Introduction

The Aerial Photography Field Office (APFO) has been asked to contract “minimally processed” 16-bit per band imagery for the Forest Service and the Natural Resources Conservation Services. These agencies request imagery in the 16-bit format because it can be used for automated classification studies, among other tasks. However, displaying this imagery “on-screen” can be problematic; besides the extremely large file size, the imagery will often appear black unless some form of adjustment is applied. The main reason for this display problem is that the data has been captured at a 12-bit bit depth (and 14-bit by one sensor), but the image file format only allows a 16-bit (2 byte) bit depth. The issue of bit depth, as well as the question of what type of stretch, or contrast enhancement, should be used will be discussed in this paper.

Imagery collected with a digital sensor is done in a linear manner, while film and the human eye are sensitive to light in a non-linear manner. Consequently, there is an expressed opinion that digital data should be stretched using a non-linear method in order to approximate our natural perception of visual stimuli. This paper will introduce the differences between using these two methods, and will end with an explanation of how to apply these stretches within commonly used geospatial software.

In digital photography, a stretch will expand the range of tonal values used in the output image, so that a larger number of the possible dark to light tones in a given scene are used. A linear stretch will use a formula which is generally applied in the same manner to all pixels in the image. A non-linear stretch will use a different sort of calculation, one which is more likely to be logarithmic rather than arithmetic.

The question of which stretch is appropriate is not well documented. Most literature available describes the various types of stretches (also called contrast enhancement, or adjusting the gamma), and occasionally gives recommendations for situations in which one might be preferable. A few writers state the hypothesis that data acquired in a linear manner should be stretched in a non-linear manner.

Software packages which deal primarily with raster data (such as ENVI and ERDAS Imagine) make adjustments for the 14-bit data in a 16-bit “container.” In software, such as ArcMap (version 9.3.1) which does not make an adjustment, the image will appear to be black unless a stretch is applied by the user. For users unfamiliar with this issue, instructions for stretching, using these three software packages, are included in the Appendices.
Digital Data Collection

Digital imagery data is collected in a “linear” manner. A linear data collection means that a digital sensor records the photons of light as it “sees” them, while our eyes, and film, perceive light in a more logarithmic manner. Something which is twice as bright, in terms of the number of incoming photons, will not appear that way to the human eye. This is a protective natural mechanism, used by all of our senses, which prevents them from being “overloaded” by outside stimuli.

Digital mapping cameras use a semiconductor to capture the light particles, called photons, striking the sensor surface. These photons have been reflected off the surface being photographed. When the photons strike the semiconductor, which is typically a charge-coupled device (CCD), a small electrical charge is recorded and is converted to voltage. Additional circuitry in the camera converts this voltage into digital information. The output voltage from the sensor is a direct linear response to the number of photons that strike the surface. In other words, if one pixel records 100 photons it will have twice the voltage of a neighboring pixel that only records 50 photons. A good analogy is a parking lot full of tightly grouped buckets used to catch rain. The parking lot is the sensor, each bucket represents a pixel, and the rain corresponds to the photons. If one bucket receives twice the number of raindrops, it will have twice the volume of water.

When imagery is acquired using modern digital mapping cameras, the data is stored in a proprietary format that is intended for use only by the camera manufacturer’s processing software. This proprietary format needs to be converted into a format, such as the industry standard TIFF, that can be read by typical GIS software. When converting the data to a standard format, the vendor will have to choose between maintaining the original values collected by the digital camera’s sensor (“radiometrically uncorrected”) or adjusting the values, in an attempt to approximate the ground conditions at time of exposure. Some of the possible adjustments include color-correction, dodging and burning, and tonal balance; these adjustments will correct for such issues as tonal differences within a scene, or effects of atmospheric conditions, time of day, or lens characteristics.

The number of pixels displaying each tonal value can be plotted in a graph called a histogram. Understanding histograms is an important part of understanding stretches, and will be discussed in the next section.

Figure 1: A digital sensor records the number of photons striking it, and the information is converted to voltage.
Figure 2: An un-stretched image with the corresponding histogram. Notice that the image is dark, and that the histogram’s values are predominantly in the lower range of potential value. Graphic sources: CDIO Institute for Africa.

Background on Histogram Fundamentals

A histogram is a graphical representation showing a distribution of data, and often looks similar to a bar chart. When applied to imagery, histograms display the distribution of “brightness” values from pure black to pure white and often include a curved line in addition to, or instead of, bars. Although there is no standard looking image histogram, the “ideal” histogram is a bell-shaped curve that covers nearly the entire length of the x-axis. A histogram is created by recording, along the x-axis, the number of brightness values for all the individual pixels in the image. For example, the brightness values of a sample image consisting of nine pixels are shown as a bar graph and histogram in Figure 3. Pixel Brightness is plotted along the x-axis, where pure black is located at the origin and pure white is the maximum value.

The industry standard is to assign a Digital Number (DN) value of zero to pure black, and pure white is assigned the maximum DN value that the image’s bit-depth will hold. For example, an 8-bit image will have a pure white value of 255. Digital Numbers will be explained in the next section, on bit depth.
The distribution of the DN values (i.e., the histogram curve) describes the general characteristics of an image, such as overall brightness and tonal contrast. *Figure 4* shows the relationship between the histogram and the general tonal characteristics of the aerial image by comparing an image and its corresponding histogram on four variations of the same image: dark and bright, high and low contrast. The first image shown in *Figure 4* is “dark” because most of the pixel values are at the low end of the tonal range. It is extremely important to understand that this type of pixel distribution often occurs when dealing with radiometrically uncorrected digital image files (often incorrectly referred to as raw files). Uncorrected (un-stretched) images may appear black or very dark until some type of stretch is applied.

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**Dark Image**

Histograms clustered at the left end correspond to dark images (which may or may not indicate an underexposed image).

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**Bright Image**

Histograms clustered at the right end correspond to bright images (which may or may not indicate an overexposed image).

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**Low contrast Image**

Histograms with a small spread between the “bars” correspond to low contrast images. Image with little contrast are mostly gray (or dark/bright if the image is also under/overexposed).

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**High contrast Image**

Histograms with a very large spread between the “bars” correspond to high contrast images.

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*Figure 4: Variations in histogram distributions. The histograms superimposed on the thumbnail examples are for Luminosity, and are a composite of all three bands. The examples were created in PhotoShop.*
The histogram displays a lot of useful information to the user, such as overall brightness, image contrast, and data clipping, but it cannot tell you if the image is a good representation of the scene at the time of exposure. It’s important to note that a correct histogram is scene and time dependent. An aerial image of the white gypsum dune fields in New Mexico will have a significantly different histogram than an aerial image of a green tree canvas of Olympic National Forest in Washington.

Background on Bit Depth

*Bit depth* involves the way in which digital data is stored. In its most basic form, the digital signal is either a 0 or 1, like a light switch being on or off. Digital data is stored with *Digital Numbers* (DNs), which are created using the binary number system. With binary numbers, all of the columns in a number record a multiple of 2, and the value recorded in each column will be either 0 or 1. The base 10 system, used for most of our arithmetical thinking, has columns for ones, tens, hundreds, thousands, etc. and values from 0 - 9. In contrast, the binary system has columns for ones, twos, fours, eights, sixteens, thirty-twos, sixty-fours, one hundred twenty eights and upwards. The number 10000000 would be 128, since there is a 1 in the 128s column and all of the other columns are empty. The number 11111111 would equal 255, since there is one each of 1, 2, 4, 8, 16, 32, 64 and 128; 255 is the sum of these numbers.

Bit depth refers to the number of different values which can exist in a given “storage unit.” In the case of imagery, the storage unit is a pixel, or “picture element” (*Figure 5.*). A pixel is the most basic element of any digital image, and when a user zooms in on an area, pixels will be visible as individual squares. Each square will have a tonal value, expressed by its *Digital Number*. In digital aerial photography, the pixel has a *Ground Sample Distance (GSD)*, also called *resolution*, indicating the distance on the ground covered by that pixel. Each band (red, green and blue) will have its own DN for each pixel; together they create the visible color.
Eight bits form a byte, and byte is the suffix used in common computer terminology. A megabyte is a million bytes. Table 1 shows the possible number of values available when combining bits into two blocks of eight (2 bytes). The 16-bit per band imagery data acquired by USDA-FSA-Aerial Photography Field Office (APFO) stores the DNs in a 2-byte format.

<table>
<thead>
<tr>
<th>Number of Bits</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible Value</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>16</td>
<td>32</td>
<td>64</td>
<td>128</td>
<td>256</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of Bits</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible Value</td>
<td>512</td>
<td>1,024</td>
<td>2,048</td>
<td>4,096</td>
<td>8,192</td>
<td>16,384</td>
<td>32,768</td>
<td>65,636</td>
</tr>
</tbody>
</table>

Table 1: The number of potential tonal values

With imagery, bit-depth translates to mean how many possible tonal variations can be displayed per pixel. An 8-bit per band image stores eight bits of data and therefore has 256 possible values for each pixel. Images with greater bit-depth allow for significantly more information to be stored for each pixel - each additional bit doubles the number of potential values. A 12-bit image has sixteen times the number of possible values as an 8-bit image (4,096 vs. 256). A smaller bit-depth will not show a smooth transition between values, and the display will have a noticeable jump from one value to the next, which is called “banding.” Figure 6 shows the banding effect on a simple black-to-white gradient image. If an image has fewer values to distribute, banding may result in the display.

Eight bits: With 256 tonal values the transition seems to be continuous:

Six bits: 64 tonal values:
In natural color digital imagery, a DN is recorded for each band (red, green, and blue), in a range from 0 – 255. Most imagery in current use is viewed at an 8-bit bit depth, and therefore displays 256 potential values for each band. A natural color image is actually a red-green-blue (RGB) banded image, and requires separate storage for each of the three bands. An 8-bit per band natural color image will have $256^3$, or 65,536 possible combinations of colors. 16-bit per band imagery would have 65,536 possible tones per band, totaling 281,474,976,710,656 (i.e., greater than 281 billion) possible colors for a three band image.

If a natural color RGB image has an 8-bit bit-depth, it requires 24-bits of storage per pixel (3 bands x 8-bits = 24) and technically should be referred to as a 24-bit image or 8-bit per band image (but should not be referred to as an 8-bit image). For simplicity, the terms 8-bit and 16-bit will be used with the understanding that this means per band.

**Human Vision and Digital Data**

Human vision does not operate linearly (assuming common illumination conditions). One important characteristic of human vision is that our eyesight is more sensitive to contrast than to absolute intensity (luminance). Contrast, which is the difference in the color and brightness of one object as compared to another object, is the driving force in our visual perception. Our vision is based on the differences of brightness between objects, and not on the overall brightness of the scene.

If we evenly distribute an image’s tonal values based on the perceived brightness of human vision, we might expect uniform gradations of tones from black to white; the middle tone would be a value of 128 (the rounded value half way between 0 and 255 on an 8-bit image). Figure 7, below, shows the difference between equal steps of intensity (the way a linear camera sees the scene) versus equal steps of brightness (the way human vision interprets a scene).
At first glance, it might seem logical that the linear response in Figure 7(a) is the normal human perception of tonal distribution because of the gradual changes in the highlight tones. But that is false, because in an image, very little separation in the shadows would be discernible between the first and second tonal values in diagram (a), and it would be difficult to see details in “darker” tones. A close examination of Figure 7 will reveal that the second tonal value in (a) has the same tonal value as a step that is halfway between values four and five (from the left) in (b). This simple step chart visually shows why a digital camera, which captures the scene’s brightness in a linear fashion, records significantly more data in the brighter areas of the scene, resulting in an unadjusted image histogram which is skewed to one side.

14-bit data in a 16-bit format

The initial problem with the “16-bit” imagery, as acquired with current mapping cameras, is that it did not begin life in a 16-bit format. Digital sensors, at present, acquire the data at 12 to 14-bits, while the TIFF format, which is used to present the data, is only available as 8 or 16 bit (1 or 2 byte) files. (This applies to most other raster formats as well.) In addition, most image viewers can read only 8 and/or 16-bit images. As a result, the 14-bit image (in the case of the image used for demonstration purposes in this paper) is put into a 16-bit, or 2 byte, “container” and the columns designating 1024s, and 2048s are set to zero.

As mentioned earlier, a byte is comprised of 8 bits, and is the standard data storage size for computers. This is why a computer’s internal memory (RAM or Random-access memory) and hard drives are listed according to the number of bytes they will store, such as a megabyte (MB, a million bytes), a gigabyte (GB, a billion bytes), or a terabyte (TB, a trillion bytes). To improve read/write access of imagery data, standard image file formats store pixel information in whole blocks of bytes. Each pixel uses its own byte (or bytes if more than 8-bits) to store the DN value associated with that pixel. Each byte in computer memory has an address assigned to it, which allows the computer processor to access any byte directly. This greatly increases the speed at which a computer can access image data to do things like redraw the image on the screen or modify the brightness.
pixel values. An analogy of this memory address would be a very large post office with millions of PO boxes. Each PO box, which contains a unique mailing address, represents the pixel data that the computer can use to grab or store DN values. Getting mail directly from the box is a lot faster than standing in line at the post office to get a stack of mixed letters.

This constraint of using whole bytes to store pixel information can cause confusion in users who are working with radiometrically uncorrected digital imagery. In addition to doubling the storage memory, the image appears to be “black” on computer monitors when viewed with some software programs. 12-bit files have a maximum of 4,096 possible tonal values, but two bytes of data could potentially contain up to 65,536 values. A computer reads the data as a “normal” 16-bit image and has no way of knowing that the file uses only 1/16th (4,096 / 65,536) of the possible values that a full 16-bit image would have.

Figure 8 shows the digital number distribution for a typical 12-bit image, with no tonal adjustments, plotted on a histogram which is a 16-bit “container.” The image would appear almost totally black. The histogram displays the different tonal values of the image on the far left side of the chart; the lower values represent the darkest of the dark tonal values. 61,441 possible values (the difference between 65,536 and 4098), in the brighter range of the spectrum, would be missing.

![Histogram](histogram.png)

Figure 9: A standard black to white gradient, with the blue line indicating the darkest 1/16th part of the range.

**Linear and Non-Linear Stretches**

Stretching is a method which distributes the total DN values for an image over a wider range of potential values. An 8-bit per band image would have 256 potential tones which could be displayed for each band. In the examples below (Figure 10), values from 84 -153 (a range of 69 values) are stretched to use all 256 values.

![Linear and Non-Linear Stretches](linear_nonlinear.png)
There are several methods for stretching, but they all fall into the two basic classes of Linear and Non-Linear. In Figure 10, for both methods the dark areas will appear darker, and the light areas lighter. In the Linear Stretch, the values are distributed in an even, arithmetical manner over the larger range. The areas with a large concentration of values (the two peaks) will have a slightly larger range of values.

The method on the right is the Non-Linear Stretch. In this example, more contrast will be visible between those values in the middle of the histogram, and less contrast will be seen between the lighter values at the right of the histogram. In this example, some of the lower original values will become much darker in the non-linear stretch. The mathematics involved in making the stretch will not be an even operation, which is the same for all values; instead it might be some sort of logarithmic function, or it could be an even more complicated computation.

Methods for stretching will frequently re-distribute only those DNs falling within the main “curve” of the histogram distribution. The smaller numbers of pixels which may be pure black or pure white will not be used, in a practice known as “clipping.” Examples of clipping may be seen in Appendix 2, on stretching data using ENVI. Clipping, by definition, causes an image to lose some information.

Stretching a “16-bit per band” image with 12-bit data would distribute the 12-bit values over the extra range available in a 16-bit file format. If the Digital Number values are spread over 1 - 65,536, instead of 1 - 4,096, possible DNs, gradations in tone would be more obvious to the viewer, and the contrast would be greater, because the different tones would be farther apart if plotted on a histogram.

Another option for working with this image would be to convert the 12-bit data to an 8-bit file format. This might seem a sensible thing to do, since the images can be more easily viewed and worked with in an 8-bit format, and the images may be converted to 8-bits eventually anyway, for ease in viewing. Software in personal digital cameras will convert the exposure to an 8-bit format, and compress it as a JPEG file, unless it
can be set to deliver an uncorrected file. But this downward re-sampling would result in data loss, and for digital aerial imagery, converting to 8-bits is best not done at this point.

Initially, the most obvious method of dealing with the problem of 12-bit data in a 16-bit format would probably involve distributing the values evenly throughout the space available, in some sort of evenly proportional arithmetic distribution. This is called a Linear Stretch, and is shown in *Figure 11*. However, the larger part of the histogram curve would remain in the darker tonal values.

![Figure 11: A Linear Stretch of the 12-bit data in a 16-bit file format.](image)

If an uncorrected 12-bit image is stored with two bytes (16-bits) of data per pixel in each band and therefore displays as solid black on computer monitors, it cannot be used easily for GIS or other visual applications. *Figure 12* compares the Linear Stretch with a Non-Linear and Standard Deviation Stretch (this is another form of a linear stretch.) The corresponding histograms give a picture of how the tonal values are distributed within the different images.
**Linear Stretch**
A proper linear stretch will display all of the pixel information without any data clipping. However, the midtone values are stored in the lower DN range and will look very dark.

**Non-linear Stretch**
Applying a gamma (or non-linear stretch) to the image will shift the midtones to the correct brightness levels.

**Standard Deviation**
A standard ArcMap Standard Deviation stretch (n=2) will severely clip the shadow and highlight data (notice the pure white “dirt” road) and add significant overall contrast to the image.
It is important to stretch the image before converting it to a lower bit-depth format. If the image is dropped to 8-bits first, the data is truncated to 16 possible DN values (1/16 x 256 = 16), which will cause severe banding.

![Figure 13: Banding (right) in a 16-bit image after conversion to an 8-bit bit depth.](image)

The version on the right in Figure 13 was dropped to 8-bits, probably before being stretched, and displays very few different colors - this is an example of banding. There are large areas of purple, brown and tan with no gradations in the display.

The example on the left is much lighter, and displays a greater range of tonal values, making the image appear much smoother when the display is zoomed out to a normal viewing level. This image was adjusted in Photoshop, with the goal of creating an image which is aesthetically pleasing. An experienced user could run the image through several iterations, using different methods, in order to produce an optimal image. Similar adjustments may not be possible in programs such as ArcMap, just as geospatial analysis is not possible in Photoshop. Image processing software programs would have a number of more advanced tools for stretching imagery.

### Choosing a Method for Stretching

What would be the advantage of using a non-linear stretch? A white paper by Bruce Fraser, for Adobe, states that film captures light in the same way as our eyes do – one which uses “compressive nonlinearity.” He states that this is the case with all of our senses, in order to avoid “driving our sensory mechanisms into overload.” He explains that if we double the number of photons reaching our eyes, we do not perceive this doubling as being twice as bright. Doubling the number of photons reaching the digital sensor will record as doubly bright, while our eyes, or film, will not perceive it to be twice as bright.
The same idea was expressed by Jerry Lodriguss in a book on astrophotography. He writes “Because the human visual perceptual system does not work in a linear manner, a non-linear curve must be applied to “stretch” the linear data from a DSLR camera to make the tonality of a photo match the way our visual system works.” (He later states that the DSLR and CCD cameras both work well for recording astrophotos).

ENVI offers the option for a “Photographic Stretch,” and the instructions explain that it “corresponds well to the response of the human eye.” This lends credence to the idea that non-linear stretches are more human-vision friendly. When using this module, the bands are “nonlinearly scaled” individually, and then joined again to create an RGB display. The documentation for the stretch does not provide any information on what is being done to the imagery during the stretching process, and it does not explain the rationale behind the development and use of this stretch.

A Non-Linear stretch will enhance contrast in parts of an image where this is lacking. However, some information may be lost, as pixel values may be combined in other parts of an image. An explanation of the equalization stretching process is given by Jay Gao, in *Digital Analysis of Remotely Sensed Imagery*:

The histogram of most images rarely has an equal distribution. It is more likely to be bell shaped. This kind of pixel value distribution suggests that the large majority of pixels are confined to a small range that is indicative of a low contrast. On the other hand, few very extremely bright or dark objects are likely to occupy a wide range of DNs. Consequently, there is an imbalance in the number of pixels at a given DN. This imbalance represents an inefficient allocation of pixel DNs. Intuitively, the predominant pixels should be represented in a wider range of DNs so that the subtle spectral variations among them can be readily differentiated. This imbalance is ideally remedied through histogram equalization. This nonlinear contrast manipulation technique achieves an enhanced contrast at the expense of losing minor details in the input image. In the output image, distribution of pixels is roughly equalized through aggregation of minority pixels of a similar gray level into one value. Therefore, the output image always contains fewer levels of DN than the raw image. The DN range vacated from the aggregation is used by pixels of a predominant quantity. In this way, the spectral distance or disparity between any two adjoining DNs is artificially broadened. Since the number of pixels at a given DN varies widely, the aggregated frequency is rarely equalized no matter how differently individual frequencies in the histogram are combined. Instead, the discrepancy between the maximum and minimum number of pixels at different DNs is reduced in comparison to the raw distribution.

Identical to truncated linear stretching, histogram equalization always involves loss of information. However, the manner of loss differs widely. Unlike truncated linear stretching in which the loss is always restricted to the darkest and brightest pixels, in histogram equalization the loss can occur at any DN level if there are few pixels at this level. In other words, the loss takes place at whatever gray level so long as it has a minority of pixels. Furthermore, the degree of stretching is proportional to the frequency. Those DN levels with a higher frequency are
stretched more than those with a lower frequency. This explains why the interval between any two vertical bars is not uniform.

Histogram equalization is an effective means of contrast enhancement. A high degree of stretching is achieved at the expense of losing information for minor pixels. Both raw and enhanced images have the same DN range from the minimum of 0 to the maximum of 255. However, the raw image has a low contrast with most of the pixels having a value confined to a narrow range of DNs. They lean toward the lower end of the DNs, causing the image to have a rather dark tone. In its histogram-equalized counterpart, the dominant pixel values have shifted to the midrange, and the DN range has been extended. Consequently, more details are visible. Since the histogram is a bell-shaped curve, the loss of information is restricted to the lowest and the highest DNs. Namely, the darkest and the brightest features become indistinctive in the output image.

The Linear Stretch can be accomplished through a number of methods, such as a Min-Max Linear Stretch, a Percent Linear Stretch, and a Piecewise Linear Stretch. A paper by Salem Saleh al-Amri, et al, finds a linear stretch to work best on imagery with a Gaussian shaped histogram (the typical bell-shaped curve).

The Non-Linear Stretch would involve a non-arithmetic formula, which probably would be logarithmic, and methods can include a Histogram Equalization, Adaptive Histogram Equalization, and Homomorphic Filter. (al-Amri, et al.)

There is at present a lack of easily understandable, non-technical documentation on the relative merits of these different methods.

**Conclusion**

There are many methods for adjusting digital imagery in a viewer, and the selection of one over another may depend on the user’s needs and preferences. The algorithm used – linear or non-linear - may not be apparent to the user, and may not play a role in the selection. Visual preference is a subjective decision, and each individual might choose a linear or non-linear display option. It is difficult to prove that one method is definitively better than the other.

Fraser and Lodriguss both gave simple explanations of the nonlinearity of the human senses, and felt that stretches of digital acquired imagery should also be non-linear. In the paper by al-Amri, et al, a number of different methods, linear and non-linear, were used. Their conclusion was that the best option was a non-linear operation, but it was not the histogram equalization method available in GIS software.

The statement by ENVI that their Photographic Stretch approximates the response of the human eye adds another vote in support of the argument promoting a non-linear stretch. It was interesting to see this principle incorporated into a software module.
The issue of color is often subjective, and creating an acceptable image may be as much art as it is math and science. It is possible that in a few years computers will be able to store and process 16-bit images quickly and easily, and digital sensors will be able to acquire imagery at 16-bits rather than 12. If the imagery, as it is initially captured, has a wider range of tonal values, the issue of enhancing the imagery correctly may be less critical. But at present, it would be wise for users of 16-bit “raw” imagery to seek processing methods which can deal with these basic questions:

1) How can the 16-bit tiff be viewed in an acceptable manner, since most of the pixels will be at the darker end of the tonal range? How should it be stretched for viewing while still in a 16-bit space?

2) How can we best convert the 12-bit image in a 16-bit tiff file format to an 8-bit image, while preserving much of the tonal variety present in the initial, larger bit-depth capture?

3) What method of image enhancement will be most effective in creating an image which can be useful to the end customer?

4) How do we overcome the fact that image processing capabilities in GIS applications may not be as extensive as those in remote sensing or professional photographic software?
Sources:

http://www.cdioinstitute.org/papers/Day2/basic%20image%20processing.pdf

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http://www.csupomona.edu/~sagarver/GEO420/ppts/1introDIP.ppt

Lodriguss, Jerry. 2006. A Guide to Astrophotography with DSLR Cameras; Chapter 3 – How Digital Cameras Work, Photons to Electrons to Digits. Digital version at  

Mootz, John. Personal communication

Sullivan, Michael. Personal communication

All graphics are by John Mootz or Louise Mathews unless otherwise noted.
Appendix 1: Instructions for Stretching in ArcGIS

Although ArcGIS is not image processing software, it is possible to improve the quality of a 16-bit image with the tools it provides. Although it is possible to do a simple linear stretch, one that purely elongates the histogram, it might be better to render a linearly acquired scene (with equal steps of intensity) to one that is more “friendly to human vision” (with equal steps of brightness).

The 16-bit per band image which was used in these examples was acquired with an Ultracam sensor, which actually collected the data in 14-bits (rather than 12-bit). The data ranges, given in the ArcGIS Layer Properties box under Source, then Statistics, were: Band 1 (red): 55 -8860; Band 2 (green): 56 -6896; Band 3 (blue): 53 – 5580; Band 4 (near infrared): 79 – 11,458. The range for tonal values in 14 bits is 0 – 16,383. Remember that the range in 12 bands is 0 – 4095, and for 13 bands it is 0 - 8191.

The computer monitor will display up to 255 different tones per band (8-bits). Any output histograms or files would be for 8-bit data.

It is easy to apply non-linear stretches in an ArcMap project. Begin by clicking the image in the Table of Contents and select Properties. Select the Symbology tab on the Layer Properties dialog box, and make sure that RGB Composite is highlighted and None is selected in the Stretch Type box. Check Apply Gamma Stretch.

![Figure 14: The Layer Properties Dialog Box, with selections for a non-linear stretch of 12-bit per band data.](image-url)
and enter a value, such as 2.8, in the three textboxes to the right of the checkbox. Select From Custom Settings into the Statistics box and enter the maximum DN value that the image bit-depth supports (4,095 for an image acquired at 12-bits) into the Max textbox; do this for all three tabs (Red, Green, and Blue). The Min should be left at the default of 0 and the Mean & Std Dev (standard deviation) will have no effect on the actual stretch process. When done, click the OK button to apply the stretch.

The Gamma is the value of the exponent in an exponential equation that ArcMap uses to stretch the tonal values in a non-linear fashion. To view the imagery with a linear stretch, replace the gamma values in the above procedure with 1 instead of 2.8. An increase in gamma will increase the brightness of the midtone values without altering the darkest and lightest points. If the image looks too dark, increase the gamma a little – but remember it is an exponential function and small adjustment can make a big change.

Simple color correction can also be done with the gamma values. If an image is a little too red, reduce the gamma value by a tenth or two. Figure 17 shows an image with initial gamma values of 2.8 and the same image color corrected by changing the Red gamma to 2.6 and Blue gamma to 2.7.

![Figure 15: Stretches using a different Gamma for each band.](image)
Most images will require a little additional contrast; this can be added by clicking the Contrast button on the Effects toolbar.

The results of the stretches can be seen in the ArcGIS view, but cannot be exported into a new image. The Identify tool in ArcGIS will display the original pixel values, not the DNs being displayed through the stretch which has been applied. This means the original pixel values are still available for use with any classification modules in Arc.

If a Gamma stretch is applied using the ranges calculated by the histograms for this 14-bit data, the image displayed will be somewhat darker than a stretch which sets the maximum limit at 4095.

Stretched images can be exported from PhotoShop, but only if the software has a plug-in which allows the file to retain its geospatial properties. A basic version of PhotoShop will remove the tiff tags which position the image correctly.
Appendix 2: Instructions for Stretching in ENVI

ENVI provides a wide range of tools for working with imagery; it is primarily raster based software, while ArcGIS works primarily with vector data. Many of its features are fairly intuitive, and easy for a new user to understand and learn. When the image is opened, the software understands that this is not 16-bit data, and adjusts the display accordingly. The user will not be faced with a black image, but with an image which can be used for visual analysis as well as for automated classification. The initial display may suit the user’s needs, and there would not be a reason for further stretching.

The image used for the examples is the same one which was used for the ArcGIS instructions. It was 14-bit data, with the highest Digital Number (DN) being 8860 for the red band. As with other software, the three bands for red, green and blue must be interactively selected as the image is being opened in order to display a natural color image.

ENVI opens imagery with a default 2% Linear Stretch, which means that 98% of the input image’s pixel values are stretched over an 8-bit display. (This was called a “truncated Linear Stretch” by Jay Gao.) The Input Histogram shows that the software recognizes the file as 14-bit per band data.

Figure 16: The initial default display for a 14-bit image in ENVI
ENVI’s display includes a main window, a zoomed in area, displaying the section in the small red box, and a Scroll window, displaying the entire image, with a red box around the area shown in the Display window.

There are several methods available for applying stretches to imagery. The easiest option to find is through the dropdown Enhance menu, with six stretch options which can be applied to the image.
Selecting the *Interactive Stretching* option will open the window shown in *Figure 19*. Only one band is displayed, and it will be necessary to select “R”, “G”, and “B” individually to apply stretch options to the entire image. The option selected through the *Enhance* dropdown window will apply the stretch to all three bands.

The range of the data used in the stretch is given in the *Stretch* boxes, and can also be seen by the position of the sliders in the Histogram graphic. In the example below, ENVI has applied a linear stretch to the red band using the histogram calculated from the *Scroll* window. The total range it uses is between 101 and 4298, but the stretch is applied only to DNs 135 through 1903.
Calculating Statistics

The statistics for the image can be calculated using the Statistics selection under Basic Tools from the main ENVI menu bar. ENVI calculated the same tonal ranges for the image as did ArcGIS, verifying that this test image is 14-bit per band data. These ranges were: Band 1 (red), 55 – 8860; Band 2 (green), 56 – 6896; Band 3 (blue), 53 – 5580; Band 4 (near infrared), 79 – 11,458. (The range for tonal values in 14 bits is 0 – 16,383. Remember that the total number of possible DNs in 12 bands is 0 – 4095, and for 13 bands it is 0 - 8191.)

The statistics box also displays the number of Digital Numbers (DNs) in each bin. Each bin combines 35 DNs for the red band, 27 DNs for the green band, and 22 DNs for the blue band, and would correspond to the distribution of DNs into the 256 tonal values available for display on the computer monitor. This is the alignment which would change with different types of stretches.

The histogram for each band can be viewed individually in the Statistics window, or all three of them can be viewed together. The Statistics calculations can be exported as a file; examining these numbers can help to explain what the software is doing with the Digital Numbers and the display.

![Figure 20: The Statistics Results, displaying the histograms for each band, and the number of pixels falling into each of 256 “bins,” which determine the brightness of the pixel. The three bands combined produce the color visible to a user.](image-url)
Using the full range of DNs for each band, as calculated by the statistics, can be done by selecting Band as the Histogram Source, for all three bands. The Input and Output histograms then are identical because the image in un-stretched.

The dark gray image behind the histogram window, on the left, is the un-stretched image using the full range of data values. It would not be very useful!

A stretch could then be applied to each of the three bands, using the full range of 14-bit tonal values. In Figure N, the non-linear Equalization stretch has been applied to the red band data.
Figure 22: The red band with an Equalized stretch based on the full band.

For comparison, here is a linear stretch using the histogram from the display image of the red band.

Figure 23: The red band with a Linear stretch based on the image.
Figure 24 displays the result of an Equalized stretch applied to all three bands, using the full range of data values.

Within the Interactive Stretching window, the user can select the Stretch to be applied, as well as the histogram source to be used when applying the stretch. The range of DN values to be stretched (or clipped) can be set. These settings will need to be applied to each band individually; if this is not done, the image may contain a combination of different stretches.

There are many potential options for stretches, and it would be take some time to discover the “best” one, especially since that sort of value judgment would tend to be subjective.

ENVI allows the user to export an image to ArcMap. The output image will be a temporary file, 8-bit per band, and will incorporate the stretch applied in the display window. This can then be exported as a .tiff, .img, or other image format.
In Figure 25, below, the Histogram Equalization stretch (right part of image) has been exported, and is compared with the original 16-bit image, with a gamma stretch applied (left part of image). The Histogram Equalization stretch produces an image which is a good deal lighter in tone than many other stretches.

There are several other methods for creating and exporting stretched images within ENVI. From the main Toolbar, under Basic Tools, there is an option for Data Stretching. In this option, the output image has been
selected as a subset of the larger (16-bit) image, and three of the four bands have been selected. In the next window, the user can select the stretch type, and in the Gaussian stretch, can select the number of Standard Deviations from the mean to include in the image.
Another set of options can be found under the Transform drop down menu. This example shows the

![Figure 28: Options available under the Transform drop-down menu.](image)

Photographic Stretch, which presumably will imitate a photographic range of tones; this type of stretch, in theory, supports the hypothesis that imagery should be stretched in a non-linear manner. The online help states that “the Photographic Stretch is used to enhance the color of a true-color input image to produce an RGB image that corresponds well to the response of the human eye. These results look more like realistic color photos. The bands of the true-color input image are nonlinearly scaled then co-added to produce this stretch. “

ENVI’s help does not provide any information about what is actually happening with this stretch. The user selects only the size of the scene to be stretched, and the output options.

![Figure 29: The Photographic Stretch Parameters.](image)
The resulting stretched image can then be exported to ArcMap as a geotiff. ENVI will allow the user to select an active ArcMap window for viewing, or it will start a new session.

![Figure 30: Exporting the Photographic Stretch to ArcMap.](image)

![Figure 31: The Photographic Stretch image over a version processed in PhotoShop.](image)

In this example, the “photographic stretch” image is the lighter green square in the corner. It is superimposed on a version of the image stretched in Photoshop at APFO.
ENVI also allows a user to incorporate Histogram Matching and to manually edit the lookup table. The Arbitrary stretch allows the user to arbitrarily move the sliders in a histogram, in order to create an optimal stretch. These options will require a more extensive knowledge of image processing, and of the software’s capabilities.

ENVI presents the user with a great many options for stretching imagery, and exporting a stretched image as a .tiff image. Most of these methods require very few steps, and are easy to complete, although a file export will be slow. Users can experiment with these options, and select the one which best serves their needs. An important thing to remember is that a 16-bit image can be viewed by the software, without any stretch applied, because only the bins with data will be recognized and read.
Appendix 3: Instructions for Stretching in ERDAS Imagine

ERDAS provides a great many tools for dealing with image stretching. The Help article on Contrast Adjustment provides good basic information on the software’s functionality, and also provides some background on basic image enhancement information.

Enhancing an image in the Viewer is much faster than enhancing an image on disk. You can apply some trial and error enhancements in the Viewer to find your desired results, then apply those enhancement values to the image data file if needed.

To display or print an image, lookup tables are used in IMAGINE to translate file values into brightness values. The Contrast Adjust dialog provides image enhancement and feature extraction tools by editing the lookup tables for the displayed raster layer. In addition, you may perform raster editing (that is, permanently change pixel values in all or part of the image) via a lookup table operation.

Raster editing will permanently change an image file if the edits are saved, and the user is warned to be careful in its application. In ERDAS, the lookup table can be edited manually, or through changing the histogram graph. There are also options to export a new image.

The Contrast Adjustments window can be opened by selecting Contrast from the Raster dropdown menu in the Viewer window. Some of the contrast options can be selected directly from this menu. Select General Contrast for more detailed options.

![Figure 32: Selecting a contrast option in ERDAS Imagine.](image-url)
Contrast Adjustments can be selected from the Method box, and the histograms for each band can be opened by clicking the Breakpoints… button.

In the following examples, the Histogram Equalization stretch is applied, with the resulting histogram displayed. Again, the Red band displays a range from 55 – 8860, implying that this was 14-bit data. As noted previously when this image was used in other software, the explanation is that this was acquired using a Vexcel camera, and the higher DN’s may be noise.

To see a comparison of the effects of stretching on individual pixels, observe a comparison of a lighter pixel (located where the white crosshairs meet) with three different stretches applied.

In the 14-bit image, the input pixel values are: Red, 1553; Green, 1129; and Blue, 965. In the Histogram Equalization stretch (non-linear), the RGB values, converted to 8-bit, are 239, 232, and 237, respectively (out of a possible 0-255).
Figure 33: Imagine allows the user to compare the “raw” pixel values with the Look-up table values, as the image is viewed in an 8-bit display. These values will change with different stretches; in this case the Histogram Equalization stretch is applied.

When a 2 standard deviation stretch is applied, the RGB values are 224, 211, and 221 – lower than for the Histogram Equalization stretch.

Figure 34: The same pixel examined in Figure 33 now has a 2 standard deviation stretch applied, and the near-white pixel becomes a little darker.

When a 3 standard deviation stretch is applied, the tone is somewhat darker, and the RGB values are 193, 183, and 190 – lower than for the Histogram Equalization and the 2 Standard Deviation stretch.
Figure 35: The same pixel examined in Figure 33 now has a 3 standard deviation stretch applied, and the near-white pixel becomes even darker.

The pattern is reversed when a darker pixel is selected. A pixel with 12-bit values of 210, 260, and 327 is displayed as nearly black in the Histogram Equalization stretch. The values are now 9, 1, and 6. In moving from 12-bit to 8-bit data, if a DN of 260 for the green band is now 1, it would mean that at least 260 DNs are now represented by either a 1 or a 0. The aggregation of DNs is different for the three bands, but it is obvious that any contrast which might exist in the darker tones would be lost in the stretch and conversion process.

With the Standard Deviation stretches (not shown) the pattern is the reverse of the one seen with the lighter pixel. The 2 Standard Deviation stretch is displayed with RGB values of 25, 5 and 17, while the 3 Standard Deviation stretch is lighter yet, displaying at 61, 47, and 63.

Imagine offers a great many tools for working with imagery, and can export the file with to an 8-bit image with a desired stretch applied. Users of imagery acquired through APFO who use Imagine will probably be aware of its capabilities, and would be able to adjust the contrast for viewing if needed.
Additional Examples

These three examples come from a CDIO Institute for Africa paper on *Basics of Image Processing*. Notice the changes in the histogram and in the output image from each method.

**Un-stretched Image**

![Un-stretched Image Example](image1)

**Linear Stretch**

![Linear Stretch Example](image2)

**Histogram Equalization Stretch**

![Histogram Equalization Stretch Example](image3)

*Figure 37: Three examples of images with histograms, demonstrating the effects of stretching.*
Figure 38: A 16-bit tiff (Resource) stretched in Photoshop, with histogram
Figure 39: The 16 bit Resource image with histogram, after a process of gradual stretches and conversion to 8-bits.