Migration from Contrast Transfer Function to ISO 16067-1 Spatial Frequency Response

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Abstract

With the advent of the ISO standard 16067-1 Spatial Frequency Response for Electronic Desktop Scanners it becomes useful to compare established methods, such as Modulation Transfer Function or Contrast Transfer Function (MTF/CTF) to the new standard method. This facilitates communication between companies, vendors, OEM suppliers and end users as to the actual performance being provided or specified. However, when making a change in measurement method in an established field, it is important to understand the relationship between prior measurement methods and the one being adopted. This is required to provide clear migration paths for vendors, manufacturers and reviewers from the old method to the new, while preserving the knowledge inherent in the body of data available from prior measurements. This paper reports comparisons and conversion methods between the ISO 16067-1 SFR and a common MTF/CTF method and how to relate measurements made using the two methods. A number of consumer class desktop scanners with different optical systems are compared when operated at the optical sampling rate (ppi) as well as lower and higher sample rates (ppi). Preliminary results indicate a good correlation is found between the methods though different conversion factors must be used for different sampling rates.

Introduction

One of the key performance attributes of a scanner is the ability of the scanner to appropriately resolve detail in scanned originals – both transmissive and reflective. During the initial years of consumer desktop scanner design and sales, the scanner sample rate, specified as pixels per inch or ppi, was a well correlated to the actual resolving power of the scanner. For this reason, the ppi is referred to as the “resolution” of the scanner, when in fact, it is the sample rate of the scanner. In more recent years, the relationship of the ppi of a scanner to its ability to resolve detail in an original has decreased. For instance, a 1200 ppi scanner today can not be expected to resolve twice the detail that a 600 ppi scanner could just a couple of years ago.

In fact, in the process of specifying and building scanners, the ability of a scanner to resolve detail – it’s real resolution – is described in terms of a modulation transfer function. However, the methodologies utilized to mesure and specify Modulation Transfer Function (MTF) in a scanner are not standardized, nor has the target used been standardized. This greatly complicates product design and product processes because differences between different MTF or CTF measurement methods and targets must be continually addressed. To address this problem, the ISO 16067-1 Spatial Frequency Response for Electronic Desktop Scanners was created. The ISO 16067-1 SFR Standard test enables developers, users and manufacturers to specify and verify the resolution of a scanner. In addition, a standard measurement method for scanner resolution provides a basis for more generic measurement related to the human visual system as well as various reproduction technologies for digital images based upon scanned images. Finally, the ISO 16067-1 SFR standard test enables quantitative measurements by technical reviewers attempting to evaluate the actual resolving power of a scanner as opposed to a specified ppi.

Modulation Transfer Function

MTF) is a well-recognized method for evaluating the frequency response of an optical system. In MTF measurements a sweeping sine wave is “input” to the system and the modulation of that sine wave at the output of the optical element is measured. Unfortunately, while MTF has been applied in optics for some time, the application in scanners is less standard. Modulation Transfer Function, as typically defined presents several challenges for mass production of scanners. First, obtaining a swept sinusoidal input target on a reflective media is difficult. In addition, the modulation of the media itself will enter into the result measures – the modulation of the target will typically decrease as the frequency increases. For truly accurate measurement, the target must be measured using a microdensitomer or similar device. This is not practical in a high volume environment.

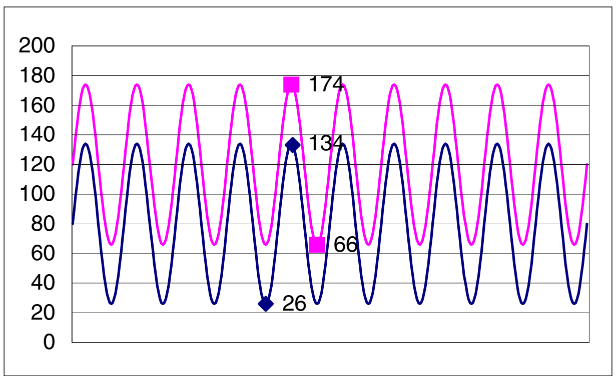
A second issue with MTF is that it is typically measured in a manner that requires some normalization of the optical electronic contrast function (OECF) of the scanner. Typically MTF is calculated as:

$$MTF = \frac{MTF_{max} - MTF_{min}}{MTF_{max} + MTF_{min}}$$

Equation 1. Min/Max per cycle method to compute MTF.

Where MTF_{max} and MTF_{min} are the maximum and minimum value in the sinusoidal modulation. The figure below shows two sinusoidal modulations with the same modulation range (max-min) but with different nominal average reflectance.

The following two MTF results are calculated using the above formula:



	Max	Min	MTF
Curve 1	174	66	0.45
Curve 2	134	26	0.675

Figure 1. MTF calculated using min/max per cycle method.

Note the significant difference in MTF reported. In this trivial case, normalizing to an average reflectance of 128 resolves the difference, but in a more general case where the OECF of the scanner is not well controlled, the problem becomes difficult if not insoluble.

Modification to MTF addresses the limitations of traditional MTF – namely the requirement for sinusoidal input target and the lack of exposure control. Two modifications to MTF are done. This new method will be referred to as CTF in this paper – however it is often called MTF.

In CTF the input target is not a sinusoidal but a square wave test chart (alternating dark and light line) at a given frequency or set of frequencies. This is a less pure measurement for two reasons. First, the square wave represents an impure frequency input and second, the CTF target is not a sweep – it provides only particular input frequency. However, the square wave target is much more cost effective for a product test.

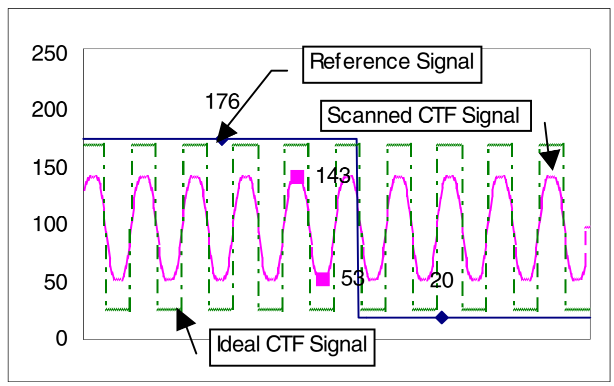
The second factor is a modification of the calculation method. In CTF, the modulation of a high frequency pattern is compared to the modulation of a low frequency pattern.[1] The resulting number is between 0 and 1 and represents no modulation to perfect modulation. CTF is calculated as:

$$CTF = \frac{Test_{max} - Test_{min}}{ref_{max} - ref_{min}}$$

Equation 2. Reference method to compute CTF/MTF.

In this case the reference pattern provides a more robust estimate of the contrast range of the scanner without MTF modifications. However, CTF still requires a linear response from the scanner and one that does not result in saturation or clipping in either the test or reference patterns. More information about MTF/CTF as applied to reflective flatbed scanners can be found in reference 1.

Figure 2 below shows the signals for a typical CTF test. Shown are the reference signal that provides a measure of the contrast of the scanner, a representation of an ideal CTF signal (the square wave) and the scanned CTF signal. The scanned CTF signal is modulated by the limited optical resolution of the scanner. To calculate CTF for this example use *Equation 2,* and the max and min values shown in the graph. Using these values the results obtained are:



	Max	Min	CTF
Reference	176	20	
CTF Signal	143	53	0.58

Figure 2. CTF/MTF calculated using a reference.

Note that in the example shown, the signal is not centered around 128 counts. If the signal were shifted up or down by an offset in the scanner response, the CTF calculation would be the same.

Summary of CTF/MTF

Although these tests have been utilized in the industry they are not standard methods as applied to scanners. As such, they cannot be relied upon when changes in the manufacturing process are made. For instance, hanging vendors or changing target vendors or materials can render results not comparable. When comparing competitive products, as reviewers may do, the multiple ways to calculate MTF can cause confusion and misalignment with specifications. Targets used with MTF tests are not a standard therefore are not controlled or easily available and variations in the printing and imaging process can produce, wide variations of the same test. Finally, variation in the exposure or OECF of differing scanners may cause variations in results that are difficult to identify or rectify.

ISO 16067-1

The ISO 16067-1 was created to address these problems for consumer class scanners. The standard is based upon the ISO 12233 for electronic still pictorial cameras. Spatial Frequency Response (SFR) for scanners utilizes a slanted edge with a sharp contrast of 8 to 1. This tool utilizes this contrast between gray and dark gray to compute the SFR values. The slanted edge is used because it removes aliasing effects by changing phase relative to the sensor elements[2]. Slanted edge SFR is noise durable and has super sampling capabilities,[3] which can sample to four times the Nyquist sampling rate. The 16067-1 SFR test target includes a gray step target that can be used to measure the OECF of the scanner and compensate for exposure and linearity difference between scanners. This is also very important for technical reviewers who are often operating scanners in a "default" mode, which means that exposure and gamma compensation, are often applied to the image. OECF is used to place SFR in a linear space because SFR is defined as a linear measurement. OECF is a table of values that SFR relates its value by approximation.[2] The accuracy of the measurement is dependent on how well this approximation is calculated. The OECF is a good analysis tool because it will distort if corrupt data is present creating easy assessment of the quality of the data.

Correlation of CTF and SFR Data

Since most processes currently include CTF tests or specifications, a method must be established to convert CTF to SFR. This enables moving from an existing process to one based upon SFR without loss of continuity.

In testing the SFR method and comparing it to the CTF method, several scanners were examined, spanning competitors, type, ppi and price points. The scanners tested were operated using various resolutions (ppi), sharpening, saturation and exposure settings. Changing these settings was necessary to verify if the SFR algorithm was capable of detecting changes or ignoring them completely.

First, scans were performed measuring the traditional CTF tests using five cycle samples, 30, 70, 105, 140, 180 line pairs per inch (lppi). All available CTF target frequencies were used to provide the maximum number of points useful to the two different measurement tools. All of the CTF tests were scanned in linear space, while separating red, green and blue and with no sharpening applied. The reference pattern for this test is a large fiducial (cross). The reference area captures a portion of the black and white transition so a high contrast is made.

Next the SFR algorithm was used on the same scanners using the Labview® executable file available on the PIMA website

SFR Calculation Method

There are two different types of executables available for SFR, Matlab® and Labview®. We utilized the Labview® file because it was easily run with Windows® and no separate software was needed. Prior to running the Labview® SFR program the test targets were scanned with various scanning parameters and the images saved. When the Labview® SFR test program is run it first asks for the SFR scanned image. Then a selection area must be created around the target image so the regions of interest (ROI) and gray scale patches can be analyzed. The gray scale patches act as a radiometric reference for the OECF of the device.[4] This is shown in the following figure.

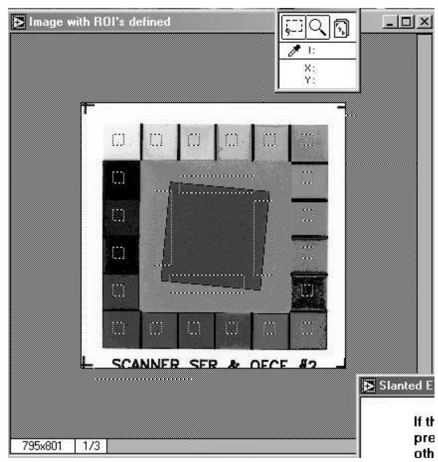


Figure 3. SFR scanner target with ROIs and gray scale selected.

The program then calculates the SFR and displays four different graphs separating RGB for each of the slanted edges of the target. At least two edges, one vertical and the other horizontal, are needed to measure both the X and Y directions. In Figure 4 two measurements for X and two for Y were provided. This can be useful in identifying anomalous data – for instance, if the X SFR is very different from the two slanted edges, one would be suspicious of the data. The SFR test does not require the target to be in linear space, and was tested by scanning with both linear and non-linear tonal transformations. Results between linear and non-linear scans were comparable. Testing was done first at 300ppi then 600ppi and 1200ppi. Scanned files became very large in memory size after 1200ppi, so these were not included in this paper, although they will be examined later in the research.

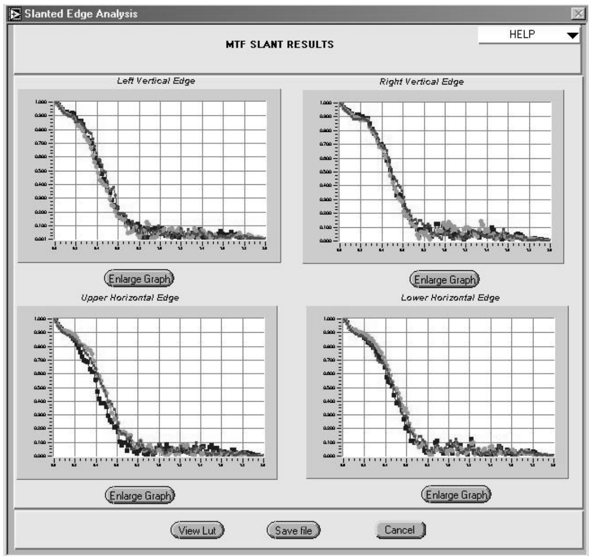


Figure 4. Output of SFR executable file displaying 4 outputs of the 4 slanted edges.

When comparing the data from CTF and SFR the SFR data was extracted corresponding to frequencies measured in the CTF tests and plotted versus the CTF data. This plot was produced with the SFR on y-axis and the CTF on the x-axis as seen in the following figures. This allows easy comparison of the results between the two tests. Although all three channels, red, green and blue were close in numbers and graphical analysis only the green channel is used. Fitting the graphical results, shown in the figures, equations were created. Several equations were tested such as exponential, linear and others, but the best fit was found with a second order polynomial. Testing the accuracy of the best-fit equation an R squared parameter was generated, which is shown with the equations in the following figures.

Impact of Sharpening on Comparison

The plot of SFR versus CTF should reveal a linear relationship because it is measuring the same physical parameter (resolution), but as can be seen in Figures 5 and 6, that is not always the case. Figure 5 shows SFR versus CTF at 300 ppi where sharpening is applied to the SFR scan and not to the CTF scan. Figure 6 shows the same measurement where no sharpening is applied to either scan. As can be seen, the application of sharpening to SFR created a non-linear relationship between SFR and CTF. This is expected, and does point out that sharpening must be considered when comparing or converting from SFR to CTF.

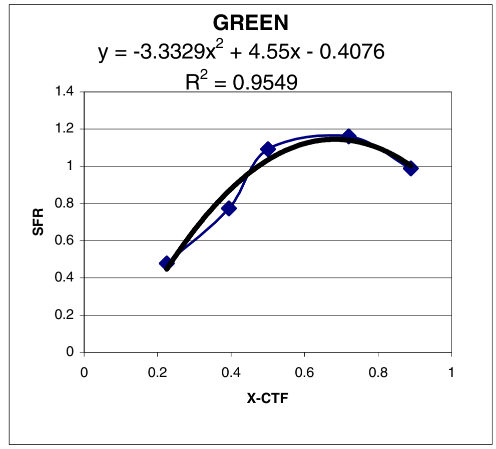


Figure 5. SFR versus CTF @ 300ppi with extreme sharpening applied.

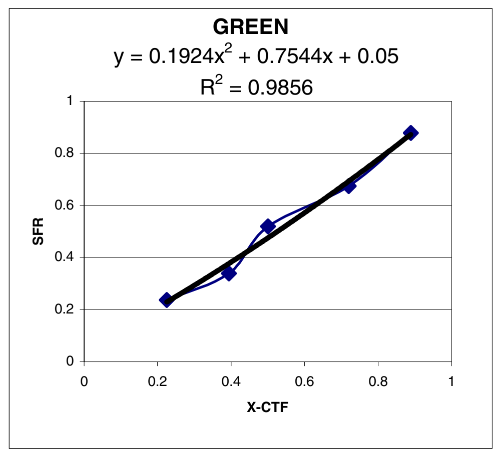


Figure 6. SFR versus CTF @ 300ppi with no sharpening applied.

Interestingly, at higher ppi, such as 1200 ppi, the relationship between sharpened SFR and non-sharpened CTF is much more linear. This is shown in Figure 7. One might expect this because at very high ppi – for a given sharpening kernel – a much smaller sharpening effect will be obtained. In addition, at high ppi, it may be expected that the optics by far dominate.

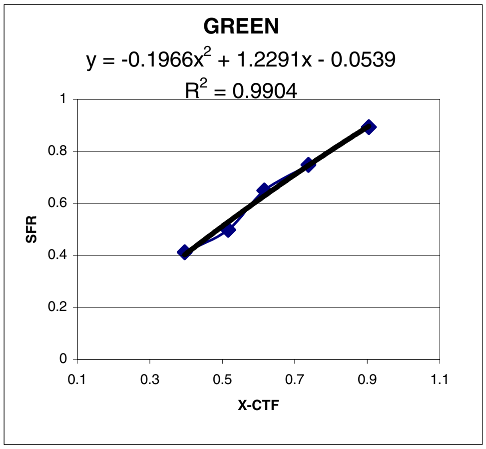


Figure 7. SFR versus CTF for the green channel @ 1200ppi with medium sharpening.

In addition to examining the impact of sharpening on SFR scans, other parameters were varied, such as the amount of saturation, noise levels, and exposure time. Although this information is not included within the text of this paper it will be examined in future work.

Comparison of SFR and CTF without Sharpening

When sharpening is eliminated from the SFR data, a linear relationship is seen between the SFR and CTF results. This is as expected and very encouraging when considering the prospect of converting CTF specifications to SFR. Figures 8 and 9 show a plot of the SFR versus CTF for 600 and 1200 ppi from one of the test scanners (300 ppi results are shown in Figure 6). Notice the relatively linear relationship and the similarity of the fitted equations. However, it is also noted that the equation is not identical for the three ppi scans.

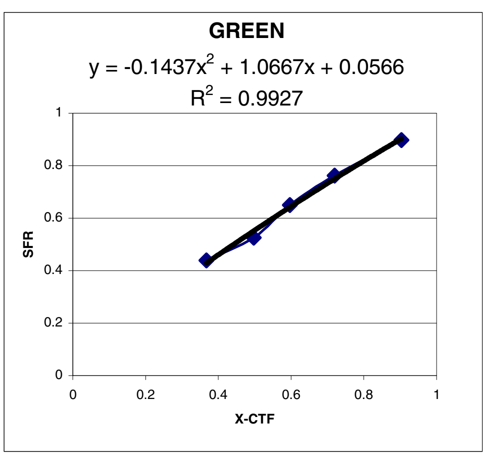


Figure 8. SFR versus CTF for the green channel @ 600ppi with no sharpening.

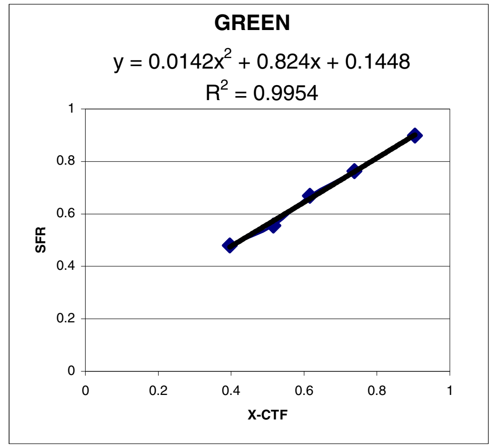


Figure 9. SFR versus CTF for the green channel @1200ppi with no sharpening.

Figure 10 shows the three curves plotted on one graph. The difference between the three curves would indicate that a single equation could not be used for conversions at all ppi.

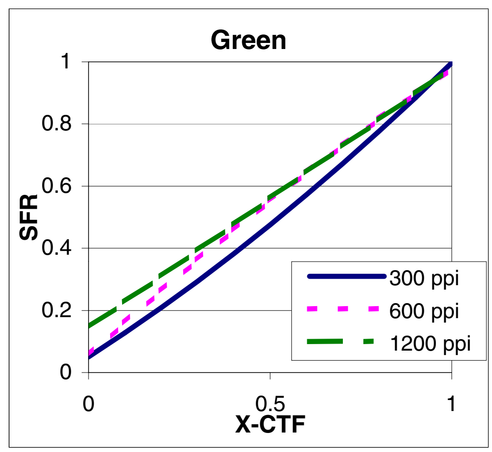


Figure 10. Curves obtained from 300, 600 and 1200 ppi with no sharpening, SFR versus CTF comparison for a one scanner.

Conclusions

A CTF resolution testing method was compared to the ISO 16067-1 SFR test. The results show the relatively linear relationship between CTF and SFR when no sharpening is applied to either. When sharpening is applied to the SFR image, the relationship becomes non-linear as might be expected, at least at lower ppi rating – however, conversion can be successful allowing comparison of non-sharpened CTF specifications to sharpened SFR measurements for a given sharpening kernel. Note that SFR itself may be sensitive to sharpening.

Curve fits allowing conversion from CTF to SFR were created for 300, 600 and 1200 ppi scans with no sharpening applied. While the results are similar and of the same character, they are not identical. This indicates that a different conversion equation will likely be required for each ppi being considered. However, since CTF is only typically specified at one or two ppi settings, this is not considered problematic. Given these results, we believe SFR will become an effective tool for use in scanner resolution specification or comparison.

Once conversion of specifications from CTF to SFR has been performed, future products can be analyzed or specified using SFR alone.

Future work will include the impact on SFR of sharpening, noise, etc., and examinations of more scanners than have been tested to date.

References

1. Gann, Robert G., Desktop Scanners, Hewlett Packard Co., 1999.
2. Higgins, E.W., Juenger, A.K., Parulski, K., *Computation of ISO Draft Standard Spatial Frequency Response,* IS&T,
3. Burns, Peter D. and Williams, Donald, *Slanted Edge MTF for Digital Camera and Scanner Analysis,* IS&T, Portland, OR, 2000, pg.135-138.
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Biography

Troy D. Strausbaugh received his B.S. degree in Electrical Engineering from Colorado State University. Troy has performed research in optical and laser development, signals and systems, microelectronics as well as photolithography. Troy is currently working on image quality for Digital Imaging within Hewlett Packard.

Robert G. Gann received his Ph.D. in Electrical Engineering from Colorado State University. Dr. Gann is currently a master engineer working on Imaging System Architecture in Hewlett-Packard's Digital Imaging organization. Dr. Gann has been working in image quality of digital imaging system since 1988 and has authored several papers and books on scanner image quality.