# Measurement of Printer MTFs

Albrecht J. Lindner[a,b,c], Nicolas Bonnier[b,c], Christophe Leynadier[c] and Francis Schmitt[b]

[a]Ecole Polytechnique Fédérale de Lausanne, Computer Vision Laboratory (Switzerland).
[b]Institut TELECOM, TELECOM ParisTech, CNRS UMR 5141 LTCI (France).
[c]Océ Print Logic Technologies, Créteil (France).

## ABSTRACT

In this paper we compare three existing methods to measure the Modulation Transfer Function (MTF) of a printing system. Although all three methods use very distinct approaches, the MTF values computed for two of these methods strongly agree, lending credibility to these methods. Additionally, we propose an improvement to one of these two methods, initially proposed by Jang & Allebach. We demonstrate that our proposed modification improves the measurement precision and simplicity of implementation. Finally we discuss the pros and cons of the methods depending on the intended usage of the MTF.

**Keywords:** MTF, printer, measure, quality

## 1. INTRODUCTION

With the growing demand for high quality reproduction of photographic images using inkjet printers, the interest in qualifying and quantifying their behavior has become increasingly important. Creating a mathematical model of a printing system serves many purposes such as printer comparison, printer simulation and compensation of the image degradation done by the printer.

Our goal is to obtain a robust characterization method for printing systems. More precisely, we want to characterize it by its Modulation Transfer Function (MTF[*]) which is based on the assumption that the printer is a linear system. A printer MTF describes how much a sinusoidal signal at the input (digital file) is attenuated by the system at the output (print-out) for each spatial frequency $f$. It is necessary to highlight the different representations at the input and output, since establishing a relation between a digital signal and a signal printed on paper is not evident. Different approaches to find a suitable measurement method have been published recently.[1,2,4] In a previous article[3] we compared the methods from Jang & Allebach[1] and from Hasegawa et al.[2]

In this article we add a third method to the comparison: the slanted edge method which is already a standard for scanners[5] and has been adapted to printing systems by Bang et al.[4] Furthermore, we present and justify a major improvement in the analysis algorithm for the method from Jang & Allebach[1] where the authors propose to do the analysis of the print-out in a different color space than the creation of the test page and thus affect the MTF measurement with a systematic error. With the improvement proposed in this article the method becomes simpler to implement and a systematic error is resolved. In addition, the measurement is based on physical properties instead of perceptual ones.

The experimental measuring setup used for all the experiments is described in Section 2. Then the slanted edge method[4,5] (section 3) and the method from Hasegawa et al.[2] (section 4) are presented. They have been implemented as proposed by their authors. The third method, from Jang & Allebach,[1] is introduced in Section 5 and the additional improvements are presented. Finally the three methods are compared to each other and the results are discussed in Section 6. A final conclusion is given in Section 7.

[*]Strictly speaking, we do not measure the MTF but the SFR (spatial frequency response). The MTF is coming from optics and is measured for continuous frequencies whereas the SFR is measured for quantized frequency values. Nevertheless, in this paper we keep the term MTF as previously found in literature.[1–3]

## 2. MEASUREMENT SETUP

The characterization methods studied here can be performed on any kind of printing system. But in order to be able to analyze and compare obtained results, it is necessary to choose and keep a fixed printing system for the whole evaluation. The printing system used for the comparison of the three methods is an *Océ TCS-500* large format inkjet printer with standard Océ uncoated paper at 600 dpi. The modifications to improve Jang & Allebach's method have been carried out on an *Océ Colorwave 600* on *Océ Red Label* paper at 600 dpi. The ink values are coded on 8 bits and only the black ink has been used (gray level mode). The scanner used for the analysis is an *Epson Expression 10000XL* which has a much higher native resolution than the printer (up to 2400 dpi). In our experiments we set the scanning resolution at 1200 dpi. This higher scanning resolution is necessary to avoid aliasing problems when scanning the print-out to measure the MTF.

Since a scanner has itself a degrading influence, it must be compensated for in the analysis. Therefore the MTF of the scanner has been measured with the slanted edge method following the standard ISO 16067-1.[5]

Jang and Allebach[1] propose to compensate the scanner MTF in order to obtain the MTF of only the printing system itself. This appears to be reasonable and thus we have decided to extend the other methods to include this compensation. Within this study, we compensated the scanner MTF by a simple division in Fourier space as Jang & Allebach proposed, despite the known issues of the possible degrading influence of noise. In their approach the division is performed in the scanner RGB color space before the calculation of the input/output amplitude ratio.

We have been using the compensation by division in numerous experiments and have not encountered any serious problems. Hence we use the division method since it provides reasonable results and can be applied to all different kinds of MTF measurement methods. Thus a direct comparison between the methods is possible. In any case the scanner should have a good characteristic, since the better are the scanner MTF values the weaker is the degrading noise influence. This division should be taken into consideration when interpreting the results.

## 3. SLANTED EDGE METHOD

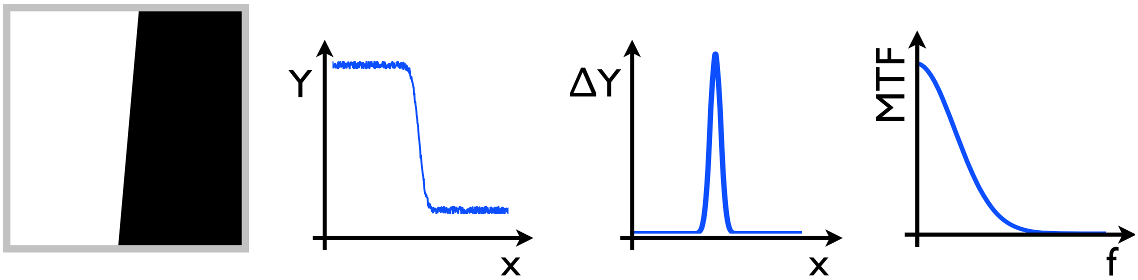
The slanted edge method is often used to measure the MTF of a scanner[5] or any capture device and can be adapted to measure the MTF of a printing system.[4] We implemented it without any improvements in order to compare it with the other methods. A brief introduction to the method is provided in Section 3.1. In Section 3.2 we investigate the influence of the interpolation method for the generation of the slanted edge and in Section 3.3 we show results from printing edges with reduced contrast.

### 3.1 Introduction to the slanted edge method

An image containing a slanted black square on white background is sent to the printer (see Figure 1). The print-out is scanned and analyzed with the method described in the ISO 16067-1.[5] Let us briefly describe this well known method in Figure 2.

Figure 1. Slanted square for slanted edge methods.

During the analysis one edge is selected as Region Of Interest (ROI). Without loss of generality let us consider the case where the ROI is the left edge of the square. The analysis is visualized in Figure 2. In each line of the ROI is a transition from black to white – a step function (a). The position of the transition of each step function is estimated and the lines are shifted, so that the transitions are all vertically aligned. Then the average of all the shifted step functions is calculated along this vertical line to reduce the influence of noise (b). The derivative of this mean step function is ideally a Dirac delta function, but in reality it is a peak of a certain width (c). The absolute value of the Fourier transform of this peak is the MTF of the system (d) (composed of the printing system plus the scanner).




(a) (b) (c) (d)

Figure 2. Basic principle for the MTF measurement with the slanted edge method. (a) left edge of the square (ROI), (b) average of $Y$ values from shifted lines, (c) derivative with noise suppression, (d) Fourier transform and normalization resulting in an estimation of the MTF.

### 3.2 Influence of the interpolation method

A slanted edge can be perfectly described in a vector image file. However, when sent to a printer, it must be rasterized since printers use a spatial grid of pixels. Different interpolation methods exist to calculate the pixel values along the edge. Hence, when generating the digital image for the slanted edge method, the question of the proper interpolation method arises since the edges are not parallel to the image grid. To test whether the interpolation method influences the measurements, we generated slanted edges by rotating a square (with horizontal and vertical edges) by an angle of 5 degrees with either nearest neighbor or bicubic interpolations. Nearest neighbor and bicubic interpolations have been chosen since the first one is very basic and the second one is a more enhanced method. Any influence of the interpolation method should be visible when comparing the results from the two interpolation methods. Figure 3 shows the results from this test on an *Océ TCS-500*: apart from small noise variations, there is no difference between the two interpolation methods.

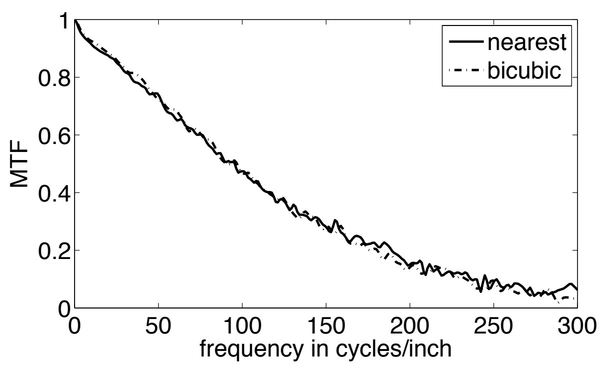



Figure 3. Result of slanted edge method for a vertical edge created with nearest neighbor or bicubic interpolation printed on an *Océ TCS-500*. Notice the small noise variation.

### 3.3 Influence of the contrast of the step

Since printing systems in general are nonlinear systems, the MTF estimated from a full contrast step is not necessarily the same as for steps with reduced contrast. In order to test that, we have been measuring the MTF with a step of half contrast. Therefore we generated a slanted square with gray level 127 (in an 8 bit image) on white background (level 255). The resulting MTFs for the vertical and the horizontal edge are visible in Figure 4.

We clearly noticed that the measurement is affected by much more noise than in the case of full contrast (Figure 3). Therefore much more effort would have to be done in order to expand the slanted edge method to take into account possible non-linearities of printing systems.

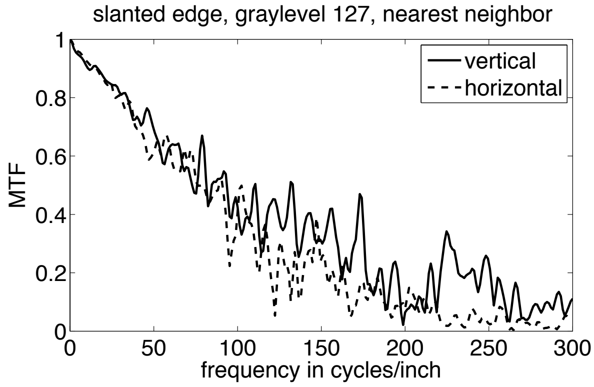



Figure 4. Result of slanted edge method for a vertical and horizontal edge printed on an *Océ TCS-500*. Gray level of square: 127 (in an 8 bit image), level of background: 255.

## 4. METHOD FROM HASEGAWA ET AL.

The method proposed by Hasegawa et al.[2] is the second method which has been tested in this research project. The method has already been discussed in a previous article.[3]

### 4.1 Introduction to the method from Hasegawa et al.

The method does not measure the MTF directly but calculates it from the measurement of the Contrast Transfer Function (CTF). This is achieved by generating a test page with six different pattern types (vertical and horizontal lines, vertical and horizontal stripes, 25 % and 50 % duty dot), where each pattern is repeated with different frequencies. An example of one of those patterns ("Vertical Stripe Pattern") is presented in Figure 5 (upper part). In the next step the image is printed and scanned (middle part). Then the input and the output image are matched on top of each other; the difference between the two after the matching is shown in the bottom part of Figure 5.

For each position $x_{ij}$, the absorbance value is at the output $A_{ij} = 1 - Y_{ij}$ ($Y_{ij}$ is the $Y$ value of CIE XYZ),

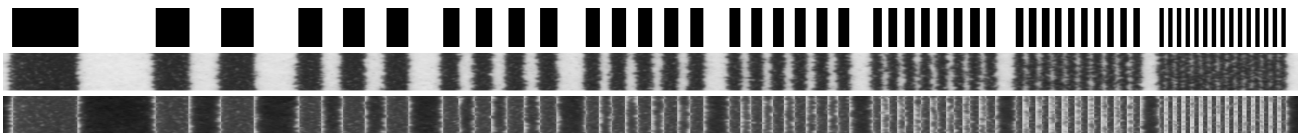


Figure 5. Vertical Line Pattern, input (top) and output (middle) image and difference (bottom), total width = 1 inch. Black is full ink coverage and white is zero ink coverage.

the intended value at the input $I_{ij} \in \{0 = \text{white}, 1 = \text{black}\}$ and the local spatial frequency $f_{ij} \in \mathcal{F}$. The means $\bar{A}_{r,f}$ are calculated for all pixels in the light region $\Omega_{0,f} = \{x_{ij} | I_{ij} = 0, f_{ij} = f\}$ and all pixels in the dark region $\Omega_{1,f} = \{x_{ij} | I_{ij} = 1, f_{ij} = f\}$ and for each frequency $f \in \mathcal{F}$:

$$\bar{A}_{r,f} = \frac{1}{n_{r,f}} \sum_{x_{ij} \in \Omega_{r,f}} A_{ij} \, ,$$

where $n_{r,f} = \#\{x_{ij} \in \Omega_{r,f}\}$ is the cardinality of $\Omega_{r,f}$, $r \in \{0 = \text{light}, 1 = \text{dark}\}$, $f \in \mathcal{F}$ . In this study we have been using $\mathcal{F} = \{10, 20, 30, 40, 50, 60, 80, 100, 150\}$cpi which are the same frequencies used in the implementation of Jang & Allebach's method (see Section 5).

In addition to that, a solid black (100 % ink) and a paper white (0 % ink) field are analyzed to calculate the averaged maximum value $A_{\text{SolidBlack}}$ and minimum value $A_{\text{PaperWhite}}$.
The CTF is then defined as:

$$\text{CTF}(f) = 100 \cdot \max\left(\bar{A}_{1,f} - \bar{A}_{0,f}, 0\right) \Big/ \left|A_{\text{SolidBlack}} - A_{\text{PaperWhite}}\right| ,$$

where the function max sets the CTF to zero if the region on the print-out which is intended to be bright is darker than the region which is intended to be dark.

The MTF is then calculated with a conversion equation cited in:[2]

$$\text{MTF}(f) = \frac{\pi}{4}\left[\text{CTF}(f) + \frac{\text{CTF}(3f)}{3} - \frac{\text{CTF}(5f)}{5} + \frac{\text{CTF}(7f)}{7} - \ldots\right] . \tag{1}$$

Hasegawa et al. also proposed a significance test[2] which has been discussed in a previous work.[3] Since we do not use it in this article the interested reader is kindly referred to the corresponding articles.

# 5. METHOD FROM JANG & ALLEBACH

The method from Jang & Allebach[1] has already been investigated and improved in a previous article.[3] This section begins with an introduction to the method (section 5.1) and a short summary of the linearization step proposed in[3] (section 5.2). In Section 5.3 a systematic error within the analysis is revealed and corrected in Section 5.4. In Section 5.5 a newly modified printer MTF measurement method is proposed based on the preceding results. This proposed method is simpler to implement and provides more reliable results.

## 5.1 Introduction to the method from Jang & Allebach

Jang & Allebach's method[1] consists in printing sinusoidal patches and to compare their amplitudes with constant tone patches. The constant tone patches have uniform values which are the maximum, the mean and the minimum of the sinusoidal patches.
One row of the test image consists of these three constant tone patches and the nine corresponding sinusoidal patches with frequencies $f \in \{10\ 20\ 30\ 40\ 50\ 60\ 80\ 100\ 150\} \frac{\text{cycles}}{\text{inch}}$. A whole test image consist of 19 rows to measure the MTF with different biases. An example of such a test image is illustrated in Figure 6.

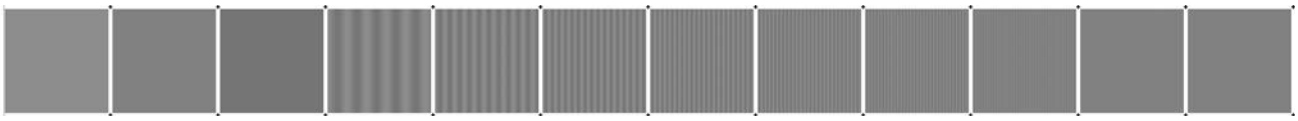


Figure 6. One row of Jang & Allebach's test image

The analysis is depicted in Figure 7. It can shortly be described as follows:

1. Within one row the three constant tone patches are processed first. For each patch, its mean is calculated in the CIE XYZ space and converted into CIELAB values.
2. For each of the nine sinusoidal patches from the same row, the modulation signal is extracted by averaging the measured tristimulus values perpendicularly to the direction of modulation. The averaged values are converted to CIELAB values and projected on the line which connects the lower and upper mean values corresponding to the constant min and max tone patches, respectively.
3. Then, for all the points projected on the line the $\Delta E^*_{ab}$ distance to the lower mean value of the constant min patch is calculated. The result is a vector of $\Delta E^*_{ab}$ scalar values which is Fourier transformed. The amplitude of the main frequency of the patch is then extracted.

4. The amplitude is compared with the $\Delta E^*_{ab}$ distance between the constant min and max tone patches and it usually smaller. Since the scanner is not compensated at this point, their ratio is not yet the printer MTF. It is the MTF of the system composed by both the printing system and the scanner.

5. For the scanner compensation we use the scanner MTF which has been separately measured with specific engraved patterns on a physical chart.[5] We then estimate how much the scanner attenuates a signal which oscillates between the min and max constant tone patches. This scanner ratio should be between 1 and the ratio calculated in the previous step. Dividing the first calculated combined printer and scanner ratio by the above scanner ratio provides the estimated compensated printer MTF.

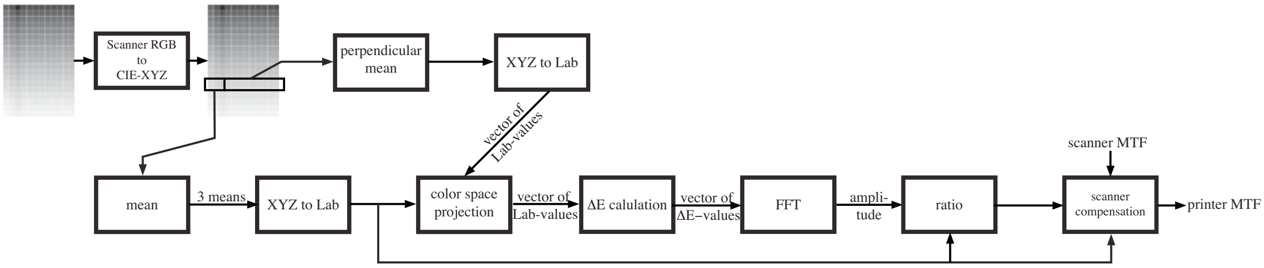



Figure 7. Flowchart of Jang & Allebach's algorithm.

## 5.2 Previous improvement

In our previous article[3] we proposed to linearize the printing system to the $Y$ axis of CIE XYZ space. To do so the printer ink characteristic curve is measured: 256 constant gray level patches are printed and their averaged $Y$ values are measured with a photospectrometer. The 256 gray level values and their corresponding $Y$ values are written in a Look Up Table (LUT). To generate a sinusoidal patch the sine wave is generated on the $Y$ axis then converted to gray values with the LUT.

This linearization step is necessary if the printer ink characteristic curve is nonlinear and thus would result in distorted sine waves on the gray level axis.

## 5.3 Error introduced by the color space conversion

The method from Jang & Allebach with our last modification[3] uses two different color spaces. Before printing, the sinusoidal waves are generated on the $Y$ axis of CIE XYZ. After printing, the analysis is done in CIELAB. Unfortunately the change of the color space may introduce errors.

The problem is that the transformation from CIE XYZ to CIELAB is not linear. The transformation equation for the $L^*$ channel is given here, since it is needed for the explanation:

$$L^* = 116 \cdot f\left(\frac{Y}{Y_n}\right) - 16, \tag{2}$$

where:

$$f(t) = \begin{cases} t^{1/3} & \text{for } t > 0.008856, \\ 7.7870\, t + 16/116 & \text{otherwise.} \end{cases} \tag{3}$$

A sinusoidal signal on the $Y$ axis 0f CIE XYZ will be distorted after the transformation to the $L^*$ axis of CIELAB. The distortion does not only add high order harmonics to the signal, but also changes the amplitude of the zeroth harmonic (base frequency). In this case, the distance between the minimum and the maximum of the signal is not any more twice the amplitude of it's zeroth harmonic. In order to illustrate this statement an easy example will be used.

Let us consider a spatial sinusoidal signal on the $Y$ axis with amplitude 8 and bias 10:

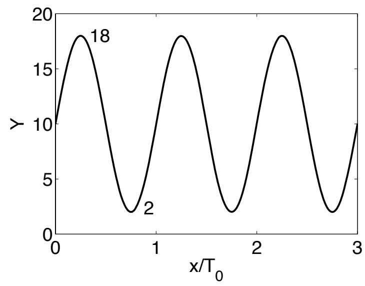
$$Y(x) = 8\sin(2\pi f_0\, x) + 10\,. \tag{4}$$

The amplitude and bias are chosen so that the sine wave is in the strongly nonlinear part of the transformation (Equation 3) and that the function $f(t)$ in the above equation is always the cubic root.

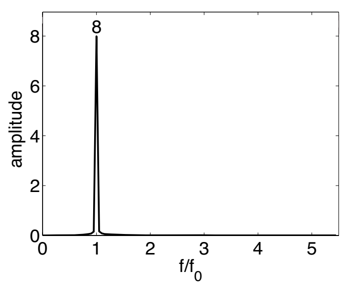
This $Y$ signal can be transformed to the $L^*$ axis (assuming $Y_n = 100$):

$$L^*(x) = 116 \left(\frac{Y(x)}{Y_n}\right)^{1/3} - 16 = 116 \left(\frac{8\sin(2\pi f_0\, x) + 10}{100}\right)^{1/3} - 16\,. \tag{5}$$

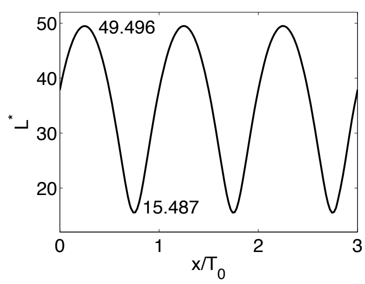
Figure 8 shows the two signals in both spatial and Fourier domains. It is clearly visible that the $L^*$ signal is distorted due to the non-linear transformation.



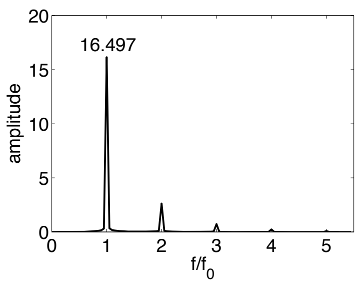

(a) $Y$ spatial




(b) $Y$ Fourier




(c) $L^*$ spatial




(d) $L^*$ Fourier

Figure 8. All four graphs show the signal from Equation 4. In the top row the signal is on the $Y$ axis and in the bottom row on the $L^*$ axis. The left column is in the spatial domain and the right one in the Fourier domain. The spatial and the frequency axes are normalized to the cycle length $T_0 = 1/f_0$ and the base frequency $f_0$ respectively. Note that the signal is sinusoidal on the $Y$ axis (Figure 8(a)), but not on the $L^*$ axis (Figure 8(c)). This is due to the non-linear color space transformation and introduces the high order harmonics visible in Figure 8(d).

When considering the amplitudes $A_{Y,\text{space}}$ and $A_{Y,\text{Fourier}}$ for the $Y$ signal in the spatial and the Fourier domain:

$$A_{Y,\text{space}} = \frac{\max(Y(x)) - \min(Y(x))}{2} = \frac{18-2}{2} = 8\,, \quad A_{Y,\text{Fourier}} = 8\,, \tag{6}$$

it is evident that they are equal.

For the signal on the $L^*$ axis, the amplitudes $A_{L^*,\text{space}}$ and $A_{L^*,\text{Fourier}}$ from the spatial and the Fourier domains differ:

$$A_{L^*,\text{space}} = \frac{\max(L^*(x)) - \min(L^*(x))}{2} = \frac{49.496 - 15.487}{2} = 17.004\,, \quad A_{L^*,\text{Fourier}} = 16.497\,. \tag{7}$$

To determine the origin of the discrepancy, we now consider the transformation of the following signal:

$$Y(x) = A\sin(\omega x) + c\,. \tag{8}$$

The expansion of the cubic root in a Taylor series (see e.g. WolframMathWorld[6]) in the neighborhood of point $c$ leads to:

$$\begin{aligned}
L^*(x) &= \underbrace{\frac{116}{\sqrt[3]{Y_n}}}_{k_1} \cdot (A\sin(\omega x)+c)^{1/3} - \underbrace{16}_{k_2} \\
&\approx k_1 \left( \sqrt[3]{c} + \underbrace{\frac{1}{1!}\frac{c^{-2/3}}{-\frac{2}{3}}}_{t_1}(A\sin(\omega x))^1 + \underbrace{\frac{1}{2!}\frac{c^{-5/3}}{\frac{2}{3}\frac{5}{3}}}_{t_2}(A\sin(\omega x))^2 + \underbrace{\frac{1}{3!}\frac{c^{-8/3}}{-\frac{2}{3}\frac{5}{3}\frac{8}{3}}}_{t_3}(A\sin(\omega x))^3 + \ldots \right) - k_2 \\
&= k_1 \left( \sqrt[3]{c} + t_1 A \boxed{\sin(\omega x)} + t_2 \frac{A^2}{2}(1-\cos(2\omega x)) + t_3 \frac{A^3}{4}(3\boxed{\sin(\omega x)} - \sin(3\omega x)) + \ldots \right) - k_2 \,. \qquad (9)
\end{aligned}$$

This expansion clearly shows that the amplitude of the base frequency $w$ is a composition of the Taylor coefficients with powers 1, 3, 5, 7, ... This is due to the fact that an uneven power of a sine creates spectral content with the sine's base frequency (the concerned sines from the powers 1 and 3 are framed in order to locate them more easily in the equation). Thus the amplitude of the sine with base frequency is not half the difference between the max and min values.

### 5.4 A ratio of amplitudes

An MTF value is defined as the ratio of the output amplitude to the input amplitude at a certain frequency. Jang & Allebach proposed to measure the output amplitude at the corresponding frequency in the Fourier domain and the input amplitude in spatial domain as a distance between the min and max values:

$$\mathrm{MTF}(f) = \frac{A_{\text{out, Fourier}}(f)}{A_{\text{in, space}}} \,. \qquad (10)$$

Unfortunately this is not correct, since $A_{\text{in, space}}$ does not give a measure of the input amplitude at frequency $f$. The ratio

$$\mathrm{MTF}(f) = \frac{A_{\text{out, Fourier}}(f)}{A_{\text{in, Fourier}}(f)} \qquad (11)$$

should be used instead. The ratio $A_{\text{out, space}}/A_{\text{in, space}}$ is not an alternative since this is the attenuation of a mixture of signals with different frequencies.

The error introduced has been calculated in a simulation for the printing system *Océ TCS-500*. Figure 9 shows the factors needed to compensate the error of the color space transformation. It can be seen that the error is less than 4 %. But even though the error is small, it is better avoiding it completely.

### 5.5 Modified measurement method and discussion

Based on the experiences described in our previous article[3] and the preceding sections, we propose a new improvement to the method proposed by Jang & Allebach: The test page is generated on the $Y$ axis of CIE XYZ[3] and the analysis is done on the $Y$ axis as well. In this case the input amplitude can be estimated as the distance between the max and min constant tone patches since the signal is not systematically distorted. This approach has three major improvements. Firstly, the analysis is much simpler since it needs neither the projections nor the $\Delta E^*_{ab}$ measures in CIELAB space (the method initially proposed used those calculations[1]). Secondly, the ratio $A_{\text{out, Fourier}}(f)/A_{\text{in, space}}$ can be used without any further corrections. Thirdly, the measure provides a physical estimation of the printing system MTF since it uses the $Y$ value for the analysis instead of the perceptual $\Delta E^*_{ab}$ distance.

For the MTF measurement, only the minimum and maximum constant tone patches are needed and the middle constant tone patch can be disregarded. Yet Jang & Allebach included it in the design of their test page and therefore we left it on our test page too. This patch can be used to check whether the linearization of the printing system to the Y axis is correct. If for instance the mean Y value of the middle constant tone patch is

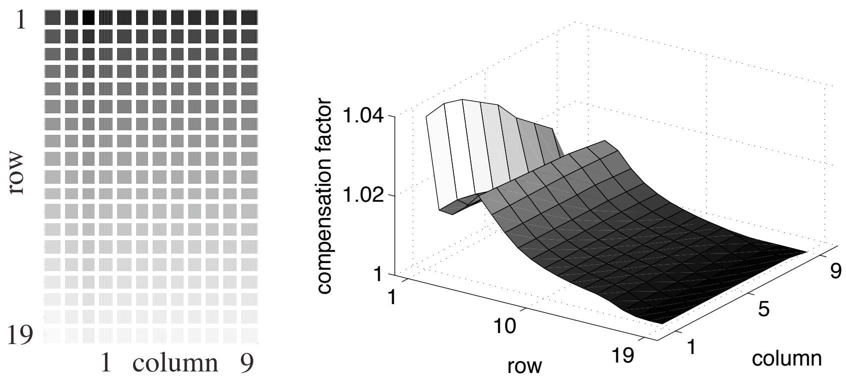



Figure 9. Left: symbolic test page with row and column numbers (the first three unnumbered columns on the left are the constant tone patches). Right: Multiplication factors for the compensation of the measurement error due to the color space transformation. Measured MTF values shoulds be multiplied with these factors to correct the error.

not equal to the means of each sinusoidally modulated patch (in the same row of the test page), the linearization has not been done properly. A resulting MTF from the new measurement method is shown in Figure 10.

Unlike in the article from Jang & Allebach,[1] in this study we limit our investigation to grayscale (using black ink) and thus do not consider color (e.g cyan, magenta or yellow) inks. Anyhow, the procedure (linearization followed by printer MTF measurement) can be extended to any other ink. A special case is the yellow ink; errors can occur since the $Y$ values of yellow ink are usually very high even for full ink coverage and thus the generation of large amplitude sinusoidal patches is not possible.

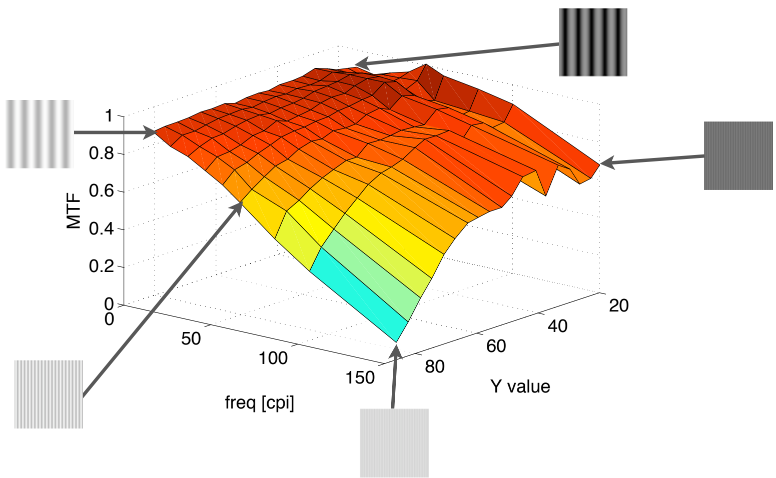
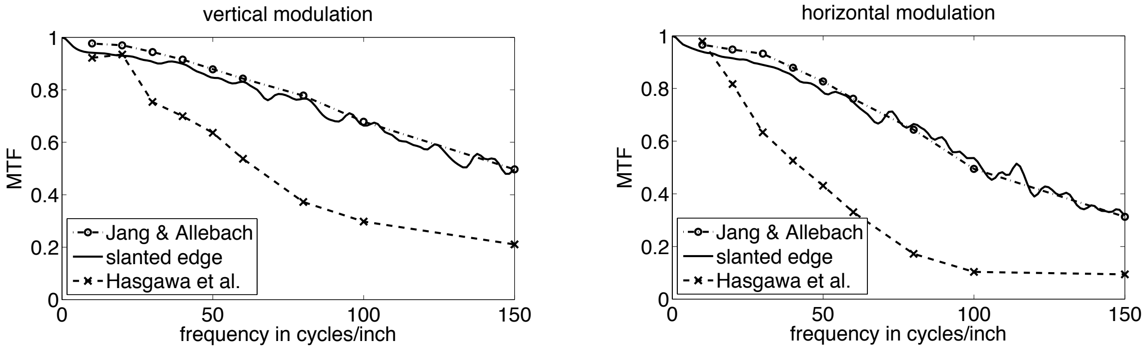



Figure 10. Horizontal MTF of the *Océ Colorwave 600* inkjet printer on uncoated paper obtained with new measurement method. Example patches and arrows have been added for some MTF values for illustration purpose.

## 6. DISCUSSION AND RESULTS

The MTF values from the three methods are plotted in Figure 11 for direct comparison. It is necessary to add that the MTF values from Jang & Allebach's method are different for different bias values. The one shown in Figure 11 is from the darkest rows of the test page (the average of the first three rows of the test page). The MTF values from lighter patches are slightly lower (as can be seen in Figure 10).

The results from the slanted edge method and Jang & Allebach's method are remarkably close to each other. This is very important to emphasize, since those two methods use very different approaches. The fact that two very different approaches end up with almost the same result raises the meaningfulness and credibility of both




(a) vertical modulation (b) horizontal modulation

Figure 11. MTF measures from all three methods (Jang & Allebach,[1] slanted edge,[4,5] Hasegawa et al.[2,3]) for direct comparison. Values from Hasegawa et al. and slanted edge method have been compensated by simple division. Jang & Allebach's values are from the shadows (the average of the first three rows of the test page).

methods. The values measured with the method from Hasegawa et al. are significantly lower and the curve is of a different type than the curves from the slanted edge and Jang & Allebach's method.

The method from Hasegawa et al.[2] is sensible to phase shifts. For example if the printed rectangular pattern is shifted by a quarter of the wavelength, the measured CTF is equal to zero. Nevertheless the exact measurement of phase shifts depends strongly on the quality of the cross-marks used for positioning in the analysis. Since the cross-marks are printed as well, they can also be affected by phase shifts which can falsify the result. The method from Hasegawa et al. has another drawback: it measures first the CTF which has then to be converted to the MTF. The conversion can be error-prone since it depends on an infinite series. This causes that also the MTF values for low frequencies are affected by the noise from high frequency CTF values. Additionally, we do not presently dispose of a survey of the meaningfulness of the conversion. Even though theoretically proven,[7] it is not necessarily applicable to printer MTF measurements.

To determine the resolution of printing systems or for quality tests, the CTF can be used and it is not necessary to calculate an MTF. But since our goal is then to use the measurements for further image processing which is based on the printer MTF,[8] we would have to use the conversion. The uncertainty of the conversion and the striking difference between the resulting curve from Hasegawa et al.'s method and the (very similar) curves from the two other methods makes Hasegawa et al.'s method less favorable for our needs. Thus, the remaining question is whether to use the method from Jang & Allebach or the slanted edge method.

The slanted edge method[4,5] is very simple to implement and the test image (Figure 1) is very easy to create and to handle. In addition, the method has already became an ISO standard for scanner MTF measurements,[5] and thus there is already experience in using it. The measured curve is very similar to the one obtained from the very different method from Jang & Allebach, which is a priori a sign for credibility. The drawback of the slanted edge method is that it does not take into account the bias dependency of the MTF. An attempt to modify the slanted edge method by printing a step with reduced contrast (e.g. a step from 0 % to 50 % ink coverage) has led to results strongly affected by noise (see Figure 4). Therefore more effort would have to be done in order to expand this method to measure bias dependent MTF values.

The method from Jang & Allebach shows that the attenuation of a printed sinusoidal signal depends indeed on its bias value. Since it already takes into account this dependency and the other two methods do not, Jang & Allebach's method is more related to our needs. It provides a more exhaustive measurement of the printing system. The importance of the bias dependency becomes clearly evident in article[8] in which we propose an MTF compensation based on the measurements presented here.

The propositions in[3] and Section 5 help to make the method from Jang & Allebach[1] more stable and less error-prone. The linearization step and creation of the sinusoidal patches on the $Y$ axis respects the fact that a printer MTF is a physical measure and assures unaltered sine waves (seen apart from quantization errors). The decision to analyze the data from the $Y$ channel instead of the approach in CIELAB bypasses the introduction of errors by nonlinear transformations.

But the method from Jang & Allebach also has its drawbacks. It is rather complicated to implement and not easy to handle. For example it is important to carefully place the printed test image on the scanner since even small angles between the direction of modulation and the scanner pixel grid may cause unexpected attenuation when calculating the mean of the sinusoidal patch perpendicular to the direction of modulation. Additionally we did not yet test how the method (with the new proposals from Section 5.5) performs with different inks. Mainly for the yellow ink it can be a disadvantage to not use full contrast test images as it is done with the method from Hasegawa et al. and the slanted edge method, since yellow ink has a lower dynamic on the $Y$ channel. This could cause noise and have a serious impact on the measurement.

The purpose and present circumstances influence the choice of the method. If it is not possible/intended to generate test pages adapted to the printing system, one could use the slanted edge method or the method from Hasegawa et al.. Those two methods may also be favorable if the device shall be characterized for images with step-like content since the test images are a more realistic simulation. If an MTF is needed the method from Jang & Allebach and the slanted edge method should be given preference, since they measure the MTF directly. If a high precision is needed for images with different local gray levels the method from Jang & Allebach should be used since it takes into account the bias dependency.

We have good and exhaustive experiences with Jang & Allebach's method; it is robust and measures reasonable MTFs. Furthermore we successfully used the measured MTFs from this method to compensate the printing system's degrading influence with a new image processing approach. This approach takes full advantage of the bias dependent measurement, as is described in another article.[8]

## 7. CONCLUSIONS

In this paper, we provide a comparison of three MTF measurement methods carried out on an *Océ TCS-500*. The comparison shows that the slanted edge method and Jang & Allebach's method measure comparable MTF values, despite their differing conceptual approaches. This strengthens the credibility of both methods. By contrast, the measured MTF values from Hasegawa et al.'s method are significantly lower and the MTF values follow a different function type (concave instead of convex).

The method from Jang & Allebach is more complete since it additionally measures the bias dependency of the MTF values which the other two methods omit. This dependency has been proven significant for our inkjet printing system *Océ Colorwave 600* and can be exploited for printer adapted image processing based on the MTF measurement.[8]

We have presented new improvements to the MTF measurement method proposed by Jang & Allebach. Our analysis has revealed a systematic imprecision in the computation of the MTF due to the nonlinear color space conversion and the related creation of harmonics. To address this issue we propose to use the $Y$ value of CIE XYZ for the analysis instead of a $\Delta E^*_{ab}$ measure in CIELAB. This change not only avoids the systematic error, but simplifies the implementation of the method.

Future research on MTF measurement methods should investigate the reliability of the method with different devices (printing systems and scanners) and measurements with color inks.

## ACKNOWLEDGMENTS

We want to thank *Océ Print Logic Technologies* for supporting this research. Many thanks especially to Frans Gaykema from the *Océ* R & D in Venlo for his help and good advice and to Isabelle Bloch from the *Département TSI* of *TELECOM ParisTech* for her support with the writing of this paper.

## REFERENCES


[1] Jang, W. and Allebach, J. P., "Characterization of printer MTF," in [*Proceedings of the IS&T/SPIE Electronic Imaging Conference, Image Quality and System Performance III*], Cui, L. C. and Miyake, Y., eds., **6059**, 1–12, SPIE (2006).

[2] Hasegawa, J., Hwang, T.-Y., Kim, H.-C., Kim, D.-W., and Choi, M.-H., "Measurement-based objective metric for printer resolution," in [*Proceedings of the IS&T/SPIE Electronic Imaging Conference, Image Quality and System Performance IV*], Cui, L. C. and Miyake, Y., eds., **6494**(1), 64940D, SPIE (2007).

[3] Lindner, A. J., Bonnier, N., Schmitt, F., and Leynadier, C., "Evaluation of characterization methods of printer MTF," in [*Proceedings of the IS&T/SPIE Electronic Imaging Conference, Image Quality and System Performance V*], Farnand, S. P. and Gaykema, F., eds., **6808**, 6808061–68080612, SPIE, San Jose, California (2008).

[4] Bang, Y., Kim, S. H., and Choi, D. C., "Printer resolution measurement based on slanted edge method," in [*Proceedings of the IS&T/SPIE Electronic Imaging Conference, Image Quality and System Performance V*], Farnand, S. P. and Gaykema, F., eds., 680807–680815, SPIE (2008).

[5] ISO 16067-1, [*ISO 16067-1:2003 Photography – Spatial resolution measurements of electronic scanners for photographic images – Part 1: Scanners for reflective media*], ISO (2003).

[6] "http://mathworld.wolfram.com/taylorseries.html."

[7] Coltman, J. W., "The specification of imaging properties by response to a sine wave input," *Journal of Optical Society of America* **44**, 468+ (1954).

[8] Bonnier, N., Lindner, A. J., Schmitt, F., and Leynadier, C., "Compensation of printer MTFs," in [*Proceedings of the IS&T/SPIE Electronic Imaging Conference, Color Imaging XIV: Displaying, Processing, Hardcopy, and Applications*], SPIE, San Jose, California (2009).