaper*.

[5] Gardner, D. Characterizing digital cameras with the photon transfer curve. Summit Imaging.