Performance Analysis of Color and Black & White Cameras

Joyoni Dey † Noah Salzman ‡ Steven Shafer ‡‡

dey+@cs.cmu.edu noah@sccs.swarthmore.edu stevensh@microsoft.com

CMU-RI-TR-97-07

The Robotics Institute
Carnegie Mellon University
Pittsburgh, PA 15213

February 18, 1997

† Department of ECE,
Carnegie Mellon University

‡ Department of Engineering,
Swarthmore College

‡‡ Microsoft Corporation,
Seattle, Washington

Contents

List of Figures

Abstract

In this report, we evaluate various cameras on a no. of criteria such as Range, Noise, Linearity, Blooming. This has been done on nine cameras obtained from different groups of the VASC. The digitizer used was the matrox in the Calibrated Imaging Laboratory (CIL). Then we apply the noise criterion fully for seven cameras in the CIL and on all the digitizers in the CIL. The digitizers are a Matrox digitizer, a RasterOps digitizer on a Sun workstation and standard Apple digitizer on a Power Macintosh. All the experiments reported here were done in the CIL.

These are end-to-end evaluations based on acquired images of standardized targets, rather than attempts to measure theoretical parameters of the system.

Chapter 1

Investigation of Range, Noise, Linearity, Blooming

1.1 Purpose

In this report we evaluate different cameras based on the camera noise, linearity, range, blooming.

1.2 Cameras and their Outputs

1.2.1 Cameras Used

The following cameras were used to test the camera noise, linearity, range, blooming and step response. More detailed noise analysis was actually done on a different set of cameras for all the digitizers and the results and discussion are given in the next chapter.

- Sony, 3CCD Color Video Camera. Model: DXC-960MD. For short called 3ccd1 here.
- Sony, 3CCD Color Video Camera. Model: DXC-3000. For short called 3ccd2 here.
- Sony, 3CCD Color Video Camera. Model: DXC-930. For short called 3ccd3 here.

- Sony, CCD video camera, no. 20288. Model XC-75. For short called ccd1 here.
- Sony, CCD video camera, no. 13137. Model XC-75. For short called ccd2 here.
- Sony, CCD video camera, no. 25211. Model XC-75. For short called ccd3 here.
- Sony, CCD video camera, no. 51188. Model AVC-D1. For short called ccd4 here.
- Sony, Video Camera Recorder, video Hi8. Model EVO-9100. For short called camcrd1 here.
- Panasonic, VHS movie camera. Model AG-180. For short called camcrd2 here.

1.2.2 Camera Outputs

There were three main kinds of cameras - the 3CCD cameras which had RGB, NTSC outputs and sometimes SVHS output ; the CCD black and white cameras ; the camcorders with NTSC and SVHS. The panasonic camcorder (called camcrd2 here) had only NTSC output. A brief description of the output follows.

- RGB output : three lines and a sync. Call this output A.
- S-VHS output : A single cable has 4 pins : Y (Luminance) and C (Chrominance) and their respective grounds. Call this output B.
- NTSC video output : single line has intensity (Y) as well as color information (I and Q). This may be a RS-170 (call this output C) or RCA jack (call this output D).

1.2.3 Digitizers

The output of the cameras are made input to the digitizer. The digitizer used was the Matrox in Calibrated Imaging Lab in CMU. It can take inputs A, B,

D. A note on digitizing B and D on the Matrox : One can only digitize the Y components of B and D on the Matrox. If one wants to digitize whole color input for NTSC or SVHS, one needs YIQ (or Y and C) to RGB converter. However there are three monochrome input channels for the Matrox, so for the RGB signal (input A), one can insert the three monochrome bands, red, green and blue into the Matrox and digitize them simultenously to get three color bands images. For some of the experiments (such as the repeititive noise) the simultaniety is important to make sure that the three R, G, B images belong to the same frame.

1.3 Experiments and Results

In the following sections the various criteria are described one at a time and their importance discussed. The conditions under which the experiments are done are described. Then the results for the various cameras are given. The results for the color cameras, black and white cameras and the camcorders are grouped separately so that it is easy to rank the cameras at a glance.

1.3.1 Range

Description of criterion and experimental setup

This is the camera's output dynamic range. The lower value of the range is is the minimum intensity of the image the camera can handle and the upper value of the range is the highest value of intensity it can handle before it saturates.

This is an important criterion when dealing with images with very dark and very bright regions. One wants to choose a camera that has big enough range so that it can handle the bright regions without saturating as well as give enough details on the dark regions. For example suppose you want to take a picture of a birthday party with the cake brightly lit while the lights are off - the ideal camera would be the one that gets the cake as well as some details of the the people around in the dark.

We first disable automatic gain control. To measure the lower bound of the lens, we simply put off all lights off and put the lens cap on to ensure that no light enters the camera. For the upper bound, the CMU colorchart (designed by Carol Novak) is used (see Figure 1.1). The colorchart has

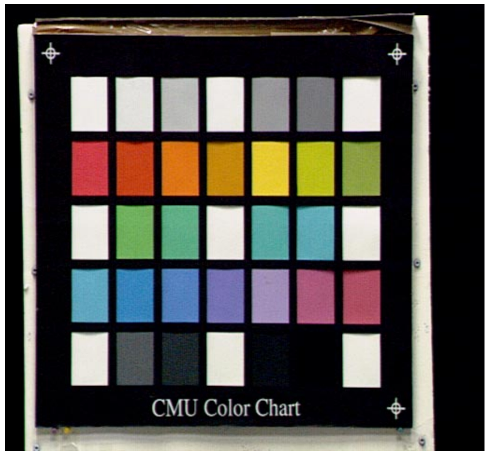


Figure 1.1: CMU Colorchart

blocks made of color papers of known reflectances. Of these blocks, 9 blocks are white and there are blocks of different shades of gray linearly varying from black to white. In this experiment, the 9 white blocks of the colorchart are considered just before the camera saturates. It is important to detect when the saturation occurs. With each click of the aperture, the brightness should increase until the camera saturates - when the camera saturates, there is a sudden jump in brightness, after which the brightness increases no more. Then we go back two clicks of the aperture. The maximum value of the white blocks obtained under such conditions is considered the upper value of the dynamic range. For a color camera, the three bands are considered separately to get the range of each.

Range for different cameras

In the following three tables, the ranges of the different sets of camera is shown.

3CCD-Color-Camera Range				
camera	*red*	*green*	*blue*	*ntsc*
3ccd1	254-0	255-0	241-1	244-13
3ccd2	255-0	254-0	255-0	255-0
3ccd3	255-0	243-0	254-0	233-9

CCD B & W Camera Range	
camera	*intensity*
ccd1	252-0
ccd2	246-0
ccd3	248-0
ccd4	226-0

Range for Camcorders		
camera	*ntsc*	*svhs*
camcrd1	249-0	255-0
camcrd2	252-0	X

1.3.2 Repetition Noise

Description of criterion and experimental setup

In this section a noise analysis is done on the video cameras. The target is the color chart. We look at a single pixel in the image and measure the intensity variance and mean over time. This is repeated for different regions in the image with different intensities. The operating regions of the cameras are near the upperbound of the dynamic range.

In this experiment for each camera, we measure the intensity variance and mean over time for a single pixel. This is done near the upperbound of the dynamic range (for the white tiles). The colorchart is used as the target. The midpoint of the white and the gray tiles are considered as shown by the dots in the image in Figure 1.2.

The mean and standard deviation over 100 frames is calculated (for each band for color image) and this is repeated 10 times. Then the average signal to noise ratio (mean over standard deviation) value over the 10 runs is reported. The darker blocks seem to have progressively lower SNR. Plots of how the SNR value falls off as the reflectance drops (that is with darker and darker blocks) is also shown for the different cameras. This is an expected result becuase the noise stays roughly the same while the signal power drops for darker blocks. Note that for this experiment one does not have to correct for non-uniform illumination across these gray blocks because we are considering the SNR which is a *ratio* of mean and std and should be free of the

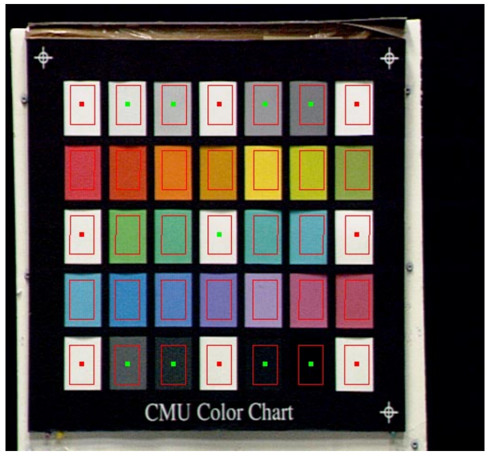


Figure 1.2: **Noise:** The points in the middle of the white and gray blocks of the Colorchart are considered

illumination non-uniformity.

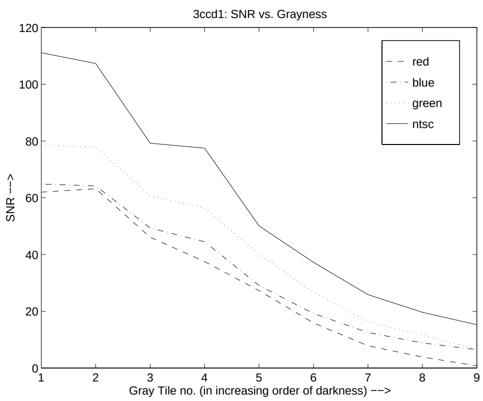
Signal to Noise ratio for different cameras

In the following three tables, the SNR for the white tiles, averaged over the nine white tiles are shown for the cameras. Note that this experiment was done in near the upperbound of the dynamic range for each camera. The SNR can vary in the other parts of the dynamic range for the same camera. In Figures 1.3 to 1.5 it is shown how the SNR varies with the grayness.

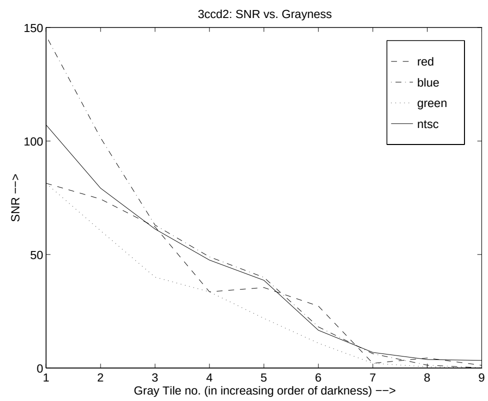
3CCD-Color-Camera SNR				
camera	*red*	*green*	*blue*	*ntsc*
3ccd1	63.2896	78.3259	62.9154	113.2379
3ccd2	79.5341	141.3502	71.9945	107.5080
3ccd3	211.7186	187.4434	192.8031-0	221.1782

CCD B & W Camera SNR	
camera	*SNR*
ccd1	110.2735
ccd2	223.0796
ccd3	154.1673
ccd4	226.3587

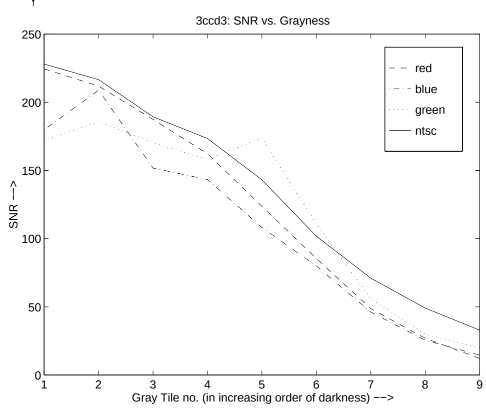
SNR for Camcorders		
camera	*ntsc*	*svhs*
camcrd1	78.2391	186.6519
camcrd2	69.9383	X



3ccd1 †



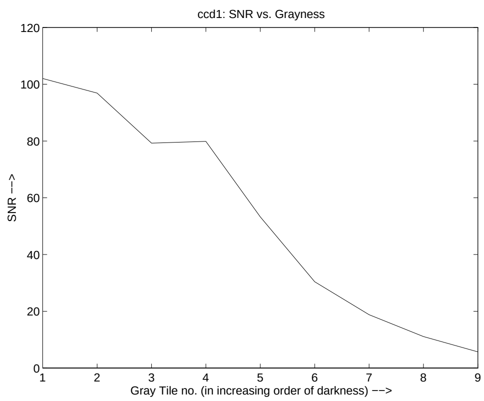
3ccd2 ‡



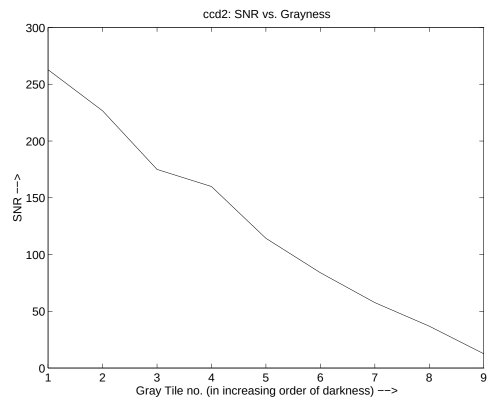
3ccd3††

Figure 1.3: **Noise:** SNR vs Grayness for the 3CCD cameras

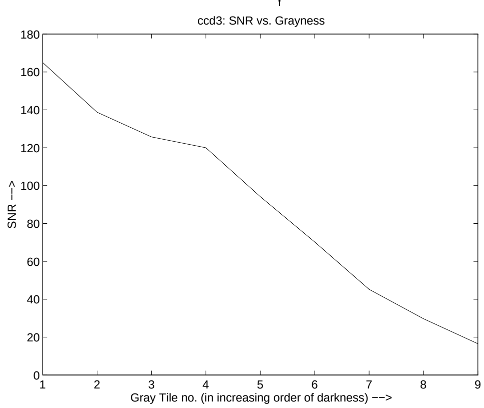
		Pixel Mean								
	Tile − >	1	2	3	4	5	6	7	8	9
3ccd1†	red	208.7630	202.0260	150.3760	112.7430	78.7300	38.2790	17.9770	7.9600	1.0450
	green	215.0300	203.2390	151.7390	116.0820	82.6810	48.2560	27.9400	16.9560	8.6940
	blue	205.5210	202.5100	154.7850	117.8230	85.6850	49.3920	30.5630	19.9450	12.5810
3ccd2‡	red	233.4260	223.4440	186.5820	153.5870	119.4170	81.1420	23.4130	3.0410	0.0030
	green	233.2980	225.3190	185.8620	148.5790	119.3340	82.5340	40.5850	6.5510	0.0110
	blue	225.0600	219.5470	185.1800	149.1050	122.6050	86.3260	48.3590	9.0410	1.6410
3ccd3††	red	234.3600	223.1200	188.4800	164.6500	133.1100	89.2200	59.6000	37.3400	18.1600
	green	218.8700	207.4200	174.4900	152.1200	122.6800	87.1700	59.0400	37.7800	22.2800
	blue	229.4700	220.3200	186.5400	163.5700	131.3800	92.2600	62.2800	39.7700	22.8800



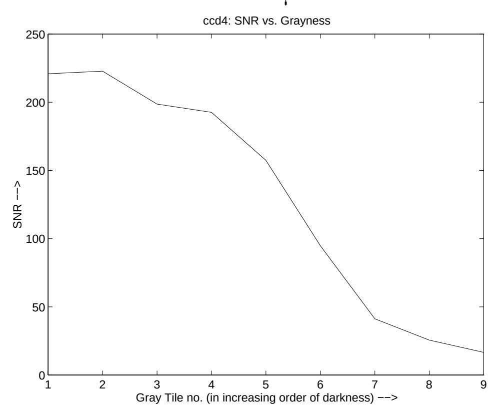
ccd1 †



ccd2 ‡



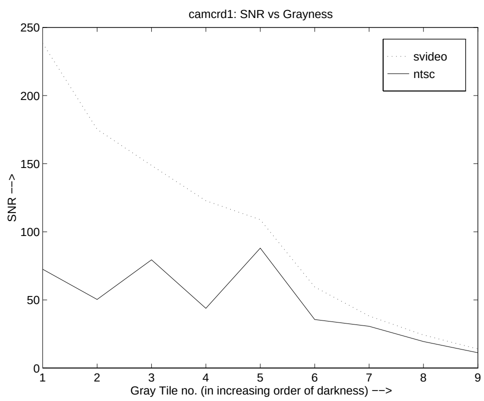
ccd3 ††



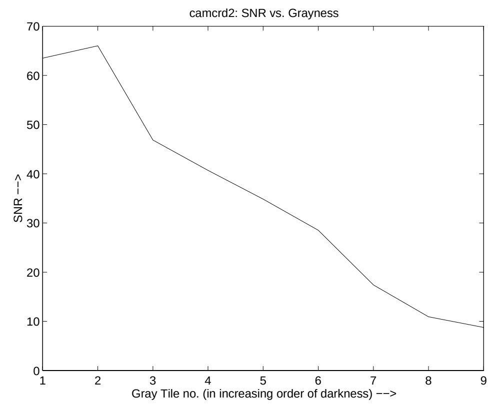
ccd4 ‡‡

Figure 1.4: **Noise:** SNR vs Grayness for the b/w CCD cameras

Pixel Mean									
Tile − >	1	2	3	4	5	6	7	8	9
ccd1 †	223.2670	203.5540	155.9220	122.2800	87.3910	46.5660	26.3660	15.1000	6.9830
ccd2 ‡	235.1810	232.0120	178.6010	121.3700	80.0570	52.9450	30.0440	15.0900	6.3950
ccd3 ††	231.8830	205.1100	158.4900	120.3380	83.0090	46.9200	27.6950	16.4110	7.7290
ccd4 ‡‡	212.4250	202.3770	176.3010	162.1190	139.3200	109.1800	77.6700	50.8250	32.0640



camcrd1†



camcrd2‡

Figure 1.5: **Noise:** SNR vs Grayness for the camcorders

		Pixel Mean								
	Tile − >	1	2	3	4	5	6	7	8	9
camcrd1 †	NTSC	218.5610	185.7270	166.2280	145.8720	114.4580	77.3660	54.3810	35.3300	19.2890
	Svideo	223.5830	193.3210	175.4250	152.8770	119.8180	83.2320	59.8460	39.7480	21.5760
camcrd2 ‡		212.0750	200.8980	167.3500	139.6050	106.9290	64.9580	42.3820	27.3850	16.9630

1.3.3 Linearity

Description of criterion and experimental setup

Supposing we have different shades of gray with reflectances varying linearly from black to white, then, under uniform lighting, the camera output response should also increase linearly from black to white. But for some cameras (mostly old cameras) the response is non-linear.

This criterion is useful when choosing a camera because if the camera has a non-linear response, the intensity value of the camera output is not a straightforward indication of the object's reflectance. For example, for a non-linear camera, an object of same color but twice as bright as another object will not look twice as bright in the camera output even under same lighting.

For this test we use the CMU colorchart designed by Carol Novak. We followed Carol's method of doing the linearity test. There are 9 blocks of gray and 9 blocks of white tiles (with 1 block in common between the two) in the colorchart (see Figure 1.1 for a typical image). Based on the mean of the white blocks, a correction for non-uniform illumination is done. Then the graymeans of the corrected image is plotted against their reflectances (which are known beforehand). For this experiment the aperture settings etc is set such that the camera is operating near the saturated end of its dynamic range. For this linearity test, the image used is the same to find the upper side of the range as described in the range item.

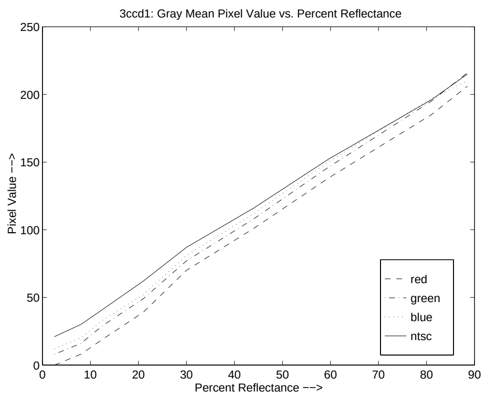
Linearity test results summary

See plots in Figures 1.6 to 1.8 for how the actual responses look. But for a quick summary of which camera is linear or not, here is a table.

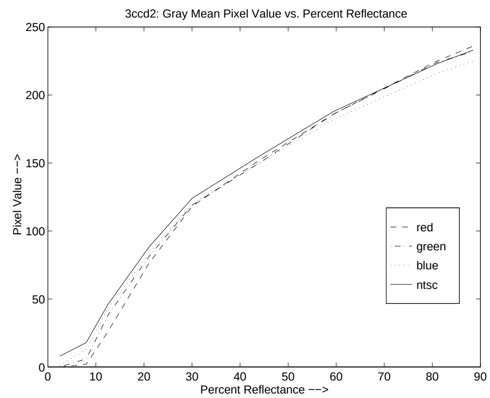
Linearity test results	
camera	*linearity*
3ccd1	Linear
3ccd2	Not Linear
3ccd3	Not Linear
ccd1	Linear
ccd2	Linear
ccd3	Linear
ccd4	Not Linear
camcrd1	Not Linear
camcrd2	Not Linear (?)

For the last camera, camcrd2, it seems from Figure 1.8 that the camera could be piecewise linear.

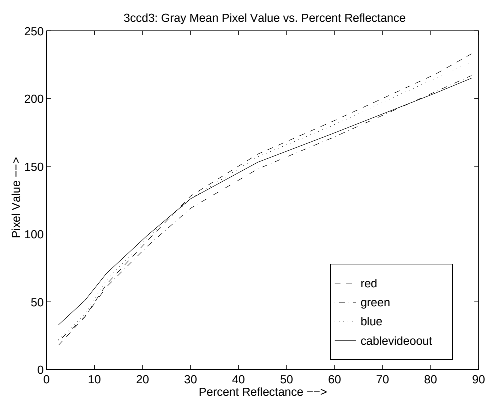
Plots to show Pixel Value vs. Reflectance (Grayness) for the different cameras



3ccd1



3ccd2



3ccd3

Figure 1.6: **Test for Linearity:**Pixel Value vs Grayness for the 3CCD cameras

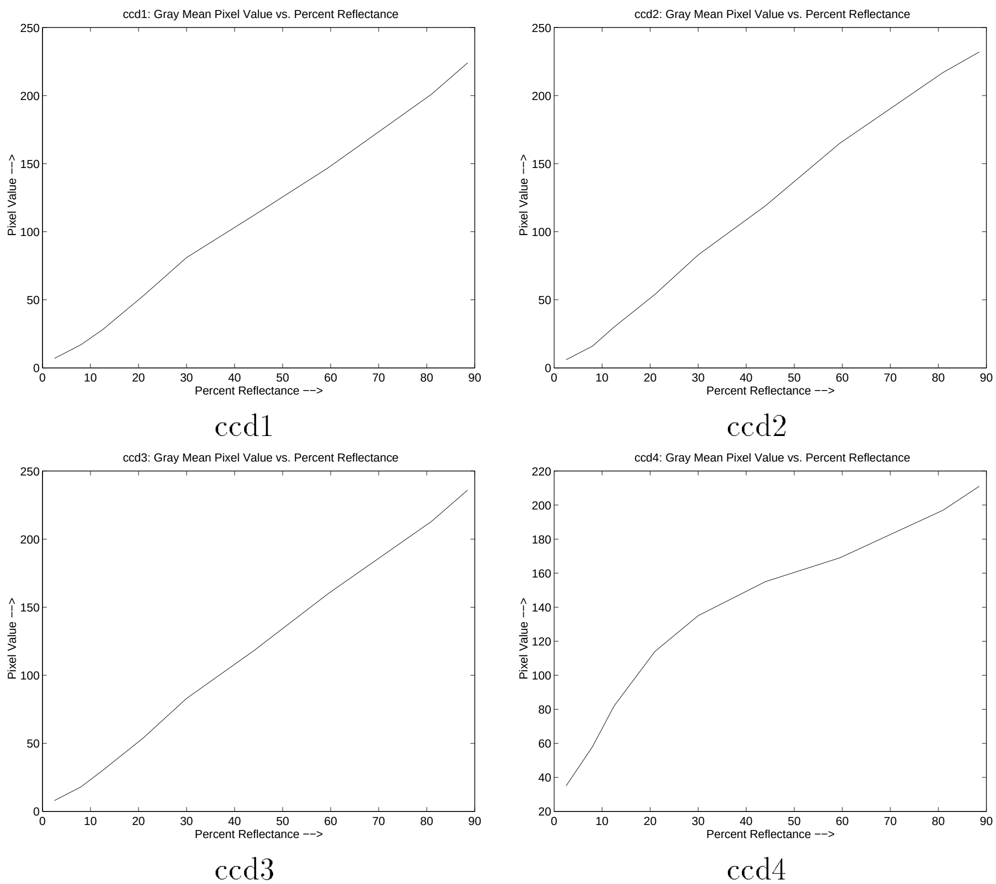
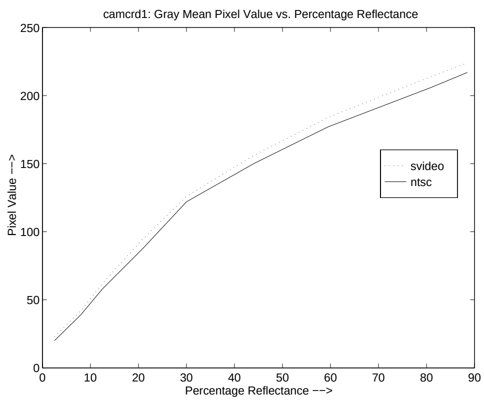
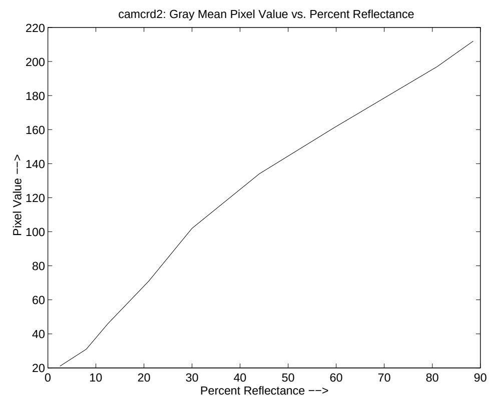


Figure 1.7: **Test for Linearity:** Pixel value vs Grayness for the b/w CCD cameras



camcrd1



camcrd2

Figure 1.8: **Test for Linearity:** Pixel Value vs Grayness for the camcorders

1.3.4 Blooming

Description of criterion and experimental setup

When the pixel value at one point is saturated the charge in one well on the CCD chip may spread tothe neighboring charge wells affecting the measured values at those pixels.

This is an important criterion to know when one is dealing with images with highlights or shiny bright regions - for example, images of metallic objects or shiny plastics. Some cameras would saturate at the highlighted region and then bloom over and the surrounding region will be affected.

In our measurements we took a bright white object in a black background and see how many pixels are affected in the black area and used that as a measure of blooming. The white region should be saturated in one or more bands.

Results

This experiment is not complete - results are available for only a subset of the cameras and for a subset of outputs. These cameras are 3ccd1, 3ccd2 (rgb), 3ccd3 (ntsc and svhs), ccd1, ccd2, ccd3. Some of these cameras *did* show blooming. These were ccd2 and ccd3. 3ccd3 showed blooming in its ntsc output, and a lesser degree of blooming in its cable output (svhs). 3ccd1 and ccd1 didnot show blooming. 3ccd2 did not show blooming in its RGB output. For 3ccd2, the NTSC output was not saturated so one cannot conclude that it doesnt bloom. Here is a table summing up what we have. Next we show the images (camera outputs for high aperture settings) on which these conclusions have been drawn.

Blooming test results	
camera	*blooming*
3ccd1	No Blooming
3ccd2	No Blooming (rgb)
3ccd3	Blooming (ntsc, svhs)
ccd1	No Blooming
ccd2	Blooming
ccd3	Blooming

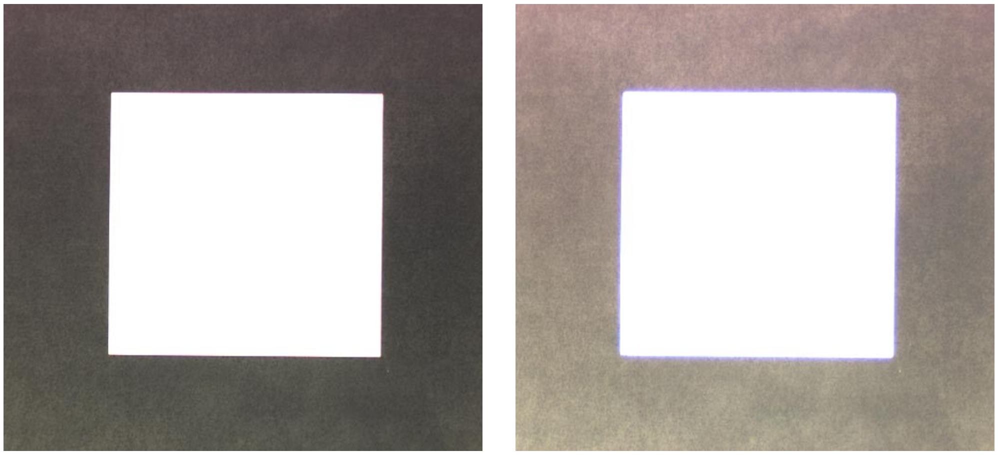
In Figure 1.9, the RGB output of 3ccd1 is shown for two successive aperture settings. The first setting is high enough that most of the white pixels are saturated. The next setting is even higher but there is no spill-over of the white object onto the darker background, even though the darker background is as a whole lighter due to more light coming from it. This last property of the change in appearance in the black background with the amount of light allowed from it is investigated in the next subsection, where we consider the value of a single pixel in the dark region versus aperture opening for the three 3CCD cameras.

In Figure 1.10, a similar result is seen for 3ccd2. The interpretation is subjective but because the boundary between the white block and the background remains sharp and well-defined there doesnt seem to be any spill-over from the white region.

In Figure 1.11, the outputs of 3ccd3 for NTSC and SVHS are shown for aperture settings high enough that the white pixels in the block are saturated. The NTSC output blooms significantly, while the SVHS does to a lesser extent.

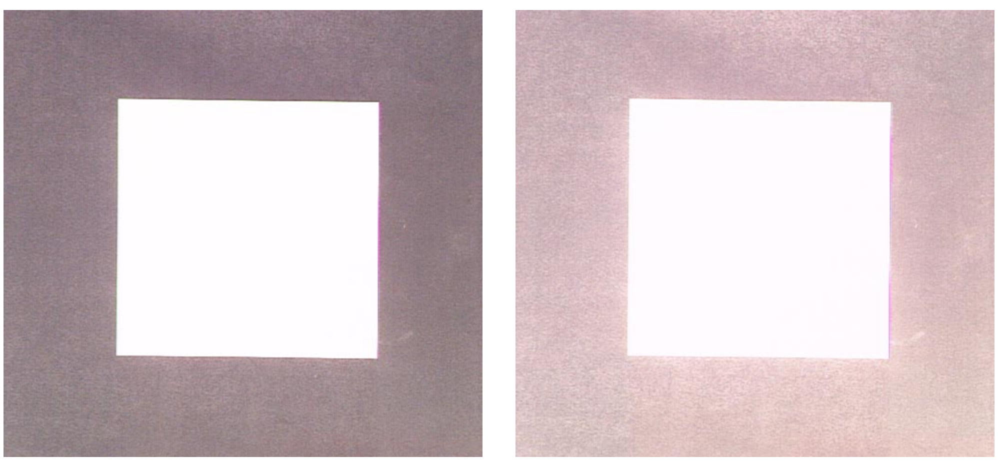
Figure 1.12, shows the blooming test for ccd1.

Figure 1.13, shows that ccd2 and ccd3 does bloom.



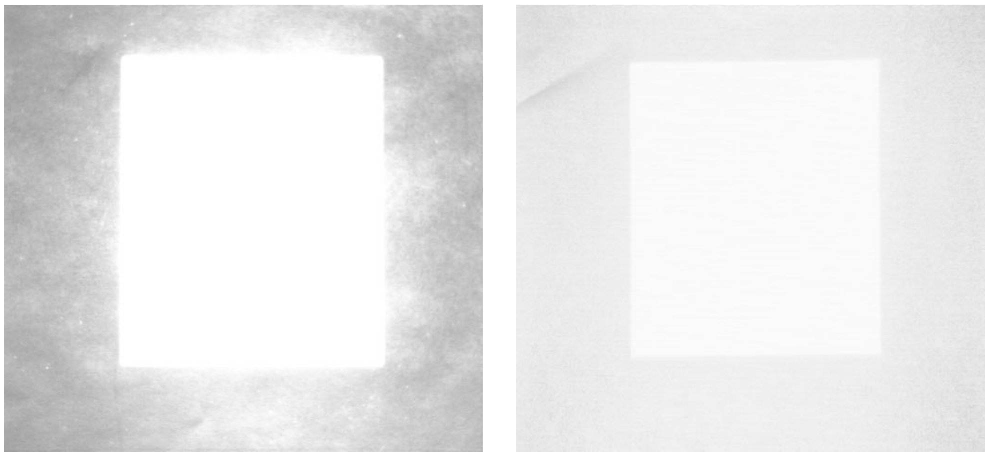
aperture 4 aperture 2.8

Figure 1.9: **Test for Blooming for RGB of 3ccd1**



aperture 8 aperture 5.6

Figure 1.10: **Test for Blooming for RGB of 3ccd2**



NTSC o/p   Cable o/p

Figure 1.11: **Test for Blooming for 3ccd3**

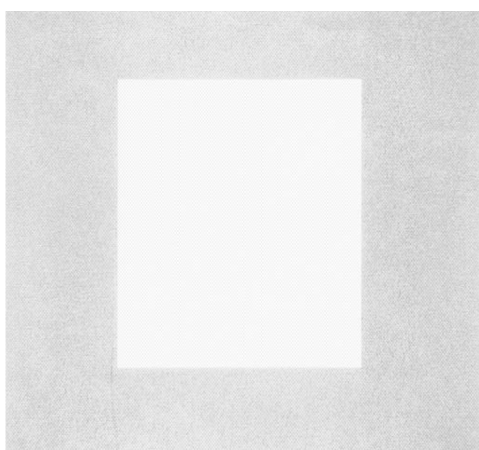
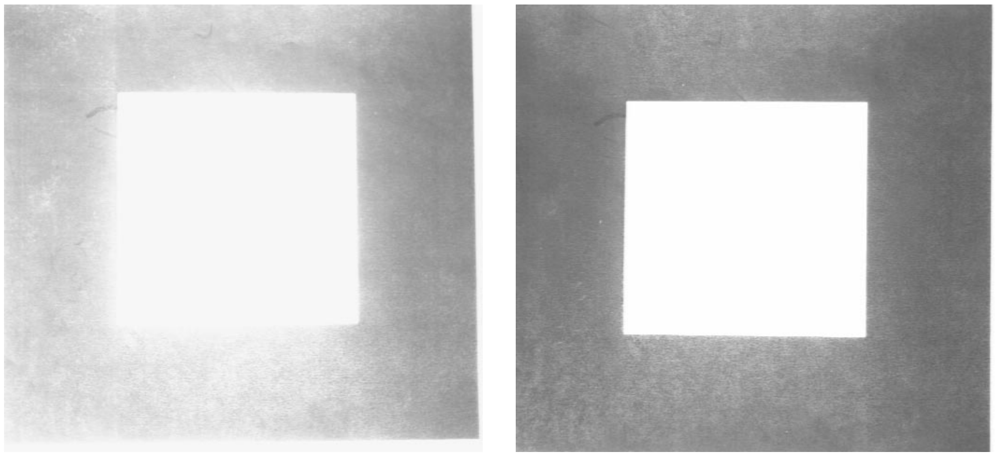


Figure 1.12: **Test for Blooming for ccd1**



ccd2 **ccd3**

Figure 1.13: **Test for Blooming for ccd2 and ccd3**

Varying incident light on a pixel

As mentioned and shown before, for the blooming test, the target is a white rectangle in a black background. As the aperture is increased, the white pixels go slowly towards saturation until they reach 255. The black region gets whiter as a whole (even if there is no blooming). This is expected because every click of the aperture doubles the amount of light entering the camera.

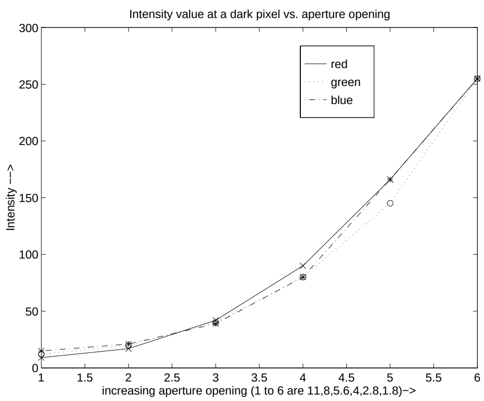
For RGB output of the three cameras 3ccd1, 3ccd2, 3ccd3, a test is done on the data obtained from the blooming test. For a pixel in the black region, the intensity values are checked for different aperture settings. The tabulated results for 3ccd1, 3ccd2, 3ccd3 are given in the next page.

In Figure 1.14, these values are plotted as a function of aperture-opening and we see that a sort of parabolic curve results for 3ccd1 and 3ccd3 while a linear curve is seen for 3ccd2 (except for 2 readings in the red band).

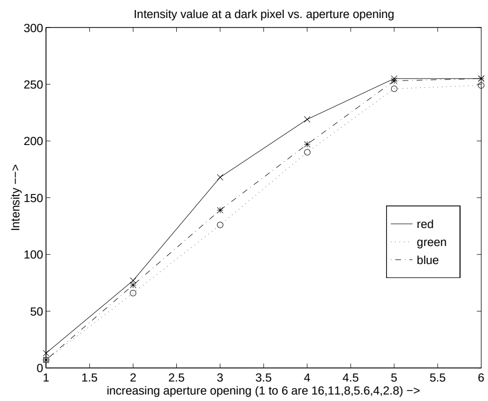
3ccd1 : Intensity at $(110, 110)$			
aperture	*red*	*green*	*blue*
11	9	12	15
8	17	20	21
5.6	42	42	39
4	72	70	67
2.8	166	145	166
1.8	255	255	255

3ccd2 : Intensity at $(110, 110)$			
aperture	*red*	*green*	*blue*
16	13	7	7
11	77	66	73
8	168	126	139
5.6	219	190	197
4	255	246	253
2.8	255	249	255

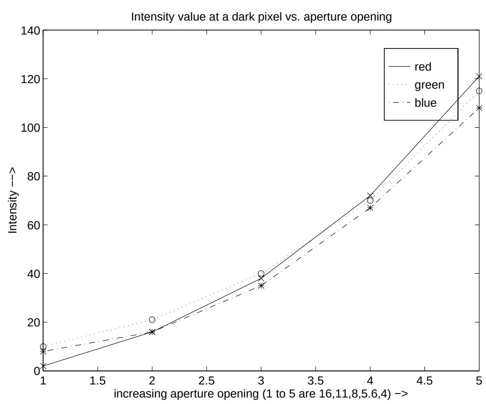
3ccd3 : Intensity at $(110, 110)$			
aperture	*red*	*green*	*blue*
16	2	10	8
11	16	21	16
8	38	40	35
5.6	72	70	67
4	121	115	108



3ccd1



3ccd2



3ccd3

Figure 1.14: Intensity vs aperture setting at a single (dark) location

Chapter 2

Noise Analysis for CIL cameras

2.1 Procedure

The digitizers and cameras used for this noise analysis are located in the Calibrated Imaging Laboratory.

The digitizers used are a Matrox digitizer on a Sparcstation with a resolution of 512x512 pixels, a RasterOps digitizer on a Sparcstation with a resolution of 640x480 pixels, and a Power Macintosh 8100/100 with a standard Apple digitizer set to 320x240 pixels.

The cameras used were two Sony 3CCD color cameras, models DXC930 and DXC3000; two Sony B&W cameras, models XC75 and AVCD1, a Toshiba B&W camera model ; a panasonic B&W camera, model ;and a Canon RC-360 color digital still video camera. The lenses used were the Cosmicar c-mount TV zoom lense on the Toshiba, Panasonic, and Sony XC75 cameras; a Sony mini bayonet mount lens on the Sony AVCD1 (the only lens which will fit this camera); and a Fujinon bayonet mount zoom lens on the two color cameras.

For each camera, the same scene was digitized ten times using each digitizer. Before digitizing, the camera was focused on the scene and the aperature was adjusted so an image with good contrast and dynamic range was obtained. The ten images were then digitized. The procedure for the Canon digital still camera was slightly different. The canon has composite and S-video output; it does not provide digital data. Because the camera converts the images it stores to an analog signal during playback, it introduces noise. This noise was analyzed by digitizing the same picture stored in the camera ten times. To analyze the picture, the same image was taken ten times, and stored as ten separate images which were then digitized.

To analyze the data, each image was converted to the TIFF format. Matlab was then used to add the images and divide the sum by ten to obtain an average image. This average image was then used to find a standard deviation for each pixel in the average image. An average error was found for each intensity in the image, and each intensity was divided by the average error associated with it to obtain a signal to noise ratio. In order to rule out unreallistically small errors caused by CCD saturation(blooming) data for intensities greater than 250 was discarded.

2.2 Results

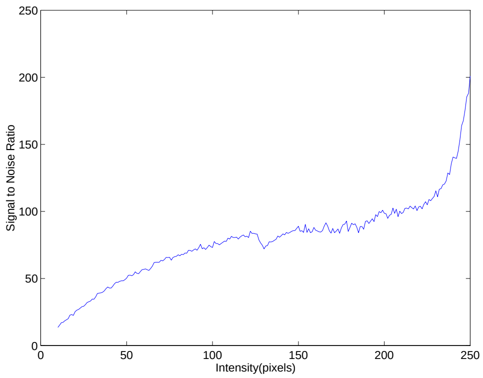
Figures 2.1-2.7 show the results for the different cameras.

2.3 Discussion

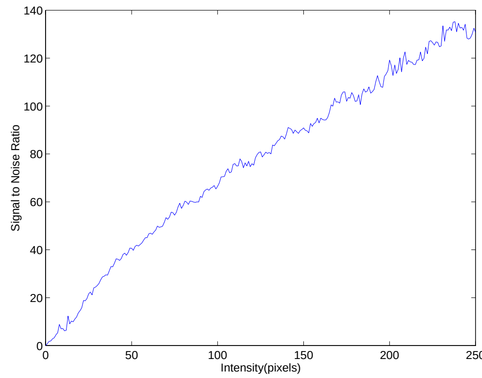
Among the color cameras, the DXC3000 is better than the DXC930, although the DXC3000 works better with the matrox and the DXC930 works better with the sun. The Macintosh digitizer should not be used for color images because it is a 16 bit digitizer, so it only has 5 bits of color information each for red,green, and blue instead of the normal 8 bits each which 24 bit digitizers are capable of.

For black and white cameras, the toshiba is the best camera of the bunch. The Sony AVCD1 produces good results in this experiment, but is a gamma corrected camera which makes it unsuitable for many imaging applications. The Sony XC75 performs slightly better than the Panasonic camera. When digitizing black & white images, the three digitizers perform approximately the same, although to produce images with low noise using the Macintosh digitizer the resolution must be set to 320x240 which is siginifcantly lower than the other two digitizers.

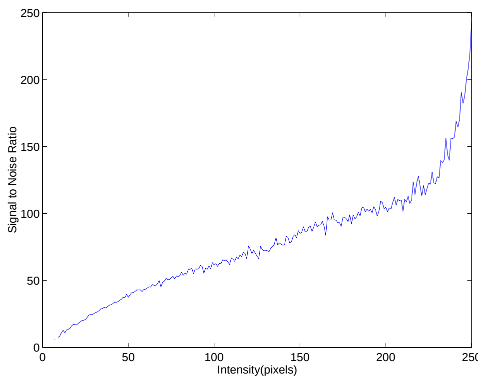
The Canon digital still camera produces a fairly noisy signal, which makes it unsuitable for most imaging requirements. It does produce usable pictures



on Matrox



on Sun



on Macintosh

Figure 2.1: **Noise Analysis:** SNR for Toshiba

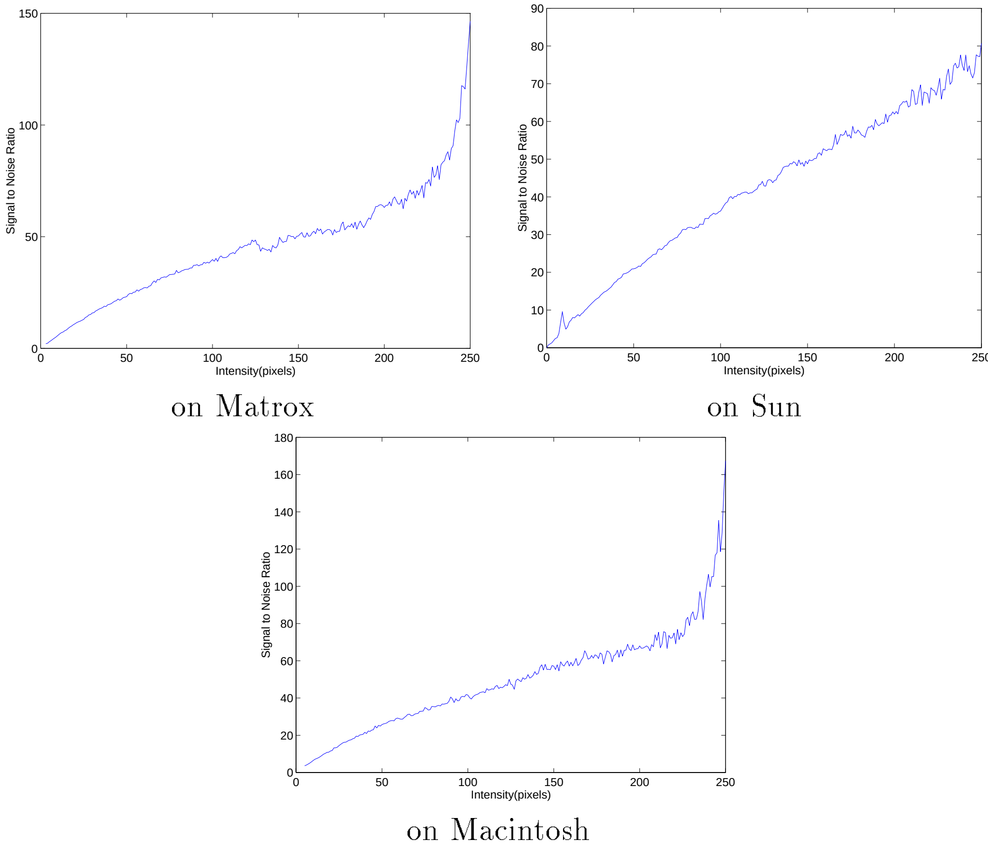
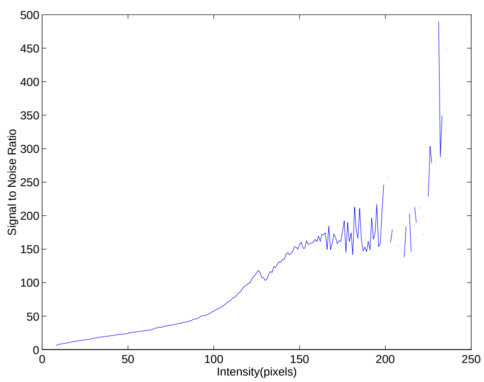
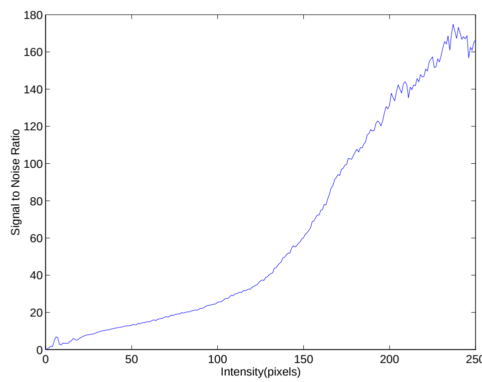


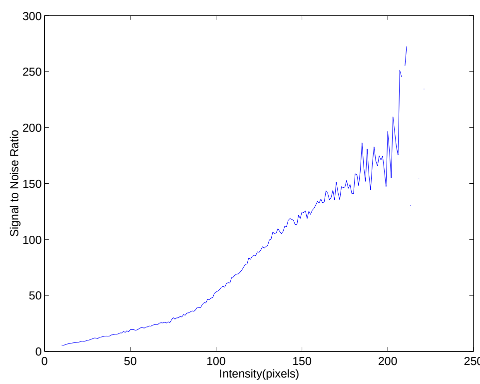
Figure 2.2: **Noise Analysis:** SNR for Sony XC-75



on Matrox

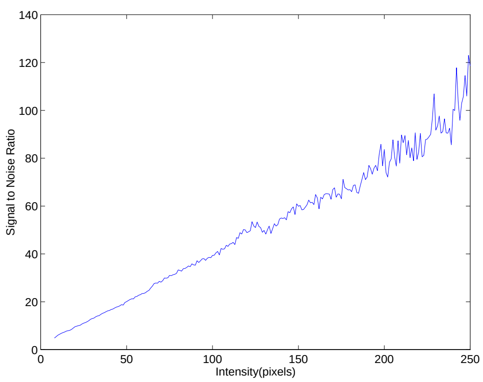


on Sun

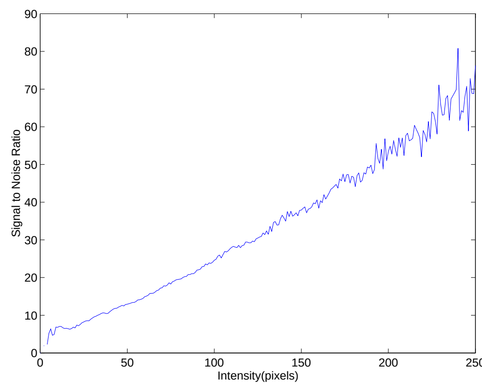


on Macintosh

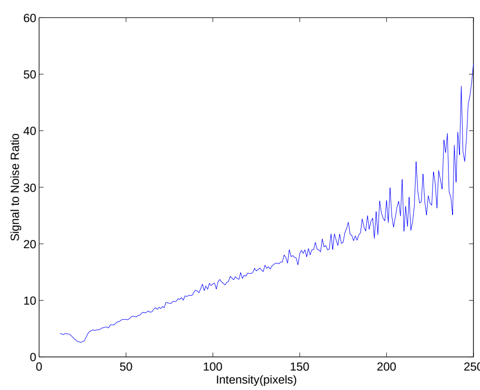
Figure 2.3: **Noise Analysis:** SNR for Sony AVCD1



on Matrox

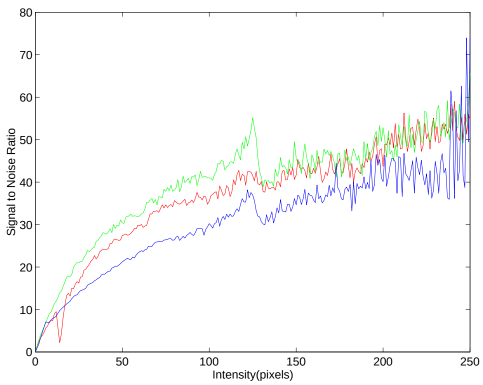


on Sun

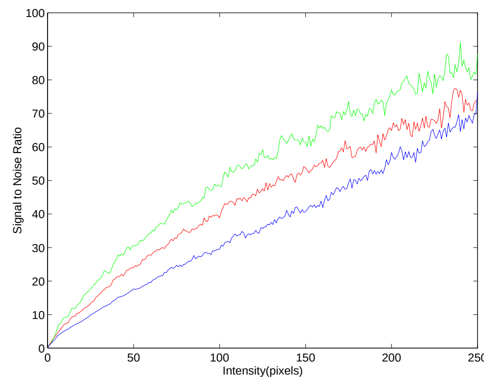


on Macintosh

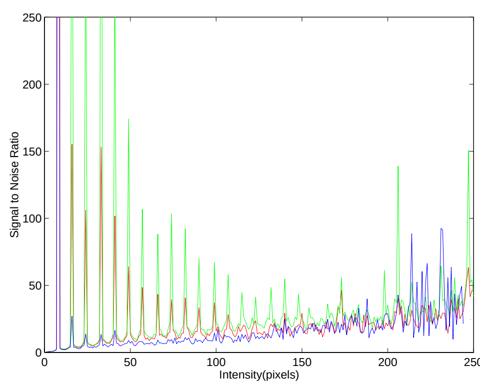
Figure 2.4: **Noise Analysis:** SNR for Panasonic GP-MF702



on Matrox

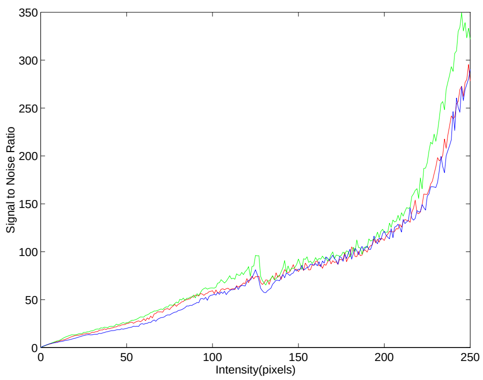


on Sun

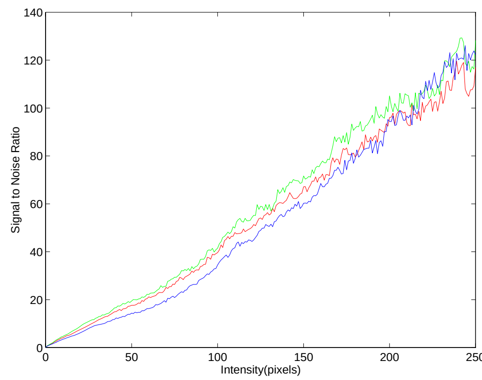


on Macintosh

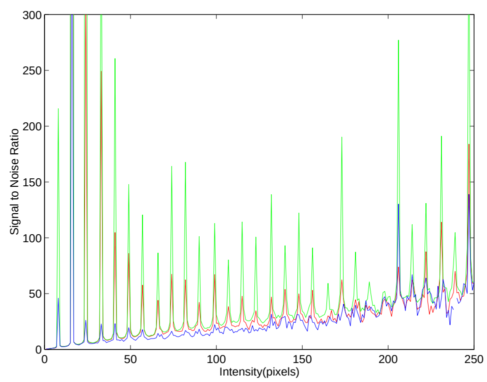
Figure 2.5: **Noise Analysis:** SNR for Sony DXC-930



on Matrox

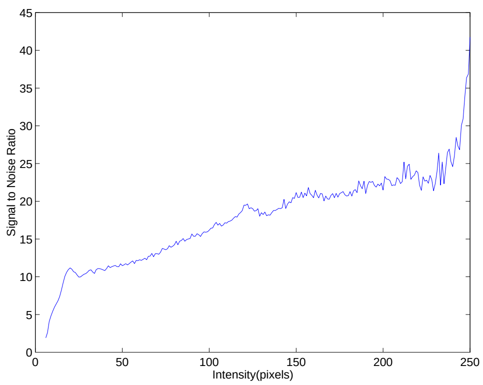


on Sun

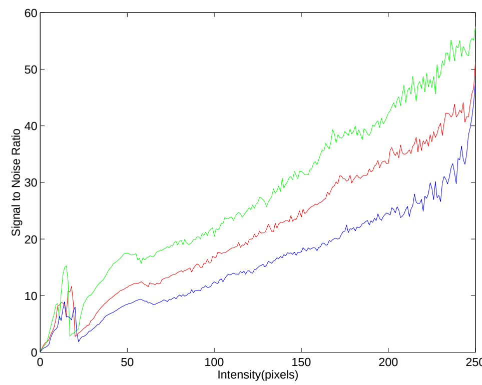


on Macintosh

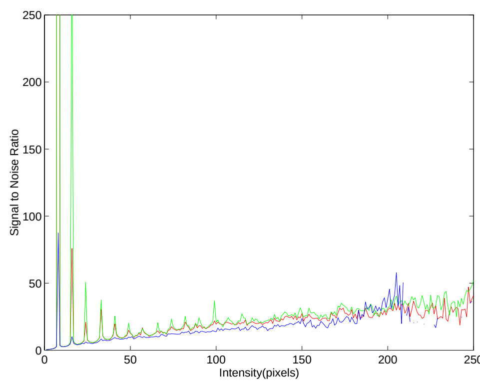
Figure 2.6: **Noise Analysis:** SNR for Sony DXC-3000



on Matrox

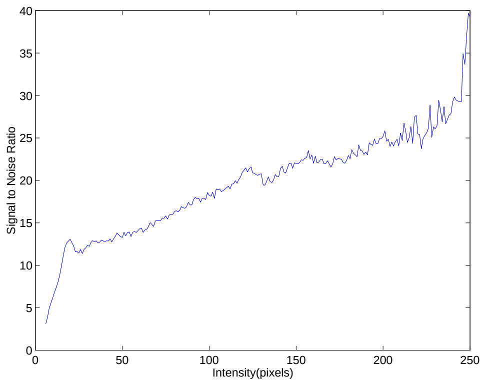


on Sun

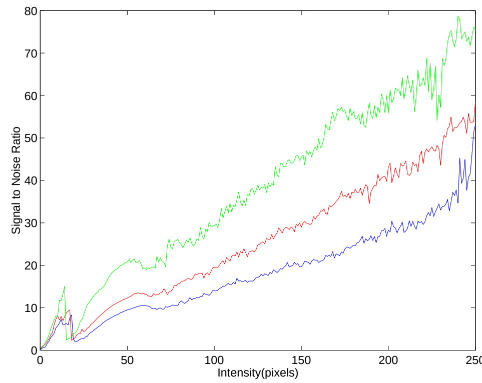


on Macintosh

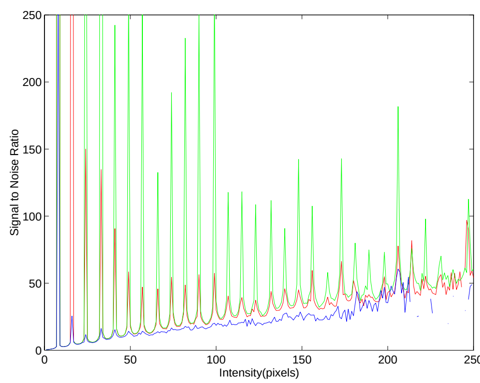
Figure 2.7: **Noise Analysis:** SNR for Canon, the average is over 10 different pictures



on Matrox



on Sun



on Macintosh

Figure 2.8: **Noise Analysis:** SNR for Canon, the average is over 10 digitizations of same picture

when adjusted right, and is useful for applications such as desktop publishing or web page use.

Acknowledgement

We wish to thank Dr. Bruce Maxwell for his advice and guidance in this work.