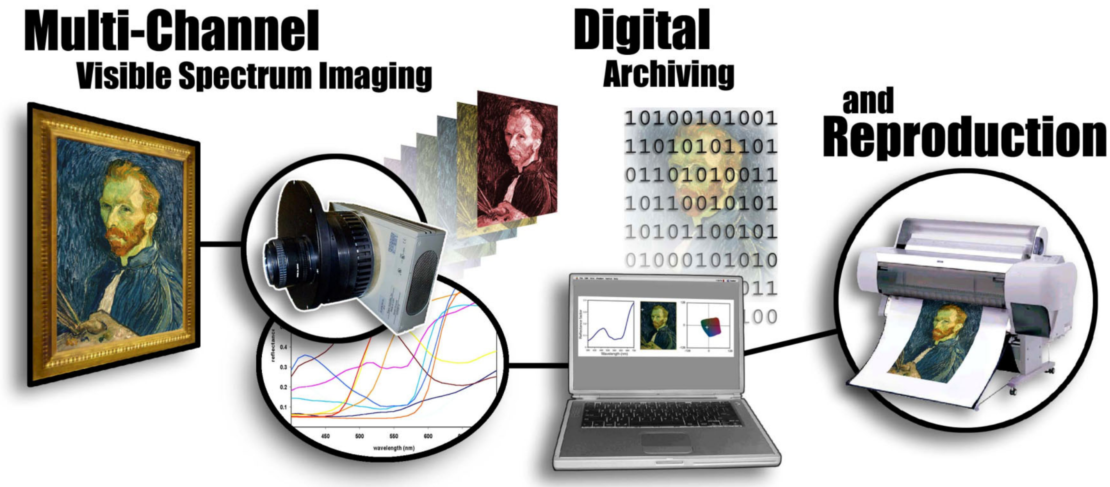

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Characterization of a Roper Scientific Quantix monochrome camera

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Abstract

A Quantix monochrome camera with a Kodak KAF6303E CCD 2-D array was characterized so that it could be used as a component of a multi-channel visible spectrum imaging system. The results of these experiments were compared to the Certificate of Performance provided by the CCD manufacturer, Roper Scientific. It was found that this particular CCD compares well to the specifications on the Certificate. The spectral sensitivities resulting from these experiments will be used for all computational simulations in future research.

Introduction

The Quantix monochrome CCD camera described in this report is currently being used, and will be used extensively in the future, in the Munsell Color Science Laboratory for research on multichannel visible spectrum imaging, or MVSI. The Certificate of Performance, provided by the CCD manufacturer, as well as similar previously performed experiments on this and other CCDs, are the basis and starting point for the experiments described here. The experiments performed included characterizing image latency, linearity, gain, noise, dark current, and spectral sensitivity. The results of these experiments could potentially have a significant effect on the broader and more experimental MVSI research.

General Experimental Procedure

Procedural details and equipment that are unique to a given experiment will be described under that experimental section.

All experiments were performed with the Quantix monochrome CCD camera, model A00K6016, with a Nikon 50 mm lens. The Grade 3 CCD in the Quantix camera is a

Kodak KAF6303E, which was tested in accordance with applicable Roper Scientific procedures. The resolution of the CCD is 3072 x 2048. Table I gives the details of the Certificate of Performance from Roper Scientific, which our experiments were compared to. In addition, the dark current is 0.051 electrons/pixel/second at a CCD temperature of -20˚ Celsius.

Table I. Certificate of Performance from Roper Scientific

Readout Speed	Gain Setting	Measured Gain (electrons/ADU)	Noise (electrons/RMS)	% Linearity
1 MHz	1 (0.5 X)	40.0	44.0	0.9
	2 (1 X)	22.0	24.3	0.2
	3 (4 X)	5.3	16.4	0.1
5 MHz	1 (0.5 X)	41.2	43.2	0.6
	2 (1 X)	21.4	27.8	0.2
	3 (4 X)	5.2	19.6	0.3

Experiments 1 and 2 were performed with the camera at a distance of 42 cm from the subject plane, which was a copy stand surface on “transmissive” mode (light diffused by a relatively uniform white plastic surface). The lens was set to an f-stop of f/11. Kodak neutral density filters, totaling ND 3.5, were used to cut down on light and lengthen exposures. Figure 1 shows the set-up for this experiment.

Figure 1. Set-up for latency experiment and linearity, noise, gain and dark current experiments.

Experiment 1: Image Latency

This experiment tested the latency effects of the CCD. Latency is the effect of the CCD not being completely "cleared" after one exposure so that the mean digital counts of the new image are higher than they would be if the CCD had been completely cleared.

The Quantix has a "clear count" mode to set the number of times the CCD should be cleared before a new exposure is taken. This mode was set to 2 for this experiment. In addition, the "ADC offset" was set to 2760 and the camera "mode" was set to "pre-exposure". The "gain" was set to 2 and the "speed" was set to 5 MHz.

A saturated exposure was taken followed by a dark image (with the shutter closed) at a known time interval from the light exposure. This was repeated 10 subsequent times with an increased delay between dark and light images each time. Table II shows the numerical results of this experiment.

Table II. Digital count statistics for latency experiment.

Time Delay (seconds)	**Minimum (digital counts)**	**Maximum (digital counts)**	**Mean (digital counts)**	**Deviation (digital counts)**
25	55	4095	61.74	5.08
50	55	4095	61.79	5.08
75	55	4095	61.62	5.08
100	55	4095	61.59	5.08
125	55	4095	61.50	5.08
150	54	4095	61.14	5.08
175	54	4095	60.99	5.08
200	54	4095	61.14	5.09
225	54	4095	60.97	5.09
250	54	4095	60.99	5.08

Figure 2 shows the mean pixel value versus the time delay before the dark exposure. It is obvious that while there is a slight downward trend, the change in mean values is so small that this so-called “latency”, here, could be just random noise. If there is any actual latency, it is probably so slight that it would not affect our experiments.

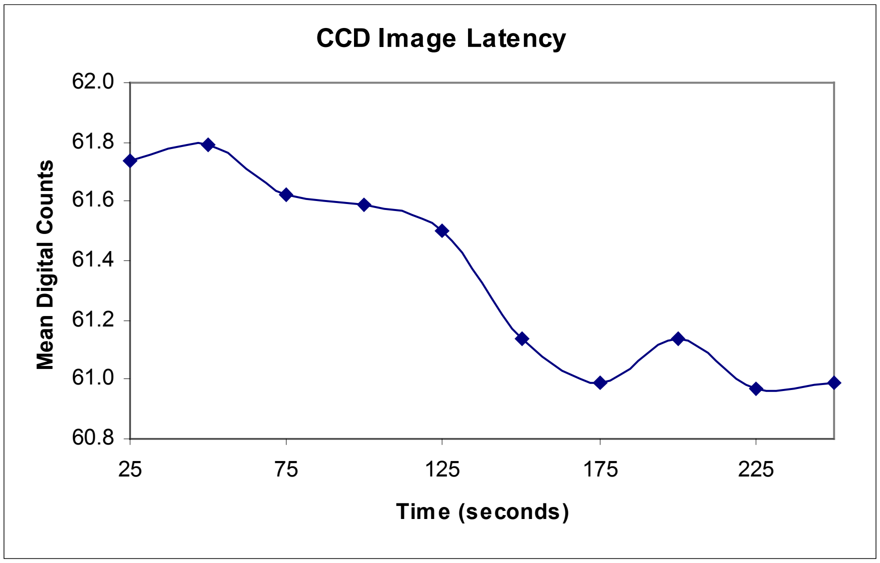

Figure 2. Image Latency of Quantix CCD.

Experiment 2: Linearity, Gain, Noise, and Dark Current

Since very little, if any, latency was found in Experiment 1, no time delay was used in this experiment. L. Taplin and F. Imai wrote the software used to control the camera for this experiment. It captured two dark images and then two light images for each exposure time. This was repeated for nominal gain settings of 1, 2, and 3, as well as speeds of 1 and 5 MHz. Therefore, since the software incorporated a loop to repeat the exposures for the three gain settings, it only had to be run twice (once for each speed setting). The exposure times for each gain setting are shown in Table III.

Table III. Exposure times used for experiment 2 for different gain settings.

Gain 1 (time in seconds)	Gain 2 (time in seconds)	Gain 3 (time in milliseconds)
1	1	50
2.5	2.5	100
5	5	250
7.5	7.5	500
10	10	750
12	12	1000
14	14	1250
16	16	1500
18	18	1750
20	20	2000
22	22	2250
24	24	2500
26	26	2750
28	28	3000
30	30	3250
35	35	3500
		3750
		4000

For each image, the mean, minimum, maximum, and variance were calculated. For each of the two light images and the two dark images for each gain setting, the standard deviation of the difference between the light images was computed. For each exposure time at each gain setting, the signal variance was calculated.

Figure 3 shows the signal linearity for the three gain settings for a speed of 1 MHz, using the first light image in each set. At a mean of 4095, the images begin clipping. Figure 4 shows the same graph with best-fit linear lines.

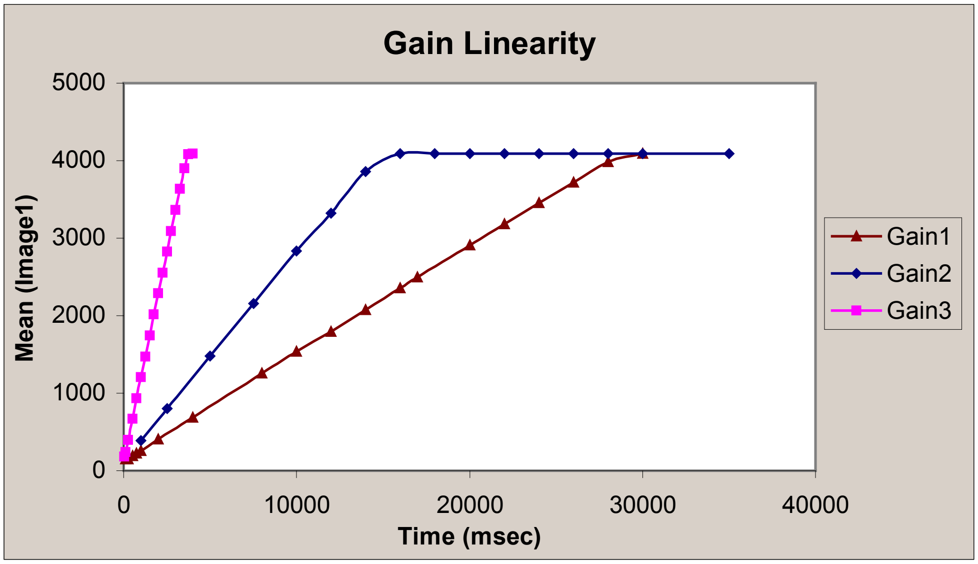

Figure 3. Gain Linearity of Quantix CCD at three gain settings for speed of 1 MHz.

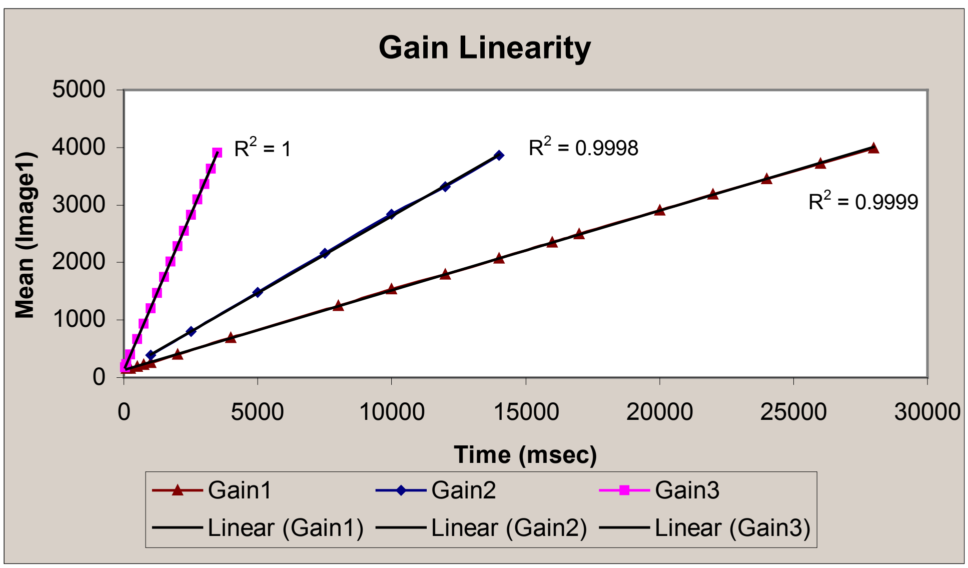

Figure 4. Gain Linearity of Quantix CCD with best-fit lines at three gain settings for speed of 1 MHz.

Figure 5 shows the signal linearity for the three gain settings for a speed of 5 MHz, using the first light image in each set. At a mean of 4095, the images begin clipping. Figure 6 shows the same graph with best-fit linear lines.

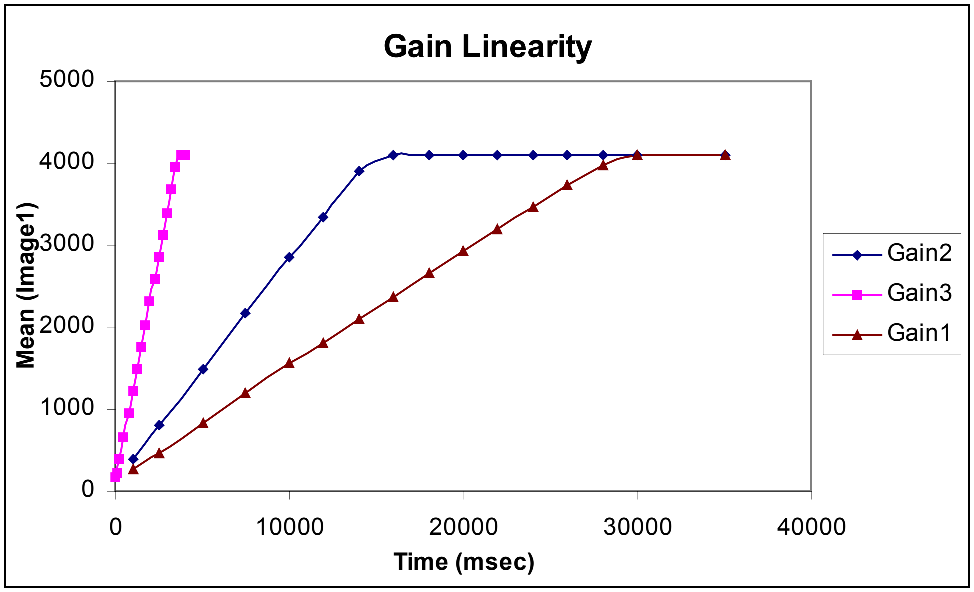

Figure 5. Gain Linearity of Quantix CCD at three gain settings for speed of 5 MHz.

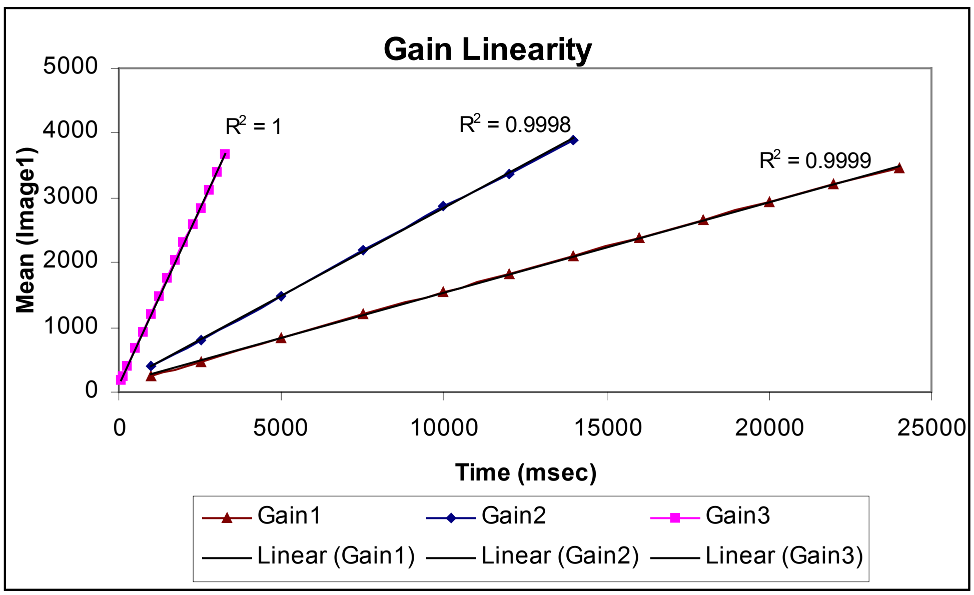

Figure 6. Gain Linearity of Quantix CCD with best-fit lines at three gain settings for speed of 5 MHz.

Gain defines the number of electrons recorded by the CCD as compared to the number of digital counts in the image. It is obvious that as the gain setting increases, the mean of the images grows increasingly faster. In other words, the slopes are greater with greater gain settings. This is true for both speed settings. With R^2 values that are so close to unity, it is obvious that the gain of this CCD is very linear. The number of electrons it takes to produce the image increases linearly with respect to the number of digital counts that are actually in the image.

Figures 7 and 8 show the signal variance for 1 and 5 MHz speeds, respectively. These plots show that the variance increases linearly for a particular exposure range at each gain setting. Figures 9 and 10 show this linear relationship for the 1 and 5 MHz speeds, respectively. Table IV shows the results of the gain and signal noise calculations and their comparison to the specifications of the Certificate of Performance. The gain is calculated as the inverse of the slope of the gain-noise graphs for each gain value. The signal noise is calculated as the y-intercept of the signal variance for a given gain value.

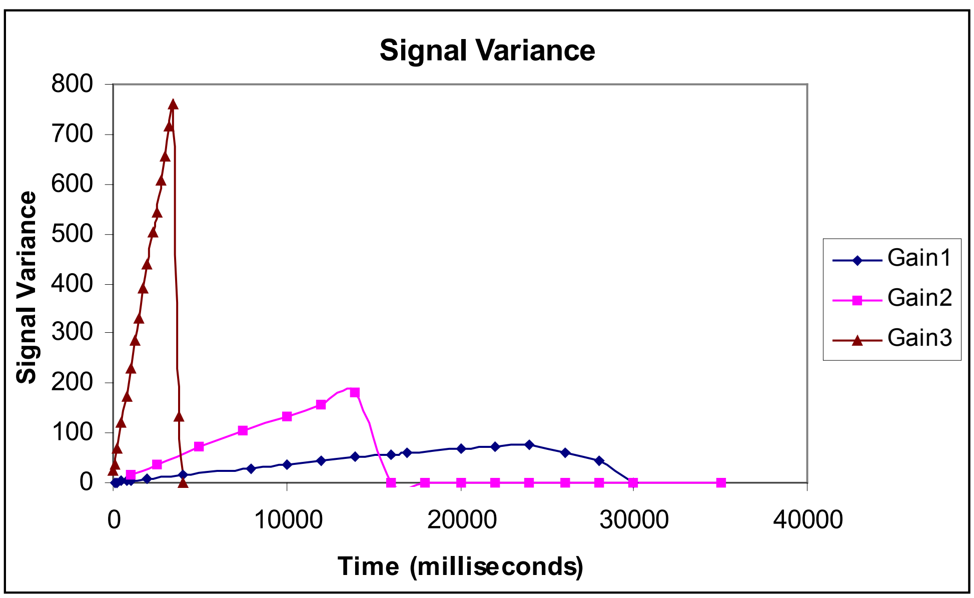

Figure 7. Signal Variance of Quantix CCD for speed of 1 MHz.

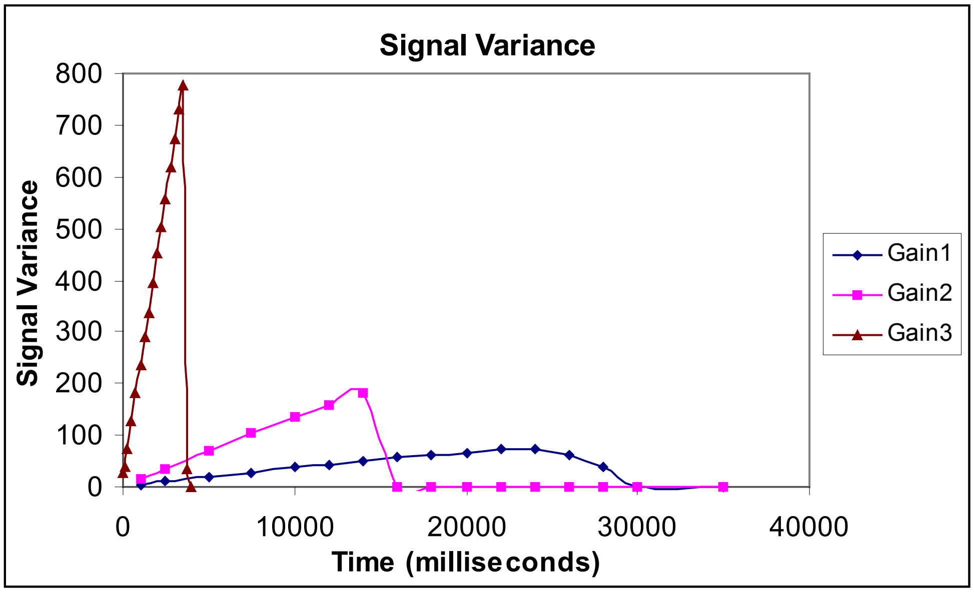

Figure 8. Signal Variance of Quantix CCD for speed of 5 MHz.

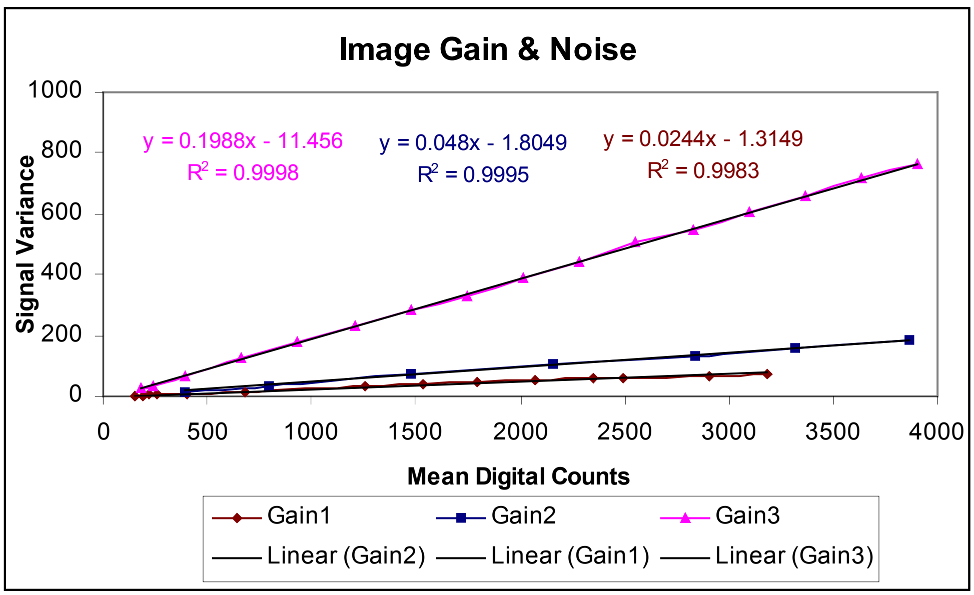

Figure 9. Image noise and gain of Quantix CCD for speed of 1 MHz.

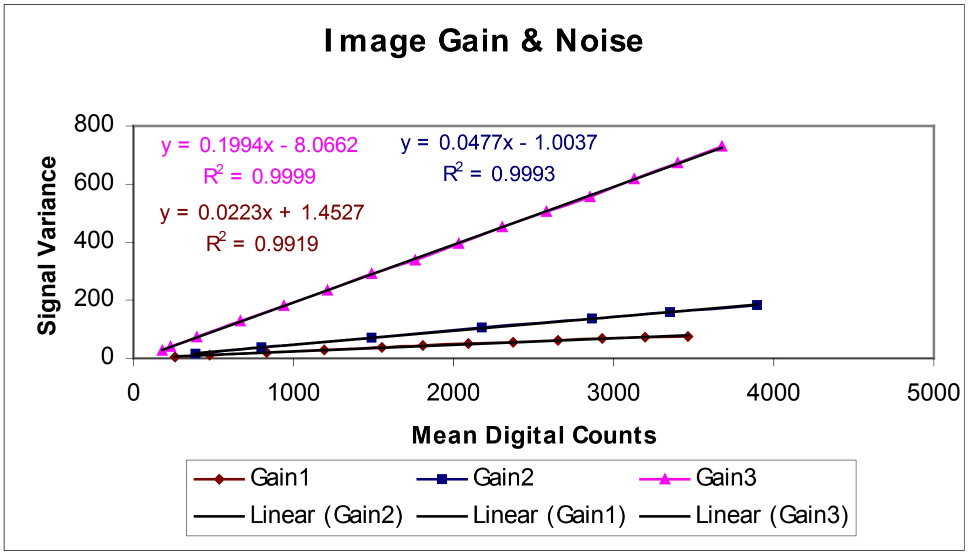

Figure 10. Image noise and gain of Quantix CCD for speed of 5 MHz.

Table IV. The gain and noise calculations compared to the Certificate of Performance specifications. Gain is defined as electrons/ADU and noise is defined as electrons/RMS.

Speed	Gain Setting	Calculated Gain	Certificate Specs Gain	Gain Difference	Calculated Noise	Certificate Specs Noise	Noise Difference
1 MHz	***1***	41.0	40.0	1.0	1.7	44.0	-42.3
	2	20.8	22.0	-1.2	4.8	24.3	-19.5
	3	5.0	5.3	-0.3	13.7	16.4	-2.7
5 MHz	***1***	44.8	41.2	3.6	4.5	43.2	-38.7
	2	22.4	21.4	1.0	5.4	27.8	-22.4
	3	5.0	5.2	-0.2	17.0	19.6	-2.6

Evaluating Table IV, the difference in gain between our calculations and the known values is very small. The reason for the large difference in noise is likely differences in methods, since Roper Scientific's experimental set-up and procedures are unknown and likely different than ours.

The dark current, as quoted on the CCD specifications sheet, is 0.051. This value is not dependant on the gain setting, only on temperature. Table V shows the calculated dark current for the different gain/speed combinations, as well as for both the dark current image sets. This was calculated by taking the slope of the dark current plots, multiplying by appropriate gain values, and then dividing by the integration time.

Table V. The dark current (electrons/pixel/second) compared to the Certificate of Performance specification for dark current at a temperature of -20˚ Celcius.

Speed	Gain	Dark Current	Certificate Specs	Difference
5 MHz	***1***	4.48×10^{-8}	0.051	-0.051
	2	2.98×10^{-8}	0.051	-0.051
	3	2.51×10^{-8}	0.051	-0.051

It is very obvious that the calculated dark current is very small compared to the Certificate of Performance. This shows that the dark current is actually much better than specified. Figure 11 shows that from 10 seconds to 10 minutes, the dark current does not increase greatly (for a speed of 5 MHz). Measurement uncertainty is probably the source of the small amount of variability that exists. The large discrepancy in results can probably be attributed to a difference in camera settings when the experiment was performed. For example, the CCD was cleared twice between each exposure for our experiment and may not have been for the Roper Scientific experiments. This might cause more dark current in their results over time, if this is the case.

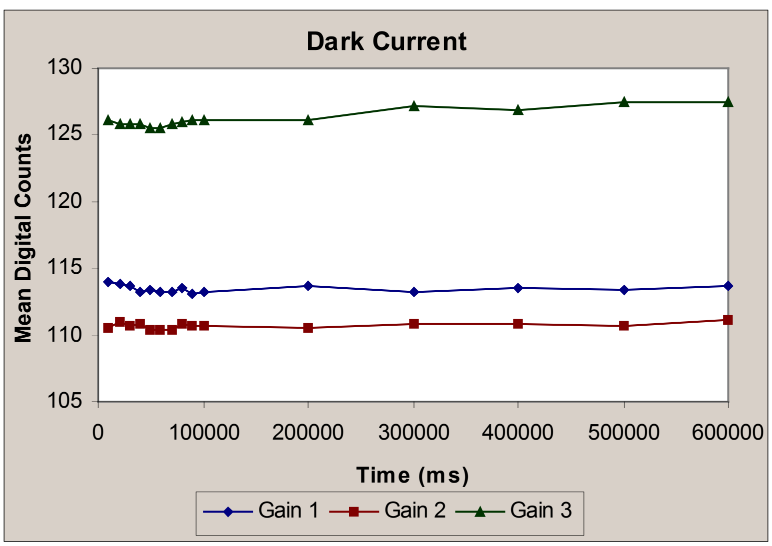

Figure 11. Dark Current Linearity of Quantix CCD for speed of 5 MHz.

Experiment 3: Accuracy of Monochromator

Measuring spectral sensitivity requires a calibrated monochromater. The accuracy of the Optronics single grating monochromator was verified. To accomplish this, a mercury-cadmium light source was used because the lines in the spectrum are known. A model 730a Optronic Laboratories, Inc. radiometer was used in this experiment with a DI-730-5C silicon photodetector. Several lines were measured and their peaks found. These peaks were compared to the known peaks of the mercury and cadmium sources. Figure 12 shows the experimental set-up for this experiment. Table VI shows the results of this experiment.

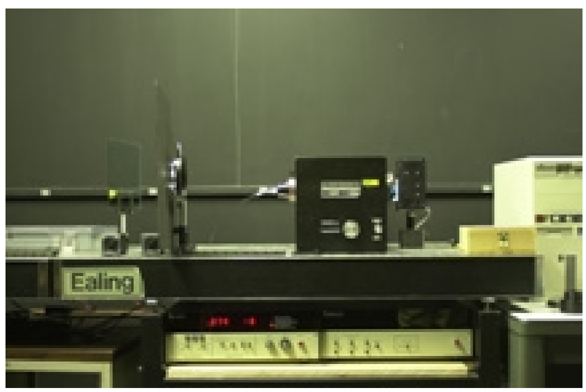

Figure 12. Experimental set-up for monochromator accuracy experiment.

Table VI. Known and measured peaks of a few cadmium and mercury lines in nanometers.

Element	Actual	Measured	Difference
Mercury	435.8	435.8	0
	546.0	546.5	-0.5
	365.0	364.0	1.0
Cadmium	643.8	643.8	0
	508.6	508.6	0

For most of the visible range the wavelength errors are negligible.

A related experiment was performed to check the bandwidth of the monochromator with 2.5 mm entrance and exit slits. The mercury peak at 435.8 nm was used. Measurements were taken from 420 – 450 nm, centered approximately around the known peak. Figure

13 shows these measurements. The pink line shows the full width at half height, which extends from approximately 432- 442 nm, making the bandwidth approximately 10 nm.

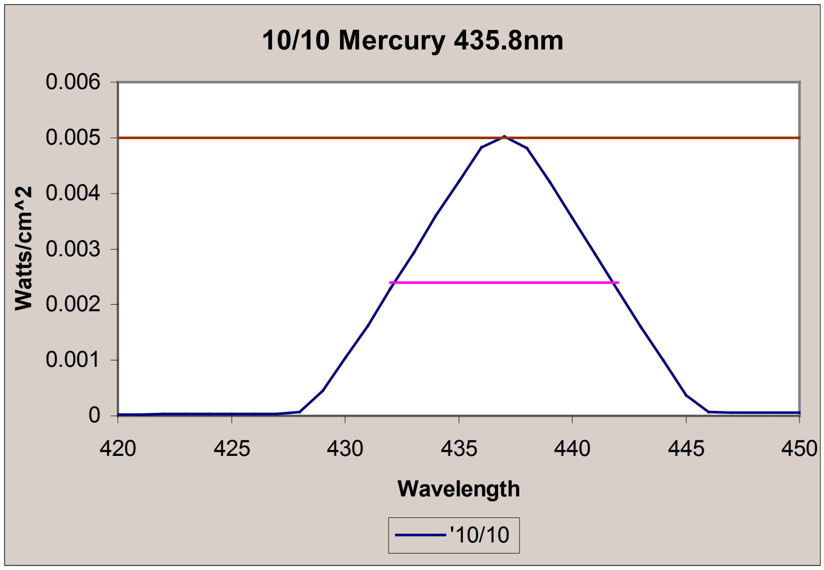

Figure 13. Radiance measurements of a mercury peak. The brown line shows the approximate top of this peak and the pink line shows the "full width at half height". This shows a bandwidth of approximately 10 nm.

Experiment 4: Camera Spectral Sensitivity

The Quantix was used to capture images of a light source at different wavelengths. At the same time, a spectroradiometer was used to obtain spectral radiance measurements of the light source. This was done for both xenon and tungsten light sources.

The first light source was an Ernst Leitz GMBH Wetzler xenon lamp with a model XLZ-1A-M10 power source of the same brand name. The second was an Optronic Laboratories, Inc. lamp, model 740-20, with a Hewlett-Packard Harrison 6274A DC power supply, Hewlett-Packard 34740A DC voltmeter set at 0.6 amperes and a 1-ohm resistor, and a General Electric tungsten bulb, model Q6.6A/T3/CL 100M. The spectral power distributions for these light sources are shown in figure 14. The xenon lamp was of much higher luminance than the tungsten lamp. For this reason, the measurements using the tungsten took much longer than those using the xenon lamp. Figure 15 shows the same plot normalized at 560 nm.

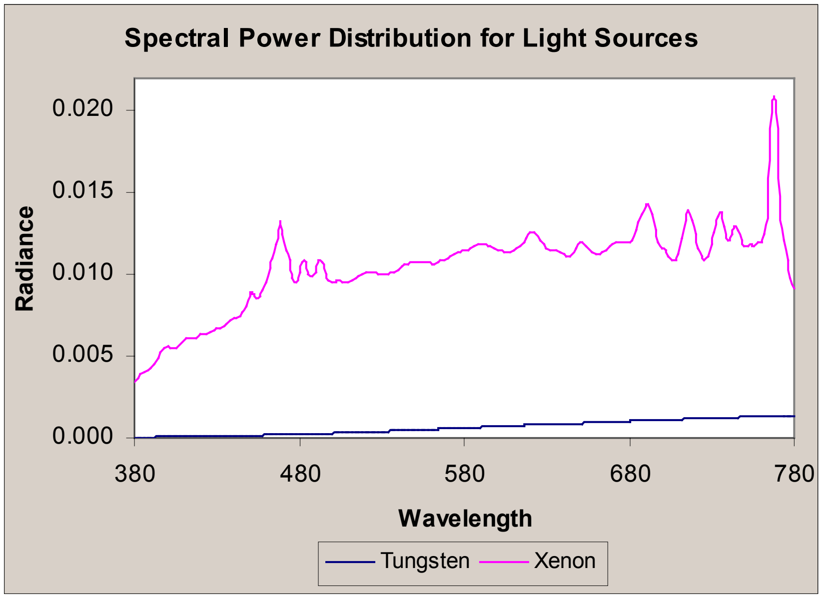

Figure 14. Spectral radiance of xenon and tungsten light sources used in this experiment.

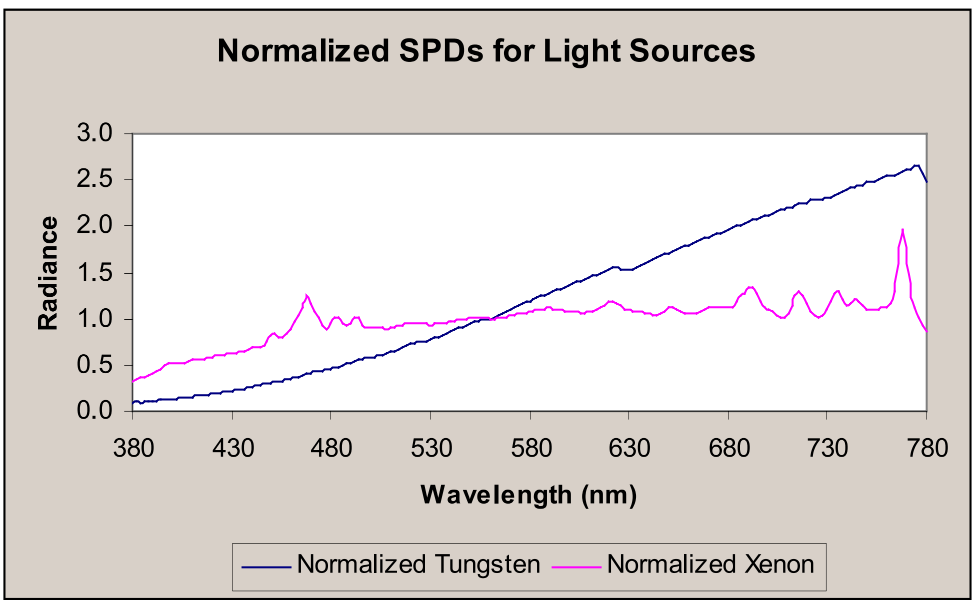

Figure 15. Normalized spectral radiance of xenon and tungsten light sources used in this experiment.

An Optronics Laboratories, Inc. single grating monochromator model 40A with 2.5 mm entrance and exit slits and a 10 nm bandpass was controlled by a model 740-1C controller of the same brand and software written by L. Taplin. The light was focused onto halon pressed to 1 g/cm^3.

The spectral sensitivities, as measured here, are a combination of the camera, the 50 mm lens, and an infrared cut-off filter. While the entire CCD was imaged, the image of the halon covered the center of the CCD, and approximately 30 pixels square within this area were used for the statistics (statistics software written by F. Imai in MatLab). The exact coordinates used were 1575, 870 (top left) - 1605, 900 (bottom right).

The images were taken at every 10 nanometers with a gain of 2 for a constant exposure time of 1400 milliseconds for the xenon lamp and 13000 milliseconds for the tungsten lamp. The lens was set to f/11 and f/5.6, respectively. At the same time, radiance measurements were taken at every 10 nanometers. Figure 16 shows the experimental set-up for this part of the experiment (including the xenon light source). A desktop computer held the software (written in Basic by L. Taplin) to control the monochromator and a field computer controlled the Quantix camera using V++ version 4.0 on a Windows 2000 platform.

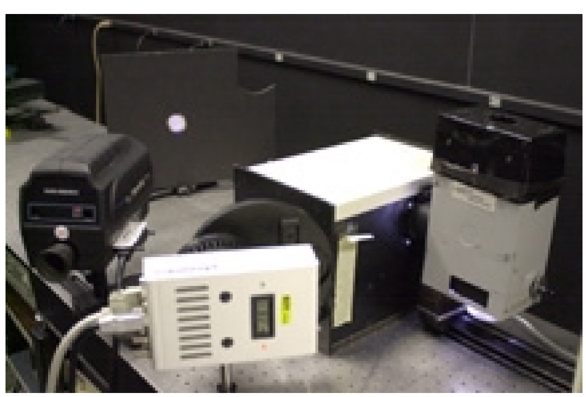

Figure 16. Spectral sensitivity experimental set-up.

Once all the images were obtained, statistics were calculated, including mean, maximum, minimum, and standard deviation for the image's digital counts. Figure 17 shows the mean digital counts for the entire set of images for both light sources.

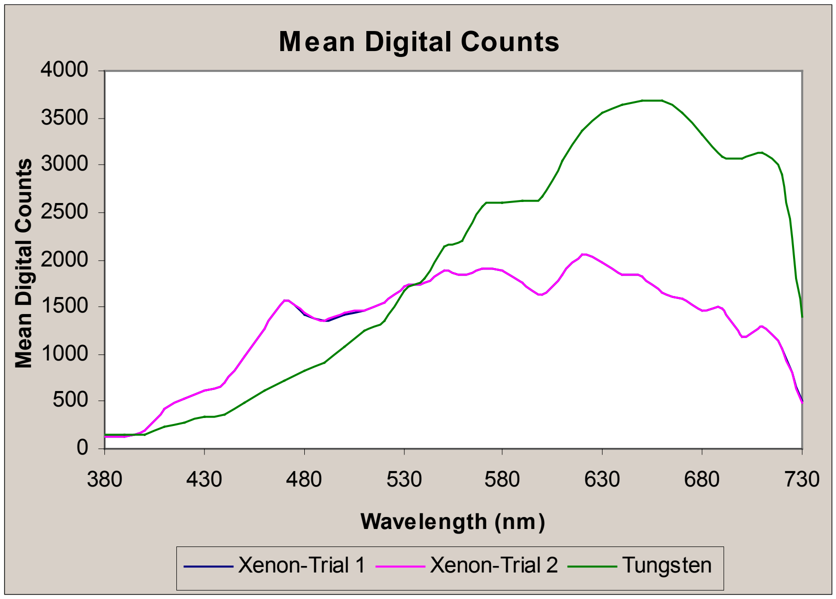

Figure 17. Mean digital count of images at each wavelength.

Next, the spectral sensitivity of the system was calculated by dividing the mean (with the dark current subtracted) by the radiance. These values were normalized and are shown in figure 18. Figure 19 shows the same data along with Roper Scientific/Kodak's results (same data) for the quantum efficiency of the 6303E CCD. This is shown by the black data set in the plot.

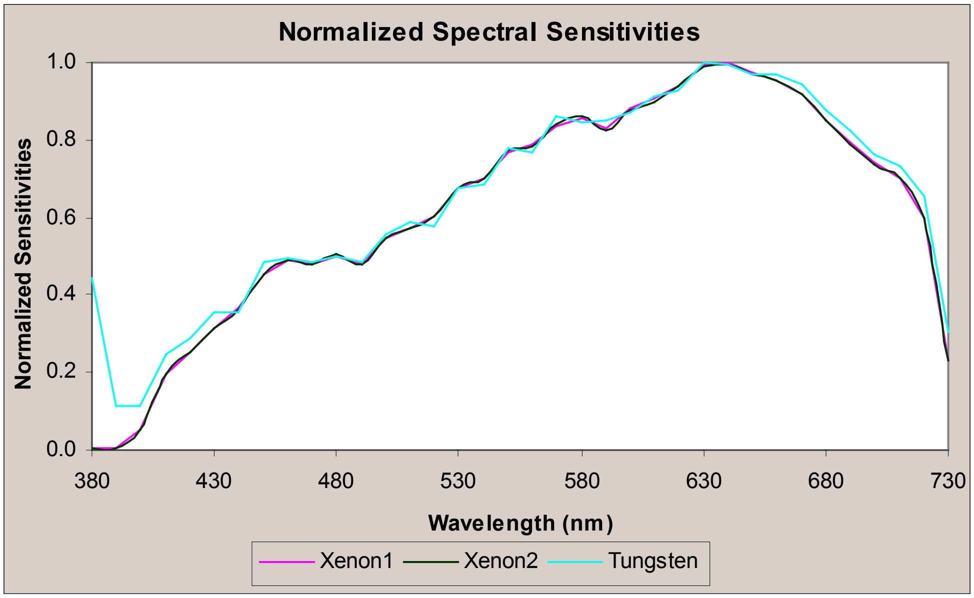

Figure 18. Normalized spectral sensitivities.

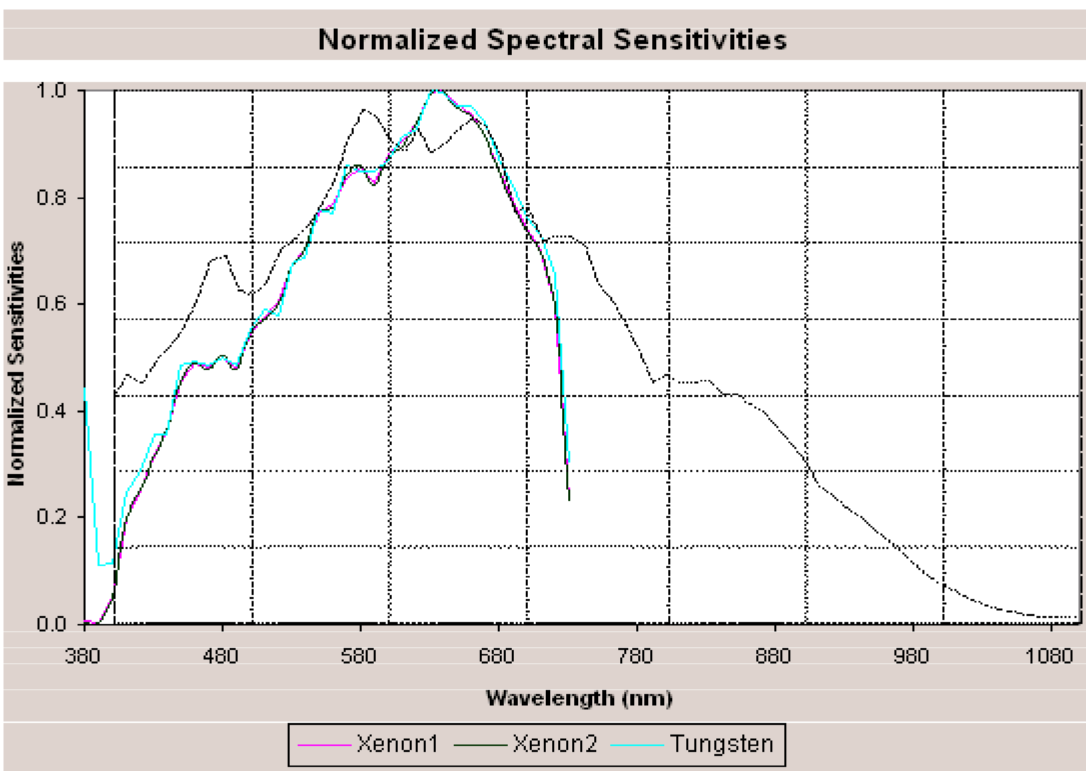

Figure 19. Normalized spectral sensitivities, with Roper/Kodak quantum efficiency (black line).

The data sets are very similar. Unfortunately, there are some small differences between the xenon and tungsten measurements. The discrepancy in the tungsten measurement could be a result of the extremely low blue content in its spectral power distribution. This could have resulted in measurements with a large amount of noise in the shorter wavelengths. This shows that spectral sensitivities measured with a tungsten light source may be unreliable, and that the xenon might be a better choice for such measurements. Therefore, the xenon sensitivities were assumed to be more approximately correct and were averaged. The averaged spectral sensitivities are shown in figure 20. The spectral data are tabulated in Table VII. In the future, these data will be used for all simulations involving this camera/CCD combination.

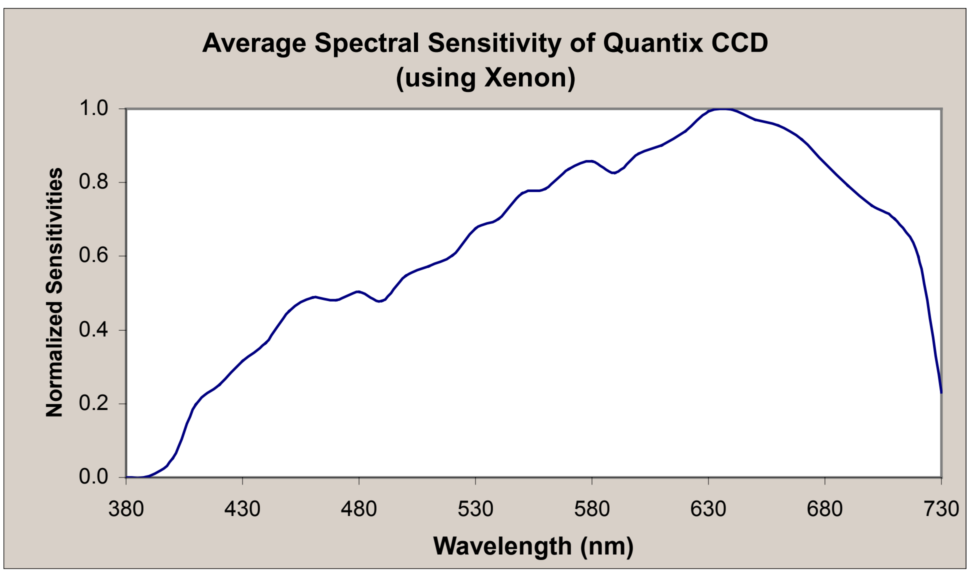

Figure 20. Normalized average spectral sensitivities.

Table VII. Average spectral sensitivities of Quantix camera with 50mm lens and Unaxis Balzor broadband near IR reduction filter (model UBO-11RE) using a Xenon light source.

Wavelength (nm)	Spectral Sensitivities	Wavelength (nm)	Spectral Sensitivities
380	0.00	560	0.29
390	0.19	570	0.29
400	0.14	580	0.29
410	0.12	590	0.29
420	0.10	600	0.30
430	0.09	610	0.32
440	0.08	620	0.34
450	0.08	630	0.36
460	0.07	640	0.37
470	0.07	650	0.37
480	0.08	660	0.37
490	0.11	670	0.37
500	0.14	680	0.38
510	0.17	690	0.40
520	0.20	700	0.44
530	0.22	710	0.46
540	0.25	720	0.47
550	0.28	730	0.47

Conclusions

Experiments were performed to verify and quantify the performance of a KAF6303E CCD in a Quantix monochromatic camera. Latency seemed to be only a negligible problem, and therefore, did not need to be accounted for in subsequent experiments. The difference between the calculated gain values and the gain values given on the Certificate of Performance were very small. However, the noise differences are quite large. This will be a problem only if noise variance is used in calculations, for example, using Weiner estimation when reconstructing multispectral images. In addition, the dark current noise was nearly zero in our experiments, compared to the more realistic result shown on the Certificate of Performance, 0.051. The large discrepancy in results can probably be attributed to a difference in camera settings when the experiment was performed. Finally, the camera spectral sensitivity was reasonably close to the nominal data supplied by Kodak.

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