Evaluating Commercial Scanners for Astronomical Images

Robert J. Simcoe
Associate Harvard College Observatory
rjsimcoe@cfa.harvard.edu

Introduction:

Many organizations have expressed interest in using consumer class flat-bed scanners to digitize astrophotographic plate collections. This paper is an attempt to quantitatively measure the performance of several scanners to help answer that question but with a particular focus on using them for spectrographic plates. The two scanners picked were the Epson V750 flatbed scanner, which has seen use in Europe at several locations and can do up to 8 x 10 inch (200mm x 254mm) plates and a Nikon film scanner that is primarily designed for 35mm film. Both claim resolutions in the 4000-4800 pixel range.

Finding Ways to Quantify Scanner Performance:

## The underlying technology of the scanners: Pixel sizes:

The heart of a commercial scanner is a linear CCD array.   Historically these arrays were three lines of pixels, one each for red, green, and blue.   The color filters are typically integral to the chip and may also include a micro lens that makes the fill factor (using the lens to focus the light over the channel stopper area onto the active area) for each pixel close to 100%.

Fig 1. Pixel dimensions of NEC UPD 8870 chip
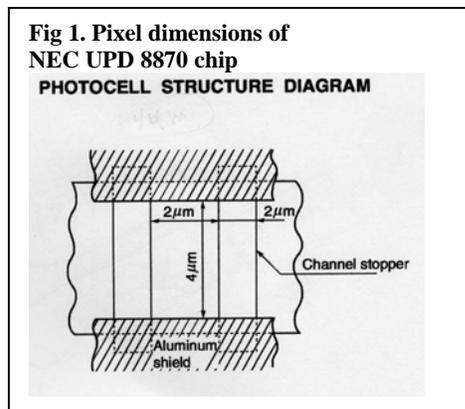
The X –Y dimensions of the pixels are limited by the conflicting physical problems of dealing with the long, thin silicon die that result from the large number of pixels in the lines and the desire to have a large active area to achieve true dynamic range. For practical reasons associated with cutting and attaching long narrow chips to a package so that it is electrically and optically correct, early die sizes were limited to being about 35mm-50mm long and a generally 2 mm wide. Recently, some of the vendors are able to deal with longer die ~ 75mm long for the high end scanner market.

Since the length of the die is limited and the number of pixels needed to cover the maximum scan width (typically 8.5 inches) is fixed for a given dpi, the width of the pixel is limited to what can fit into the ~ 40 mm maximum active die length.   Figure 1 shows the pixel size for an NEC 1200 dpi scanner chip (4um [2 um active] x 4 um).   To achieve

1200 dpi over the 8.5 inches of the flatbed scanner platen the chip must have 8.5 x 1200 or 10,200 active pixels in the line. There are also some dark pixels at each end of the line and a few invalid pixels at each end as well, so that typically there might be an additional 50-64 pixels in a line that are not used for imaging.

Fig 2 Pixel dimensions of most recent NEC CCDs
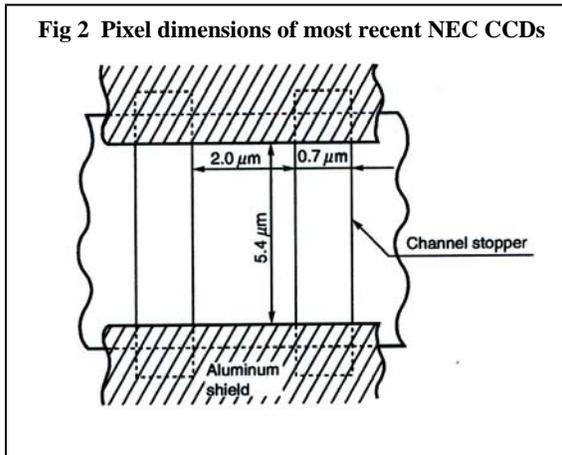
So if we assume that the total line is 10300-10,600 pixels, at 4 microns per pixel the length of the active pixels is ~40.8 mm, the length of the whole array is ~42.4 mm and the die itself may be ~50mm which is typical of many linear CCD arrays used for flat bed scanners.

The optics of the scanner must map a pixel on the 40.8 mm active line length onto a virtual pixel on the 8.5 in length of the scanner. That means that the lens in the scanner will reduce the 216 mm length to 40.8 mm so the lens has a magnification of ~5.29 x from the chip pixel perspective. This translates the 4um x 4um pixel of the chip of Figure 1 to an effective pixel of 21.2 um x 21.2 um at the scanner platen.

Figure 2 shows a pixel size in use by a number of more modern scanner chips. The channel stop is reduced to .7 um from 2 um and the Y value of the pixel is increased to 5.4 um from 4 um.   This means the photon gathering area is increased from 8 square microns to 14.6 square microns giving the well 1.8x more area which results in a better dynamic range – one of the marketing features of most recent scanners.

A 1200 dpi scanner chip with the more recent pixel size would be 10,200 x 2.7 um or 27.54 mm of active length. This smaller chip length makes the CCD less expensive.

Figure 3   Overlapped pixel structure
PHOTOCELL ARRAY STRUCTURE DIAGRAM-2 (Odd-even pixel)
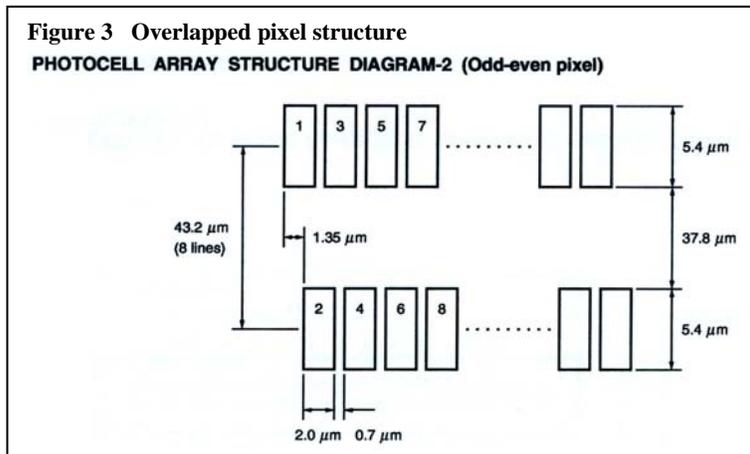
However the lens system must now magnify by 7.84 x (rather than 5.29 x) to fill the 8.5 inch platen and the effective pixel size become 21.6 um x 42.3 um and has X-Y asymmetry.

The least expensive of today's scanners typically claim 2400 dpi and high end scanners are claiming 4800-6400 dpi. How can they do this and stay within the limits imposed by silicon and packaging technology? The answer is that they overlap rows of pixels (see Figure 3) which are approximately the 1200 dpi size and construct "sub pixels" at the "higher" resolution. Scanner software can construct a "virtual" pixel array that takes "real" pixel values and uses them to interpolate

values for intermediate "non-optical" pixels. By using overlapped pixels, the actual values of the "real" overlapping pixels can be used instead of a linear interpolation (which was how earlier scanners made resolution claims), this way the interpolation can be non-linear and bear more relation to non linearities in the image.

The most common overlap is to have two rows of pixels for each of the three primary RGB colors. This is often called a six line sensor. There is an on chip color filter covering the dual pixel rows for each color. [One NEC chip (UDP 8884) actually has 4 overlapping rows, with each row ¼ pixel offset from the adjacent rows.]

This two row overlapping allows a chip that has actual pixel sizes appropriate for a 1200 dpi to claim to be a 2400 dpi scanner, because it "really" has that number of pixels, but the CCD can have the same small die length. The problem, of course, is that the pixels are not looking a independent areas of the real image and so are not able to contribute high frequency information to the final digitized image. One advantage of this approach though is that it simulates the action of an anti-alias filter, which tends to reduce moiré patterns caused by the interaction of image detail with the pixel array.

Figure 4 uses color to show how two rows of overlapping pixels can be combined to generate twice as many sub-pixels. The bottom row shows the sub-pixels and the colors in those show the source of data for each sub-pixel. Each sub-pixel gets half of its data value from each of the two pixels that overlap to form the sub-pixel. Note that in the Y

Figure 4 Making Sub-Pixels
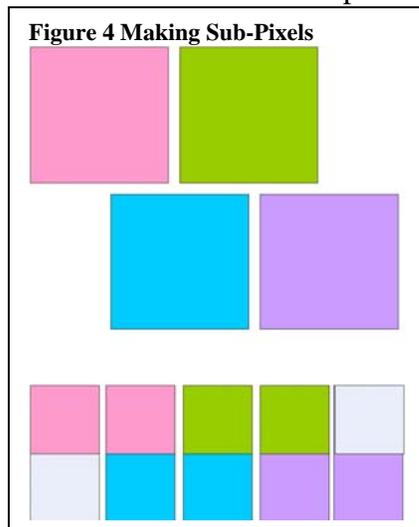
direction the processes is similar, but in many cases the actual physical pixel is twice as long in the Y direction to begin with. However, the mechanical stepping motor system can step in sub-pixel increments in the Y direction, often in much finer increments than even the sub-pixel in the X direction. Sub-pixels can be constructed in the Y direction as well, but they will generally have less "true" spatial resolution in Y because the true "optical" pixel is longer in that direction. The sub-pixels are just optical pixels that have been divided into multiple pixels with the same value. The values can only change in a meaningful way when the sub-pixel crosses between the boundaries of two optical pixels.

Digitizing Spectra plates

We wanted to evaluate two particular scanners, the Epson V750 and the Nikon 9000 ED film scanner to see if they could be suitable for digitizing the spectra plates at the

University of Toronto. In particular we wanted eventually to compare the digitizing results with those attainable with a PDS machine.

The Epson scanner claims a resolution of 4800 dpi over an 8.5 inch width and 6400 dpi over a 5.9 inch width and has two lenses which are moved by motor into place for the two different resolutions. The Epson scanner can step over an 11.5 in length in the Y direction and claims 12800 dpi in the Y direction indicating that the minimum mechanical step is about 2um.   The Epson scanner specifications indicate a CCD with 6 lines and 122,400 pixels in the 4800 dpi mode and 6 lines with 113,280 pixels for the 6400 dpi mode.

The Epson scanner claims 16 bit digitizing, and indeed it has a 16 bit A/D converter. However the number of electrons that a full well can hold is probably on the order of 30-40,000 electrons, which means that each electron would represent ~two bits in the converter.   The reality is most of the low order bits out of the 16 bit converter are noise from the electronics since the pixel wells really support only about 8-9 bits of real distinguishable information.

The Nikon film scanner claims 4000 dpi over 6 cm width and has a stepping limit of 90 cm. The Nikon scanner indicates that they use a 10,000 pixel 3 line CCD (with no color filters since they control color with LED lighting sources).   The literature (DEM2006) that indicates that the effective pixel size for Nikon is 6.35um x 6.35 um but the same paper shows MTF results (see Figure 3 in that paper) for the Nikon scanner that indicate that the X and Y dimensions of the effective pixel is rectangular and not square.

It will be necessary to do some detective work to get a better idea what the true optical pixel size is for both scanners.

The Epson scanner hardware:

I managed to get a broken Epson v700 scanner on Ebay so that it could be taken apart to understand how the machine was constructed and particularly to understand more about the linear CCD chip used.   The major features of this scanner are identical with the V750 that we have to use for actual tests with the difference being that the V750 optics have anti reflection coatings (V750 literature) and there is more software that comes with the V750 machine.

Taking the device apart to get at the actual CCD array enabled measuring the total array length at about 56.8 mm (the part covered with the RGB filters and measured through the glass window) with a precision caliper. The overall length of the package for the device is 71mm.

Since the specification indicated a 6 line 122,400 pixel array, the length of a line should be 122,400/6 or 20,400 pixels.   If the pixels were of the 2.7um x 5.4 um variety that seems in general use at NEC, then the active line length would be 55.080 mm and extra dark pixels and room for amplifiers can easily account for the additional measured

~1.8mm. The measured array length is then quite consistent with an X pixel dimension of 2.7 um. Given that the Epson scanner also touts having a wide dynamic range it is also seems likely that they are using a Y pixel dimension that is greater than the X dimension and so an initial assumption for this scanner is that it uses the 2.7um x 5.4um silicon pixel dimensions common to many NEC linear CCD chips.

An imaging system to convert 8.5 inches to 55.08 mm would have a magnification of 3.922.   This would lead to an effective pixel size of 10.59 um x 21.18 um in the 4800 dpi mode. This effective pixel size assumes that a cylindrical micro-lens on the array fills in the channel stop area perfectly without elongating the y direction (private Epson correspondence indicates that they use a micro lens on this array).

A true 4800 dpi pixel would be 25.4mm/ 4800 or a 5.28 um square.

By overlapping each of the larger pixels with another row of pixels, Epson can create sub-pixels of 10.29/2 or the 5.28 um which has the same dimension as a true 4800 dpi 100% fill factor pixel in the X direction. But this means that without overlap, the optical resolution of the Epson scanner in the X direction is 2400 dpi.

In the Y direction, the optical pixel is 21.18 um long. This is ~4 times the length of a true 4800 dpi pixel. Sub-pixel steps in the Y direction (4 must be generated rather than the 2 in the X direction) will result in many sub-pixels with the same values since they will be constructed using partial data from the same set of physical silicon pixels.   There is simply less "real" information to work with in the Y direction.
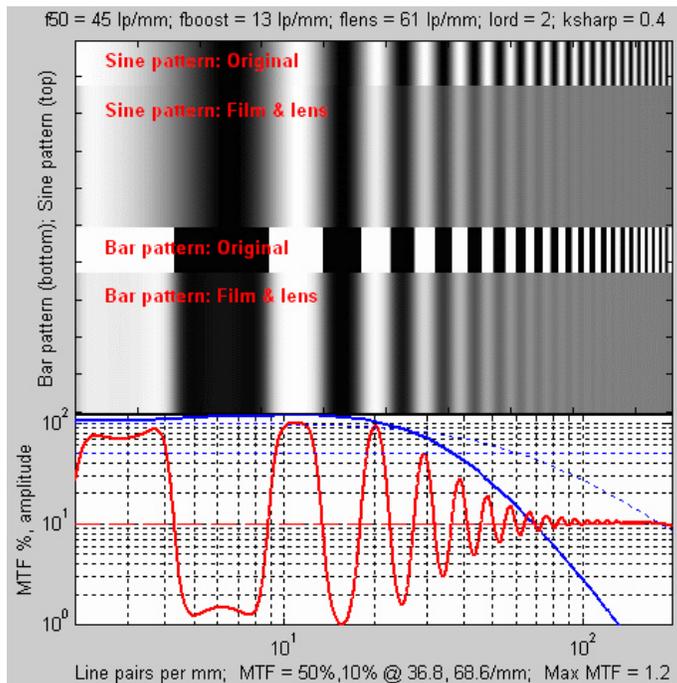
This is why many scanners will not have the same spatial resolution in the X and Y scan directions.   The Y direction specifications are often higher because they simply reflect the scanners ability to mechanically step the optics, but since the actual pixel length in that direction is larger, the specifications are essentially misleading.

The Epson scanner has two lens systems and switches between them. The primary lens system is for the 4800 dpi mode and covers the full 8.5 in platen. The 3200/6400 dpi lens system covers only 5.9 inches and claims 113280 pixels across that area.   The claimed 113,280 pixels / 6 equals 18880 pixels per line which divided by 5.9 inches gives 3200 pixels per inch. A lens system with a magnification 2.94 x would accomplish this and would project a pixel size of 7.94 um by 15.88 um at the platen.

How to measure the performance of a scanner?

Capturing an image from a film can not be perfect. To understand some of the issues involved it is helpful to understand the concept of Modulation Transfer Function (MTF). MTF is a measure of the preservation of contrast throughout an optical system. As the MTF percentage goes down, the white and black values both tend toward grey and the edges of an imaged object become blurred. Eventually high frequency information in the image is lost. Perceptually this occurs for most people around an MTF of 10%.

MTF is an important measure of the quality of the optical system and the way the optical system interacts with the CCD sensor to achieve resolution.

Figure 5 shows the effects of an optical system imaging a pattern of ever decreasing line and space sizes. Because any optical system will introduce some blurring of the edge of the lines, as shown in the figure, as the lines and spaces get smaller, the blurring begins to fill in the spaces and contrast is lost until it is no longer possible to distinguish lines and spaces.

Figure 5. Illustrating MTF (courtesy of Imatest)

MTF interacting with the sensor

"The Nyquist sampling theorem states that if a signal is sampled at a rate *dscan* and is strictly band-limited at a cutoff frequency f_C no higher than *dscan*/2, the original analog signal can be perfectly reconstructed. The frequency $f_N = dscan/2$ is called the **Nyquist frequency**. For example, in a digital camera with 5 micron pixel spacing, *dscan* = 200 pixels per mm or 5080 pixels per inch. Nyquist frequency f_N = 100 line pairs per mm or 2540 line pairs per inch.
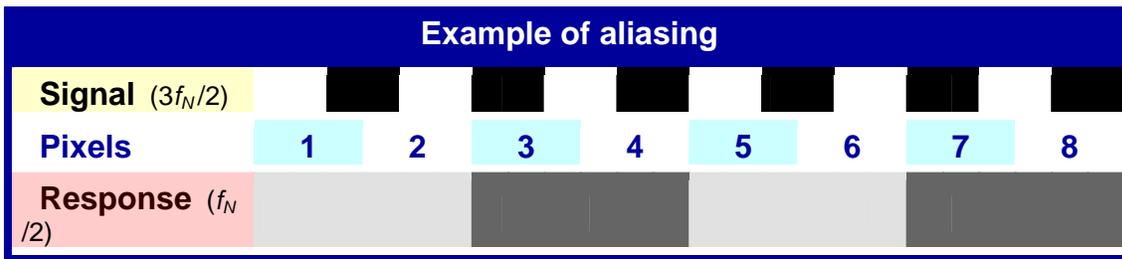
The first sensor null (the frequency where a complete cycle of the signal covers one sample, hence must be zero regardless of phase) is **twice** the Nyquist frequency. The sensor's average response (the average of all sampling phases) at the Nyquist frequency can be quite large.

Signal energy above f_N is **aliased**— it appears as artificial low frequency signals in repetitive patterns, typically visible as Moiré patterns. In non-repetitive patterns aliasing

appears as jagged diagonal lines— "the jaggies." Aliasing is visible in some of the small boxes in this article where bands of high spatial frequency interact with the low sampling rate of the monitor screen, roughly 80 pixels per inch. The figure below illustrates how response above the Nyquist frequency leads to aliasing.
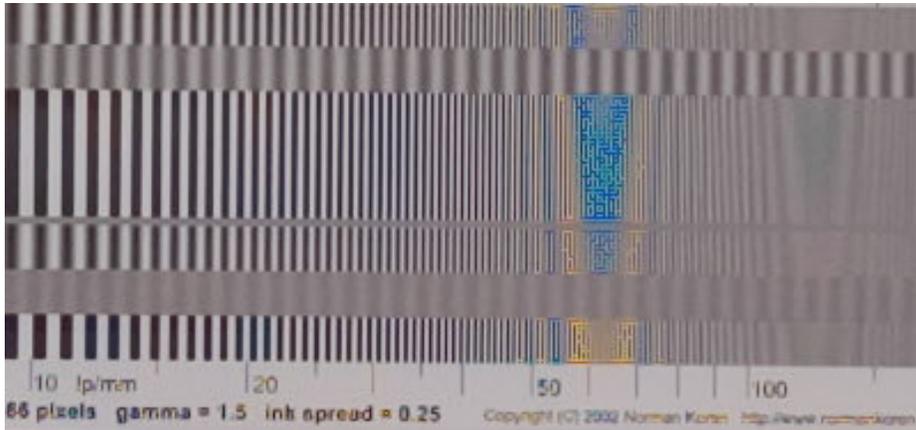

Figure 6 Aliasing

In this simplified example, sensor pixels are shown as alternating white and cyan zones in the middle row. By definition, the Nyquist frequency is 1 cycle in 2 pixels. The signal (top row; 3 cycles in 4 pixels) is 3/2 the Nyquist frequency, but the sensor response (bottom row) is half the Nyquist frequency (1 cycle in 4 pixels) — the *wrong* frequency. It is *aliased*. " * Imatest web page
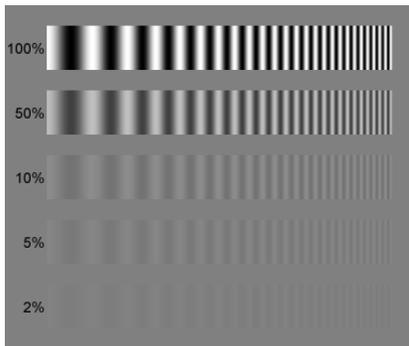

Figure 7 Contrast and resolution

If the optical MTF is good beyond the Nyquist frequency and there is high frequency content in the image, then there may be image detail beyond the Nyquist that seems real, but that detail is constructed from out of phase images and is called an alias image.

Figure 6 illustrates how high frequency alias content can generate problems if the image is not effectively low pass filtered at or below the Nyquist frequency

In the scanners that have overlapped pixels, the overlap would seem to have the effect of providing some anti-aliasing filtering as well as allowing claims of greater resolution.

Figure 7 shows visually the effects of MTF on a sine pattern of decreasing line width and spacing.
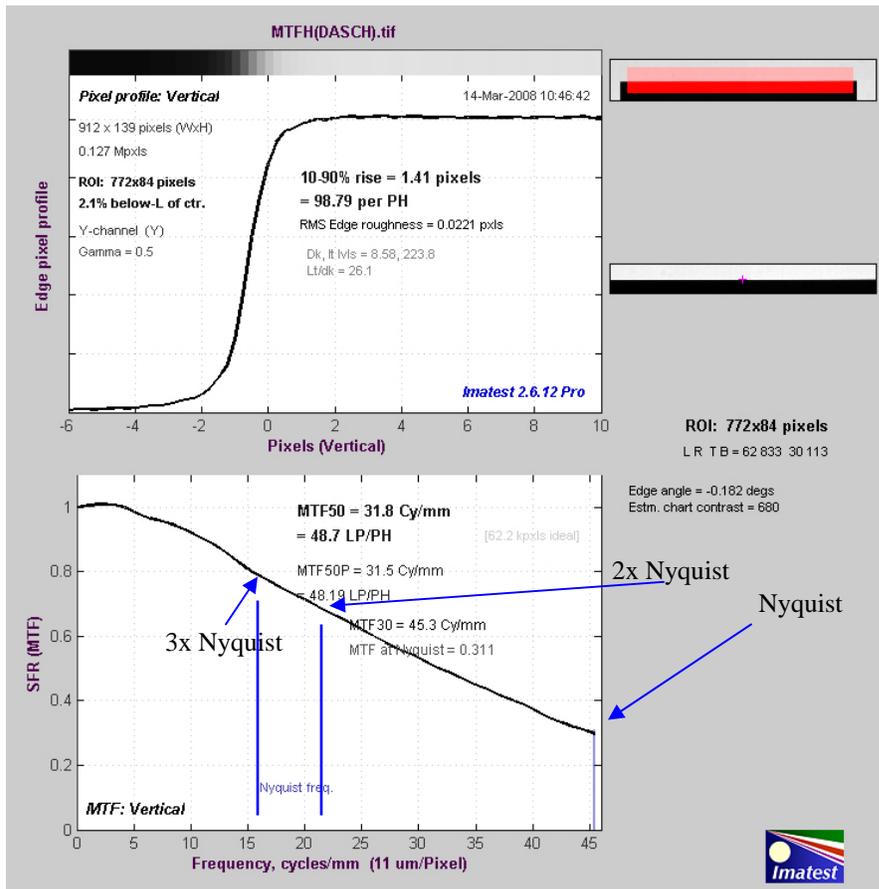
Measuring the MTF

Figure 8 DASCH MTF vertical profile

The MTF of the scanners can be measured by the slanted edge method of calculation. A sharp edge is imaged in a way so that the sharp edge is at a small angle to the line of the sensor array. This means that the line of sensors will see a black to white transition that occurs at various points in each of the pixels in the line. The computational technique then looks at the way the sensors in the line see the changing fill levels of the wells in the sensors (grey levels) and compares that to the theoretical behavior of a perfect imaging and sensing system. This was developed by Don Williams of Kodak and is described in ISO 12233. Norman Koren has developed this technique into a sophisticated tool suite called Imatest and he graciously supplied us with it to enable us to evaluate scanners.

Testing was done by scanning a high quality chrome-on-glass USAF target that had a series of well defined and measured lines and spaces. For this particular test what we wanted was just a very straight sharp edge in both the horizontal and vertical directions so that we could look at the MTF in the X and Y directions of the scanner. The X direction in on the short axis of the scanner and is the one that the linear CCD is aligned to. The Y direction is the long axis of the scanner and is the one that the mechanical scanning occurs in. The plate is tilted slightly so that in both directions the sharp edges of the image are at a slight angle to the X and Y directions of the scanner. Once the scan is complete, the software allows you to select an edge for evaluation. Figure 8 shows the results of an analysis where a horizontal line is used to understand the vertical profile. The top plot shows the sharpness of the edge seen through the optical system. In this case

the blurring at the edge is on the order of two pixels. The lower plot shows the MTF % vs. the line pair cycles. On this plot I have highlighted three different points, the Nyquist frequency, 2x the Nyquist frequency, and 3x the Nyquist frequency.   These correspond to feature sizes of 11, 22, and 33 microns respectively.

To understand the feature sizes needed to capture the information on films, we need to know what image sizes are likely to be on the film. For wide field plates we can look at the airy disk size. For a discussion o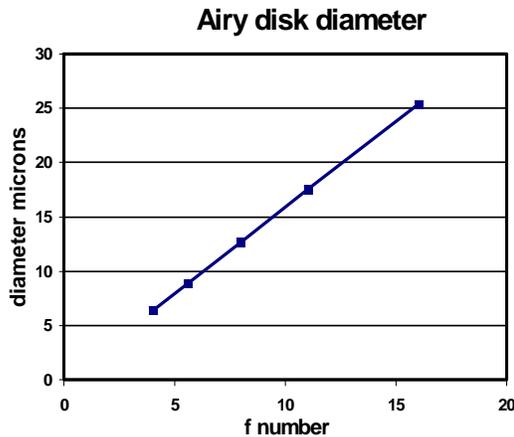f this see <u>Catching the Light</u> by Jerry Lodriguss at <u>http://www.astropix.com/HTML/I_ASTROP/FOCUS/DEFS.HTM</u> .

Airy disk diameter

Figure 9 shows the airy disk size for optical systems of differing f-numbers.   For the Harvard collection, most of the plates were taken with telescopes of long focal length. The numbers in Figure 9 are ideal numbers, the actual star diameters on plates are affected by focus, atmospheric turbulence, the brightness of the stars, and the exposure time for the plate. For design purposes we used the diameter of ~30 microns as the likely smallest star image

Figure 9

that can be discernable on the Harvard wide field plates.   This is close to the 3 x Nyquist frequencies of our 11 micron sensor and so it is appropriate to use that value for contrast degradation.

The MTF shows what happens to contrast for a series of light and dark line features. In that sense it is one dimensional. This is a good match for the case of spectral lines but not for star images. To get a sense of what happens in a two dimensional figure like a star, a simplified approach is to treat the star as a square and multiply the X and Y MTF percentages.   For the DASCH machine, which has square pixels (the measured MTF essentially identical in both directions confirming the square pixel) this simple method indicates that ,for the smallest star image, the contrast of the digitally scanned star image will be degraded by .8 x .8 or about 2/3 from what is on the plate.

Now let us look at the Epson scanner. From the discussion above, for the full size 8 x 10 wide field plate or for a spectra plate that would be larger than the 5.9 inches that is the limit for 3200 dpi scanning, the native, non-overlapping pixel is a 2400 dpi one. The pixel size is 10.59 microns x 21.18 microns.   This means that we need to look at the MTF in both the X and the Y direction.

In Figure 10 you can see the measured MTF for the Epson scanner in the 2400dpi mode. There is some but not a lot of difference between the X and Y directions. I believe this is because the MTF is dominated by the lens system in this machine. In fact in the 3200 dpi mode, the MTF is little different as well. The lens system makes the claims of high

resolution rather a mute point because apparently the two lens systems do not have the MTF to support the resolutions that the pixels might otherwise achieve. If we look at the
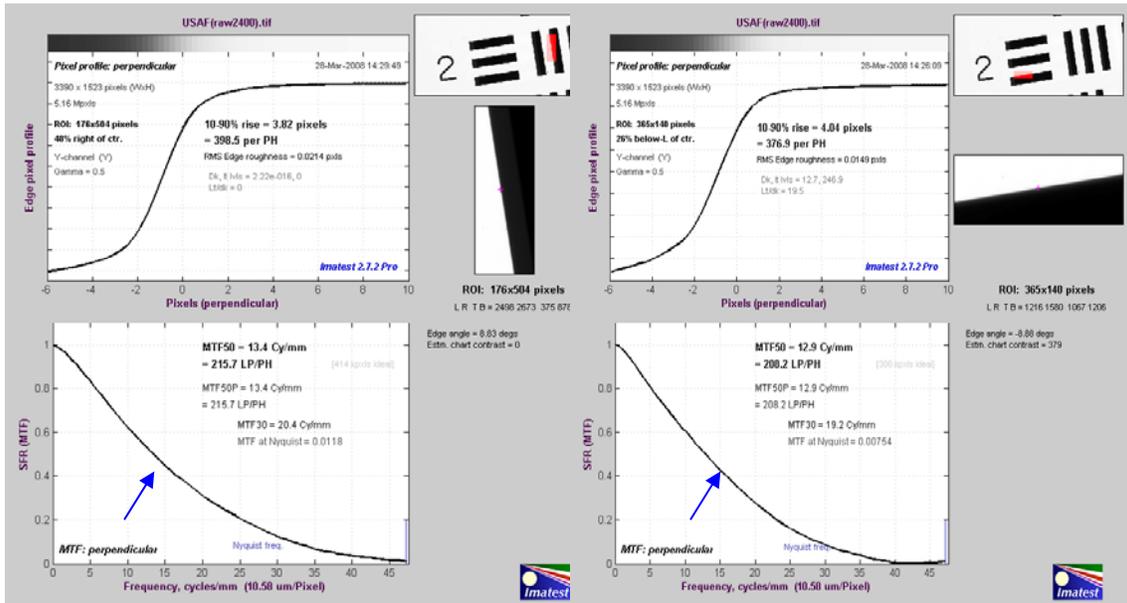

Figure 10 Epson V750 MTF X and Y

contrast for a "star" image, the Epson will give approximately .4 x .4 or .16 compared to the about .66 for the DASCH machine. Figure 11 shows a scan of the same area of a plate to illustrate the difference in contrast preservation.
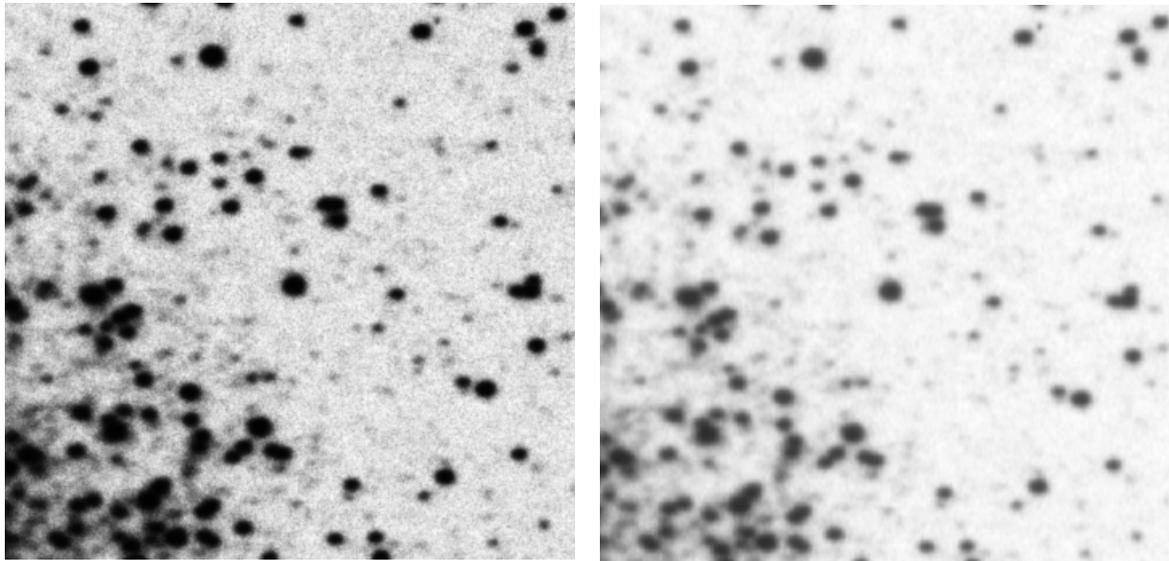

Figure 11 DASCH and Epson scans

The other scanner that we evaluated was the Nikon CS9000 film strip scanner. This is designed to scan 35mm slide film in strips. Unfortunately the software for this machine only allowed scanning in the areas it expected to see a 35mm frame so that the long spectra plates had to be scanned in sections and then spliced together or analyzed in pieces. Another problem is that the linear CCD for this machine is, as is typical, oriented

along the X axis while the scanner format requires that the plate be scanned in the Y direction. This greatly increases the scan time and also has the effect of using the least good axis from an MTF standpoint.
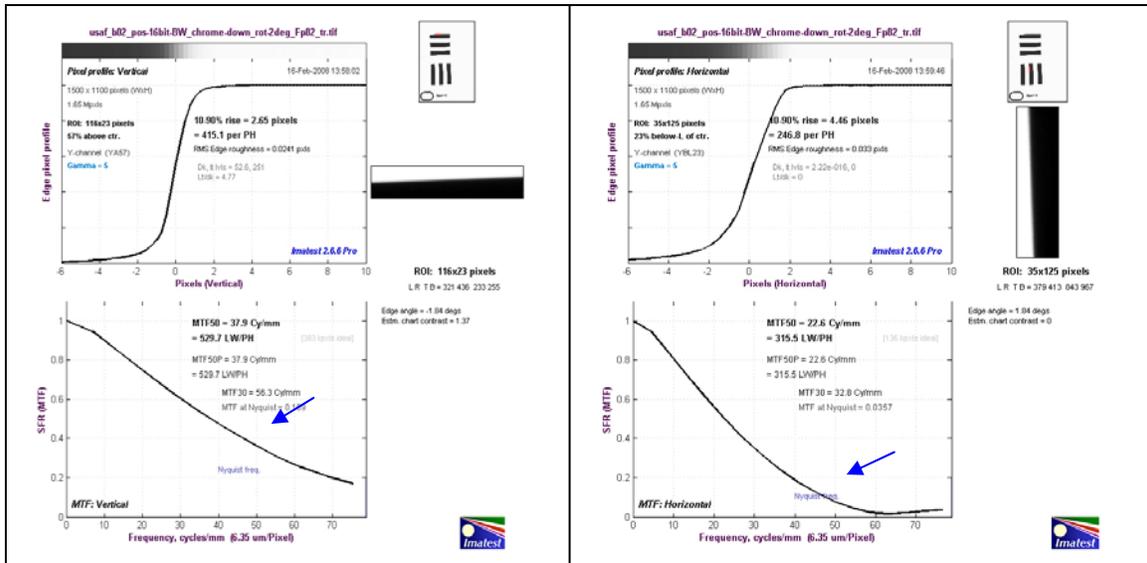

Figure 12 shows the MTF measurements for the Nikon scanner. Notice the significant difference between the X direction on the left and the Y direction on the right. The scanner specifications indicated a square pixel at 6.35 micron (4000dpi). However, the pointers in figure 12 show the 3 x Nyquist frequency for the Nikon and it is clearly significantly different in the X (.3)and Y(.05) directions. The most logical explanation for this is that the pixels are not square but are in fact longer in the Y direction.

This would indicate that the pixel size at the focus of the lens system is about 6.35 x 10.9 microns. The lens system for the Nikon appears to be significantly better than the Epson and in the X direction supports the MTF to achieve the resolution of the CCD with some contrast. Unfortunately the Y direction must be used for scanning the lines and spaces of the spectra plates. Still, the overall MTF of the Nikon is significantly better than the Epson.

Another way to look at this is to observe the line and space feature size that each machine can capture with 50% of the contrast of the original.   For the DASCH machine this is 31.7 microns, for the Nikon it is 44.3 microns, and for the Epson it is 77.5 microns.

Problems with Scanner Internal Processing

We had the opportunity to test another scanner, a Microtek i800. The internal processing on this scanner seemed to thwart the test by clipping the white levels heavily which makes the MTF analysis rather unreliable.
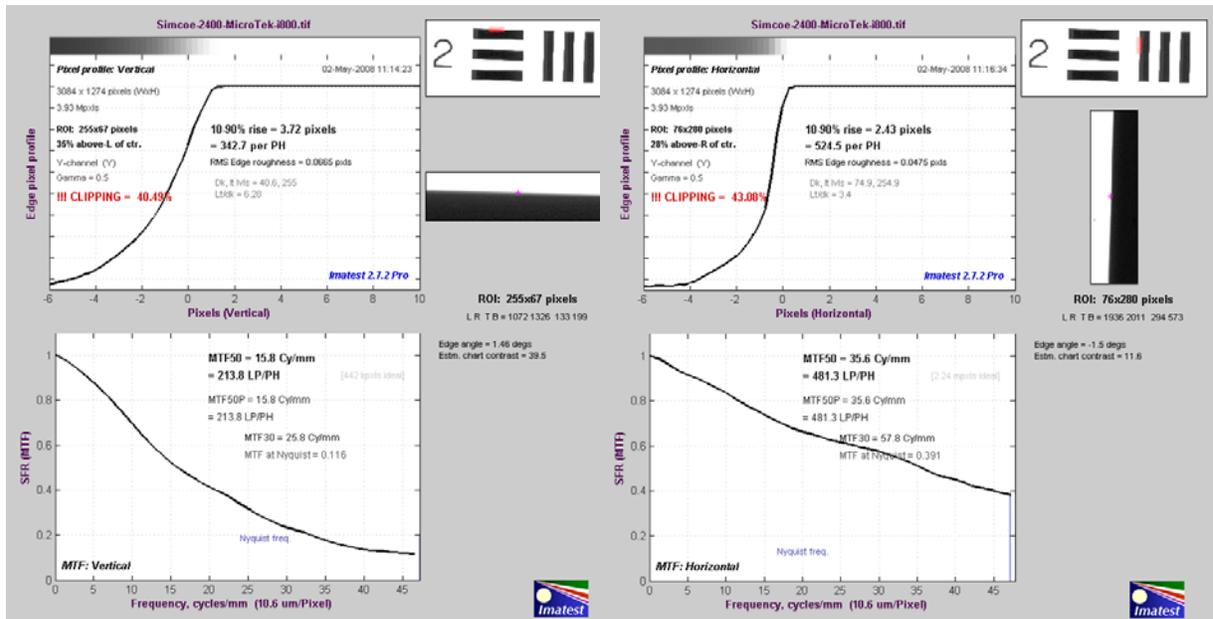
Figure 13

Figure 13 shows the asymmetry between the Y and X scan directions and the white level clipping that makes the analysis questionable. This clipping would also affect the scientific usefulness of the resulting scan data because the true shape of the grey level distribution of a star as captured on the film will be distorted in the digitization process. This kind of processing that may make color photographs look better unfortunately can corrupt further processing desirable for scientific purposes.

Conclusions

Specifications for commercial scanners are very misleading and not at all a good indication of what the scanner can do with scientific images. Most commercially available flat bed scanners achieve high resolutions specifications by using multiple line CCDs that have an overlapping pixel structure. This creates blurring of the actual image detail at the supposed resolution. The tradeoffs in the lens systems that are used to reduce the pixels at the platen to the pixel size of the chip and to try to have a reasonable depth of focus often result in an MTF for the system that really keeps effective resolutions of this class of scanner to the 1200 dpi region.

All of this leads to the conclusion that while digitization with this class of scanner can provide electronic access to the information on the plates scanned with them, the resulting image does not capture adequately the true quality of the original image. This is especially true for wide field images.

For spectral images, the Nikon 35 mm scanner seems to actually be reasonably good. Even though the form factor of the spectra plates forces scanning with the lowest resolution direction, the lens system does not need as much magnification and is likely a higher quality because this class of film scanner commands a higher price point in the market.