Physics 464 – Applied Optics
Spring 2008

CCD Camera – Dynamic Range, Bit Depth

by Ernest Ventura – 30 May 2008

Submitted to: Dr. Andres La Rosa
ABSTRACT

Two important properties of a CCD camera – the Dynamic Range of its sensor & the Bit Depth of its analog-to-digital converter.

Content Overview:

Dynamic Range
The Importance of Dynamic High Range
What Factors Affect Full Well Capacity?
An Example
High Performance CCD Sensor
What Factors Affect Dynamic Range
Bit Depth
Bit Depth, Grayscale Resolution, & Dynamic Range
Effect of Grayscale Resolution to Image Appearance
Advantage of a Higher Bit Depth
Dynamic Range & Bit Depth – The Difference
DYNAMIC RANGE

Dynamic Range shows how gradually or rapidly the transition from pitch black to pure white is in the intensity spectrum.

\[
\text{Dynamic Range (decibels)} = 20 \times \log \left( \frac{N_{\text{sat}}}{N_{\text{noise}}} \right)
\]

Where:

Grayscale Levels = \( \frac{N_{\text{sat}}}{N_{\text{noise}}} \) (a ratio, no unit)
N_sat = Full Well Capacity (electrons)
N_noise = Read Noise (electrons)

In which:

Grayscale Levels – ratio of full well capacity to read noise.
Full Well Capacity - amount of charge an individual pixel can hold before saturating.
THE IMPORTANCE OF HIGH DYNAMIC RANGE

High dynamic range come in useful is in recording a relatively light polluted site.

we’d have more “room” left to capture actual signal if our CCD sensor’s dynamic range is high as opposed to low.

High & low dynamic range must be used properly in context & is relative to whatever application a CCD sensor is meant to be used for.

Higher dynamic range is generally better, which implies a high full well capacity, low read noise, or ideally both.
WHAT FACTORS AFFECT FULL WELL CAPACITY?

_Photodiode size_ is directly proportional to Full Well Capacity

For CCDs used in photomicrography, diode sizes are typically 4.5 to 24 microns. That diode size range corresponds to 20K to 600K electrons.

_Pixel size_ is also directly proportional to Full Well Capacity.
## Pixel Size & Full Well Capacity Relationship

<table>
<thead>
<tr>
<th>CCD</th>
<th>Pixel Size (µm)</th>
<th>Full Well</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kodak KAF1401E</td>
<td>6.8 x 6.8</td>
<td>45,000 e-</td>
</tr>
<tr>
<td>Marconi CCD37-10</td>
<td>15 x 15</td>
<td>165,000 e-</td>
</tr>
<tr>
<td>Kodak KAF1000</td>
<td>24 x 24</td>
<td>630,000 e-</td>
</tr>
</tbody>
</table>
Read Noise

The impurities introduced in the process of quantifying the electronic signal on the CCD.

Read noise is the combination of the noise generated during readout of the device, including noise from the following:

- Input clocking
- Fixed pattern
- Reset transistor noise and
- Amplifier output noise

Read noise ranges from about 10-20 electrons/pixel in high quality chips (ambient temperature) and it decreases to about 2-5 electrons/pixel (cooled CCDs).
Photodiode size, Full Well Capacity, Read Noise, Grayscale Levels, & Dynamic Range in context.

The **full well capacity** is such that the maximum number of electrons it can store is approximately 1K times the photodiode’s cross-sectional area.

For example, a photodiode in a CCD sensor having a 7 x 7 micron cross-sectional area must have a full well capacity near 49K electrons.

Let’s say the **read noise** for this sensor is 10 electrons per pixel (@ a typical readout frequency of 1 MHz).

With these given CCD attributes, an estimate for the number of **grayscale levels** can be calculated. That is, 49K / 10 or 4.9K grayscale levels.

Using the mathematical definition given for **dynamic range**, we can compute the decibel value to be 20 x log 4.9K or 73.8 decibels
HIGH-PERFORMANCE COOLED CCD SENSOR

MAT CCD39-01

Square pixel size: 24 microns
Full Well: 300K electrons
Read Noise: 3 electrons

“With such a high full well capacity and a low readout noise, the sensor is able to read 100K graduations of gray.”
Taking advantage of the full potential of Marconi Applied Technologies CCD39-01

In order to maximize the ability of this incredibly designed camera, the sensor needs to be partnered with an A/D converter with a bit depth high enough to convert the 100K steps of gray.

For this sensor, it would be a 17-bit analog to digital converter, which can convert 32,072 steps more than 100K.

If we chose a 16 bit A/D converter instead, we’d have a camera outputting more than 34K levels short of its potential because the most a 16-bit A/D converter can convert is 65,536 grayscale levels.

Even though it is possible to use a 16-bit converter, the 17-bit one will bring the best out of the sensor.
An Analogy

let’s say you’re a scoutmaster and you rented a spacious campsite for a camping on a rainy weekend.

In order for your scouts to fully enjoy their activities inside, you must also provide a roof wide enough to cover the entire site.

If you do so, no portion of the campsite will be useless, but if you choose to save money and have a cheaper but smaller roof, some parts of the site may not be used due to rain.
WHAT OTHER FACTORS AFFECT DYNAMIC RANGE?

Figure 1: Variables Affecting Sensor Dynamic Range

- Dynamic Range vs Integration Time
- Dynamic Range vs Temperature
“bit depth” – the capability to faithfully convert the recorded grayscale steps by the CCD sensor.

Bit depth refers to the binary range of possible grayscale steps used by the A/D converter to convert analog information to digital values capable of being read by a computer.

An 8-bit A/D converter can convert up to $2^8 = 256$ values, while a 16-bit A/D converter can translate up to $2^{16} = 65,536$ values.

A CCD camera with an A/D converter with the higher bit depth can accurately represent more grayscale levels.
Grayscale levels = $2^\text{bit depth}$. Dynamic Range = $6\text{dB} \times \text{(bit depth)}$. 

<table>
<thead>
<tr>
<th>Bit Depth</th>
<th>Grayscale Levels</th>
<th>Dynamic Range (Decibels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>6 dB</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>12 dB</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>18 dB</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>24 dB</td>
</tr>
<tr>
<td>5</td>
<td>32</td>
<td>30 dB</td>
</tr>
<tr>
<td>6</td>
<td>64</td>
<td>36 dB</td>
</tr>
<tr>
<td>7</td>
<td>128</td>
<td>42 dB</td>
</tr>
<tr>
<td>8</td>
<td>256</td>
<td>48 dB</td>
</tr>
<tr>
<td>9</td>
<td>512</td>
<td>54 dB</td>
</tr>
<tr>
<td>10</td>
<td>1,024</td>
<td>60 dB</td>
</tr>
<tr>
<td>11</td>
<td>2,048</td>
<td>66 dB</td>
</tr>
<tr>
<td>12</td>
<td>4,096</td>
<td>72 dB</td>
</tr>
<tr>
<td>13</td>
<td>8,192</td>
<td>78 dB</td>
</tr>
<tr>
<td>14</td>
<td>16,384</td>
<td>84 dB</td>
</tr>
<tr>
<td>16</td>
<td>65,536</td>
<td>96 dB</td>
</tr>
</tbody>
</table>
EFFECT OF GRAYSCALE RESOLUTION TO IMAGE APPEARANCE

an image of a stained thin section of potato at 4 different grayscale resolutions from high to low (a - d).

6-bit - Figure 3a
5-bit - Figure 3b
4-bit - Figure 3c
3-bit - Figure 3d
ADVANTAGE OF A HIGHER BIT DEPTH

Advanced CCD cameras with 12-bit maximum resolution permits investigators to produce images with better latitude compared to those with lower resolution.

A CCD camera with a lower resolution, say 8-bit max, will be constrained to limited shades of gray rendered for display out of the camera.

With a 12-bit CCD, inspecting even the most elusive detail can be done without getting misleading results.

An 8-bit CCD may not even provide the details that will allow for accurate image inspection.

This is especially noticeable when images are zoomed in.

Another field in which a higher bit depth is advantageous is in digital photography “color-correction”.

With higher bit-depth images, you can zoom up to as much as 3200% of the original size and still have to visually look for the darkest and brightest pixels, meaning you have plenty of information.

With lower bit-depth images, the darkest & brightest pixels are not accurately detected because the neighboring pixels may have just the same intensity.

While the former provides very specific pixels that are close to reality, the latter can only give an approximate.

Therefore, images with a higher bit depth allows digital photographers to faithfully represent color-corrected photographs better than images with lower bit depth.
DYNAMIC RANGE & BIT DEPTH – THE DIFFERENCE

To capture faint (dark) signal without blowing the highlights (bright parts) out, and to acquire subtle transitions of intensity or steps in the image, a high dynamic range will do the job.

Dynamic Range is a property of a CCD sensor.

To actually render all those steps into visible digital output, a high bit depth is required.

Bit Depth is an attribute of the camera’s A/D converter.
GOOD CCD CAMERA DESIGN

It is possible for a CCD camera to have a sensor with high dynamic range but paired with a poor A/D converter of low bit depth. In this case, the amount of information (grayscale levels) the camera has acquired are not all translated into use. This is not an optimal design – a thoughtless mistake of spending a high-dynamic-range sensor.

Conversely, it is possible for a CCD camera to have a sensor with low dynamic range but paired with a quality A/D converter of high bit depth. In this case, every single intensity step will be guaranteed of rendition, which brings the most out of the sensor into use. The problem here is that a similar output can be produced using an A/D converter with bit-depth just enough to render all the steps the sensor is able to capture but not too much such that less bit-depth is unused or wasted.

For good camera design, partner-up a high dynamic range sensor to a high bit-depth A/D converter for high-end applications; a low dynamic range sensor to a low bit depth A/D converter for low-end applications. Do not pair a low-bit-depth A/D converter to a CCD sensor with high dynamic range because dynamic range will be wasted. Do not pair a high-bit-depth A/D converter to a CCD sensor with low dynamic range because extra bit-depth will be unused. It’s all about efficiency.
ACKNOWLEDGMENTS

Marconi Applied Technologies CCD39-01 Datasheet

http://www.photomet.com/
http://www.starrywonders.com/
http://micro.magnet.fsu.edu/