ABSTRACT

This report is mainly about two important properties of a CCD camera – the Dynamic Range of its sensor & the Bit Depth of its analog-to-digital A/D converter. Here’s a brief overview of the contents:

- 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

INTRODUCTION

“If I knew what I was doing, it wouldn’t be called research, would it?” – Albert Einstein

Selecting one particular topic from a list of eleven hasn’t been an easy decision for me. I spent a fair amount of time toggling between my initial choice – the CCD camera & the professor’s recommendation (an appreciated input) – Tracking Individual Particles with Nanometer Precision. After a thoughtful evaluation of the two, I made up my mind and chose the one in which I feel connected with – the CCD camera – largely influenced by my recently-discovered & continuously-growing passion in the art & science of photography.

Does it mean I know all about these stuff already? Not to the extent of making this report a useless waste of time; In fact, I know enough about “using” a camera yet know so little about its properties/attributes or operation. As a student in a technical field and a photography enthusiast, I don’t want to simply go out there & shoot photos without knowing what else is there beyond the shutter & the viewfinder. I’ve read many photography/camera books & most authors tend to leave the technical material out & concentrate more on techniques. If I view photography only as art, yes maybe then I’d
not have this curiosity about dynamic range and bit depth & all sorts of things that the
non-technical considers boring. I view photography not only as an art, but also a
science & that’s what inspires me to write this report.

**DYNAMIC RANGE**

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

In CCD cameras, the dynamic range represents the difference between the brightest
(highlight) & the darkest (shadow) regions of an image that can be recorded by the
CCD sensor.

In other words, dynamic range can be viewed as the number of steps above the read
noise floor the CCD sensor is able to record – where the read noise is the smallest
increment the sensor can resolve.

Generally, a CCD camera with a higher dynamic range produces better images than
one with a lower dynamic range because the former’s ability to qualitatively measure
the brightest & darkest intensities in an image is also better.

The following equation mathematically defines what exactly dynamic range is:

\[
\text{Dynamic Range (decibels)} = 20 \times \log \left( \frac{\text{Grayscale Levels}}{} \right)
\]

*Where:*

Grayscale Levels = \( \frac{N_{\text{sat}}}{N_{\text{noise}}} \) (a ratio, no unit)

\( N_{\text{sat}} \) = Full Well Capacity (electrons)

\( N_{\text{noise}} \) = Read Noise (electrons)

*In which:*

**Grayscale Levels** – ratio of full well capacity to read noise.

(Sometimes referred to as Grayscale Steps)

**Full Well Capacity (maximum charge storage capacity)** - amount of charge
(electrons) an individual pixel can hold before saturating.
THE IMPORTANCE OF HIGH DYNAMIC RANGE

Among other situations, one in which a high dynamic range comes in useful is in recording a relatively light polluted site. In cases where light pollution heavily consumes the well depth of a CCD camera, we’d have more “room” left to capture actual signal if our CCD sensor’s dynamic range is high (i.e. 96 dB that can read 65,536 grayscale levels) as opposed to low (i.e. 48 dB that can only read 256 grayscale levels). Of course high & low dynamic range must be used properly in context & is relative to whatever application a CCD sensor is meant to be used for. Later I will include a table that shows how many grayscale levels can be read for several decibel values of dynamic range. The lesson that can be taken away from this is that a 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, which means larger diodes have greater 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.

<table>
<thead>
<tr>
<th>CCD</th>
<th>Pixel Size (µm)</th>
<th>Typical 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>

Above: 3 different CCD cameras (each with different pixel area) & their corresponding Full Well Capacity.

We have just defined the numerator in finding the number of grayscale levels a CCD sensor can differentiate. Now let’s talk about the denominator:
Read Noise in simple terms is the impurities introduced in the process of quantifying the electronic signal on the CCD. Most of the readout noise comes from the CCD sensor’s on-chip preamplifier.

To be more apt, 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

The read noise is the denominator for dynamic range because it indicates the tiniest signal possible the sensor can read. Any signal less than this quantity is buried in the noise.

Typically, 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). Cooled CCDs are usually for scientific imaging applications.

**AN EXAMPLE**

*Photodiode size, Full Well Capacity, Read Noise, Grayscale Levels, & Dynamic Range in context.*

As mentioned earlier, full well capacity is related to photodiode size. For most high-performance cooled CCD sensors, 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

\[ 20 \times \log 4.9K \text{ or } 73.8 \text{ decibels} \]

Taking advantage of the full range of grayscale levels
Let’s pretend we have a CCD sensor similar to the one used in the above example, in which its dynamic range is 73.8 decibels, making it able to distinguish 49K shades of gray. So now what? Can we see the difference this sensor can output than one with lower dynamic range? Not unless our CCD sensor is paired with an Analog-to-Digital (A/D) Converter capable of converting every single analog signal the sensor is able to read into digital signals to be outputted into viewable screens like our computer monitor.

For the camera we are talking about, it would take a 16-bit A/D converter partnered to a 73.8 decibel dynamic range to actually maximize the full potential of the sensor. An A/D converter with such high bit depth can accommodate more than just 49K shades of gray – it can render up to 65,536 gray levels. Table 1 below will give a better summary of bit depth, grayscale levels, & dynamic range & how they are in direct proportion to each other (exponentially for bit-depth to grayscale levels, logarithmically for grayscale levels to dynamic range). “16-bit” is a quantity called the Bit Depth, the most important feature of the camera’s A/D converter. I will elaborate more on this attribute later in an effort to “deconfuse” those who don’t easily see the difference between bit depth & dynamic range.

**HIGH-PERFORMANCE COOLED CCD SENSOR**

Most high-end cooled CCD sensors usually have lower read noise & thus, an extended dynamic range. This is because these types of sensors are especially used in slow-scan imagery of photomicrographs and are designed with low noise output amplifiers.

An example for instance is the back-illuminated MAT CCD39-01. The following are its attributes:

- Square pixel size: 24 microns
- Full Well Capacity: 300K electrons
Read Noise (RMS): 3 electrons (@20KHz, when cooled)

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. Is it not uneconomical due to the more than 30K steps converting ability that won’t be used anyway? Well, as far as choosing the best A/D converter goes, we select the one with least bit depth that can convert equal or more grayscale level the sensor is able to capture. 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. So what’s the use of having an amazing sensor if the eye can’t see its highest potential? Not a good idea! Therefore, even though it is possible to use a 16-bit converter, the 17-bit one will bring the best out of the sensor.

Here’s a wild 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 FACTORS AFFECT DYNAMIC RANGE?

![Diagram of dynamic range vs. integration time and temperature](image)
We now move on to talk about the things that are responsible for how dynamic a dynamic range is. If we take a look back at the mathematical formula for dynamic range, we find that it’s a ratio in which the full well capacity is the numerator and read noise the denominator.

Earlier we enumerated the factors that affect full well capacity. Without further discussion, those are the photodiode size and pixel size. We also listed the factors affecting read noise. Those are input clocking, fixed pattern, reset transistor noise and amplifier output noise. Of course all these things in which full well capacity & read noise are dependent upon affect dynamic range, however there are a couple of other variables not mentioned that has something to do with dynamic range – temperature & integration time. The above graph graphically explains how dynamic range varies with temperature & integration time independently.

![BIT DEPTH](image)

Several times already I’ve mentioned the analog to digital (A/D) converter. This topic is dedicated to further discuss “bit depth” – one important attribute of an A/D converter. In casual words, bit depth is the capability to faithfully convert the recorded grayscale steps by the CCD sensor. In technical words, bit depth refers to the binary range of possible grayscale steps used by the A/D converter to translate/convert analog information to digital values (discrete) capable of being read/analyzed 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. Table one below provides these information for up to 16-bit converters. Clearly, a CCD camera with an A/D converter with the
higher bit depth can accurately represent more grayscale levels, thus a more detailed image.

**BIT DEPTH, GRAYSCALE LEVELS, & DYNAMIC RANGE**

The table below shows bit depths 1 through 16 and their corresponding grayscale levels and dynamic range (in decibels). Grayscale levels = $2^\text{bit depth}$. Dynamic Range = $6 \text{dB} \times \text{bit depth}$.

<table>
<thead>
<tr>
<th>Table 1 - 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

The human eye can see approximately 50 shades of gray. In order for an image to have an acceptable visual quality, the number of grayscale levels that must be rendered must not be lower than what the human eye can distinguish. Therefore a 6-bit A/D converter is the minimum requirement for an acceptable image quality.

Even though 6-bit is the minimum, it is recommended to have at least an 8-bit A/D converter to avoid producing visually obvious transition between gray levels especially in images with strong contrast.

Figure 3 above shows 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. With such a high resolution, computer software may render enough gray levels from a large palette of 4,096 shades of gray, which looks great for viewing in computer monitors. On the other hand, a CCD camera with a lower resolution, say 8-bit max, will be constrained to only 256 shades of gray rendered for display out of the camera. This is especially noticeable when images are zoomed in.

As we zoom into the image during image processing, software such as Adobe Photoshop will use the grayscale level that is of highest accuracy (closest to actual) in reproducing parts of the magnified version of the image without any alteration to the original image. With a 12-bit CCD, inspecting even the most elusive detail (especially in the extremes of shadow & highlight) can be done without getting misleading results. An 8-bit CCD may not even provide the details that will allow for accurate image inspection.

Another field in which a higher bit depth is advantageous is in digital photography. As an enthusiast/hobbyist of the field, I have been using Adobe Photoshop to perform digital image “color correction” and “sharpening” to all of my images. There are several procedures that digital photographers use for “color correction”, but for the procedure I am using, the first step is to find the darkest pixel, the brightest pixel, and the middle gray. Detecting these three pixels allows me to “correct” the shadow colors, highlight colors, and midtones of the photograph respectively. With higher bit-depth images, I can zoom up to as much as 3200% of the original size and still have to visually look for the darkest and brightest pixels. 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 me 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 like me 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 analog-to-digital (A/D) converter.

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.

**TERMS TO CLARIFY**

The following words may have caused confusion & clutter but they all pertain to the same thing almost all the time in this report. This is in an effort to be less redundant.

attribute, property
read, capture, measure
well depth, full well depth
ccd camera, ccd chip, ccd sensor
gray scale levels, steps, increments
read noise, readout noise, rms noise
etc.
CONCLUSION

As a student of a technical field and being a photography enthusiast, I am pleased with my decision to take on this topic for my research project. I have learned plenty of interesting information throughout the process. I will not enumerate all of them for brevity, instead I will say that the knowledge I gained here will definitely be a good foundation for the two photography classes I am studying this summer.

ACKNOWLEDGMENTS

Marconi Applied Technologies CCD39-01 Datasheet

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