Measurement and Analysis of MTF and its Contribution to Optical Dot Gain in Diffusely Reflective Materials

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Abstract

The optical performance of printed matter on diffusely reflecting substrate is governed by two factors: 1) Optical dot gain due to lateral spread of light within the substrate and 2) ink spread caused by physico-chemical interaction of ink and substrate. There are a limited number of studies analyzing these factors separately. In this paper we focus on the optical dot gain aspect by measurement of lateral distribution of light, i.e. the point spread function (PSF), and its analysis in terms of the modulation transfer function (MTF). Separating the two contributions, optical dot-gain from ink spread, is necessary for realistic simulation of the inkjet printing process, which is then used for printed image quality performance comparison (e.g. optical system models, virtual image chain approach, etc.). The PSF measurement methods applied can also be used for other reflective display materials in general since they do not make use of the printing process as investigated in many of the available studies. In this study we report the optical characteristics of typical substrates used in inkjet printing industry and mention examples of possible applications.

Introduction

When a electromagnetic wave is reflected from an optical surface, the reflected radiation consists of directional and diffusely reflected (or scattered) radiation. In the presence of a very smooth optical surface (i.e. surface rougness small in comparison to the illuminating wavelength) the light will be mainly specularly (directionally) reflected and will provide a mirror like image of the source. With increasing roughness of the surface the degree of specular reflection will decrease and more radiation will be diffusely scattered in all directions. In addition, scattering from subsurface voids or particles contributes to the angular distribution of the reflected radition. In addition, sub-surface scattering also introduces lateral transport of light, a.k.a. light spreading. Diffuse surfaces, such as white paper, are often used in graphical display applications, where the photo-like appearance is mainly controlled by the angular distribution of reflected light (ratio of directed and diffuse components) and surface waviness / texture. In a non-specular detection geometry, on the other hand, the visibility / readibility of small image and text details, respectively, is mainly controlled by the degree of lateral light spread. Light spread also influences the colour formation on these diffuse display.

For the analysis of the image formation performance of diffuse display materials it is therefore relevant to quantify their light spreading properties due to subsurface light scattering, which is expressed by the Point Spread Function (PSF) of the substrate. In practice, the Fourier Transform of the PSF, the so called Modulation Transfer Function (MTF), is frequently applied for the image quality analysis of imaging systems, especially if transparent films and optical elements in transmission mode are employed. However, relatively little has been published on experimental techniques for measuring subsurface light scattering and resolution characteristics of diffusely reflecting surfaces [1, 2, 3]. It is therefore a focus of our work and of this paper to provide additional practical information on reflection methods for measuring the PSF of diffuse surfaces.

In particular we investigate the lateral light spread for white paper used in several inkjet printing applications (poster, sign, document printing and packaging) in graphics industry. The paper substrate is considered as an imaging device on which the image quality can be degraded by subsurface scattering, giving rise to the so called “dot gain”. This phenomenological term describes the experimental observation that a printed dot optically appears bigger then its physical size, which is due to the subsurface scattering and lateral light transport within the paper substrate.

Various methods for the determination of the PSF (or the dot gain) of printing paper reported in literature have been specifically developed for halftone printing that make use of printed dots for the measurement and analysis of dot gain or PSF. This approach, however, has the disadvantage of mixing different spreading mechanisms namely lateral light spreading (optical PSF) and physical ink spread. In case of absorptive media the depth distribution of the colorants also influences the observed dot gain. In order to study the interdependence of physical and optical ink spread more in detail within a “virtual ink jet printing simulation” [4] both contributions – optical “dot gain” and ink spread – must be characterized independently. A volumetric optical model (e.g. Monte Carlo) is then required to realistically describe the light transport in case of non-homogenous absorption in presence of light scattering (dye- or oil-based ink on micro-porous or non-coated paper).

Here, we develop experimental methods for measuring the PSF of non printed paper. These methods are of general use for diffusely reflecting surfaces. We report PSF data for several paper substrates typically used in (inkjet) halftone printing: Four types of printing substrates were selected for comparison – a vinyl substrate, a PE coated paper with and without micro-porous coating and finally a non-coated paper.

Experimental techniques for measuring PSF of printing paper

To investigate the lateral spread of light in white paper substrates two different measuring methods were used - the Projection Edge method and the Laser Pencil method.

The most direct experimental technique for measuring lateral light scattering in paper was demonstrated by Yule and Nielsen in their original work on printed halftones [3, 5]. A high precision “knife edge” is projected onto the paper surface. The flux of light emerging from the paper and its distribution as a function of the distance from the illuminated edge can be measured by using a microdensitometer. The resulting function is the well known Edge

Response Function (ERF(x, 0)), the derivative of which provides the Line Spread Function (LSF(x, 0)).

$$LSF\ (x) = \frac{d}{dx}\left(ERF\ (x)\right) \tag{1}$$

The LSF is a direct 1-dimensional measure of the lateral distance that light can scatter from the illuminated edge.

In another experiment setup a highly focused beam of light is projected onto the paper [6, 7]. If the diameter of the illumination spot is made small enough in comparison to the distance light scatters in the paper, the decay in reflected light flux with radial distance x from the illuminated point is a direct measure of the point spread function (PSF(x, y)). The PSF can be considered as the probability density function for a photon emerging a distance x from its point of entry in the paper.

The PSF and the LSF are related as follows:

$$LSF\ (x) = \int_{-\infty}^{+\infty} PSF\ (x, y)dy \tag{2}$$

The corresponding characterization of the lateral scattering of light in the frequency domain (describing the resolution characteristics of an imaging system) is given by the Optical Transfer Function – OTF. The OTF is the Fourier transform of the line spread function. The MTF is then defined as the modulus of the OTF:

$$MTF\ (\omega) = \left|OTF\ (\omega)\right| = \Im\left\{LSF\ (x)\right\}, \tag{3}$$

with $\Im$ denoting the Fourier Transform. If the scattering surface is rotationally symmetric (i.e. light is scattered the same way in all lateral directions), then the PSF(x, y) and the LSF(x, 0) contain equivalent information and are often determined by the same set of data.

PSF measurements by Laser Pencil Method

A schematic description of the Laser Pencil Method (LPM) is shown in Figure 1. A He-Ne laser (λ = 632nm, P = 15mW) was pointed towards the paper sample under an angle of approximately 30 degrees wrt. the surface normal. The image-wise detection under 0 degree guaranteed perfect exclusion of any direct primary surface reflection, which usually are hard to perfectly exclude from the reflected signal at any specular detection geometry, even if advanced polarization techniques are used. Even small regular reflections of the first surface tend to dominate the detected signal thus making proper normalization (and thus PSF measurement) ambiguous. A microscope objective (50x *Mitutoyo)* was used to realize a Gaussian spot profile with approximately 5.6 microns in diameter ($1/e^2$). A spot scan device was used to verify the quality and size of the focused laser spot. An 8 bit CCD camera (AVT *Dolphin, 2/3", 6.45 micron pixels, intensity linearity verified*) was used to detect the reflected intensity distribution on the paper sample. The captured images were then analyzed (ImageProPlus of MediaCybernetics) in order to extract the spot characteristics. To provide appropriate magnification, a microscope objective with elongation tubes was used (5x *Mitutoyo*) in front of the CCD. The achieved addressability was 1.67 microns per pixel.

The focal position of the CCD camera was checked by focusing on small structures on the paper surface (scratches or ball pen marks). To verify the positioning of the smallest laser waist on the paper surface (along the optical axis) a high quality paper with weak subsurface scattering was used. The position of minimal beam diameter was determined and used for all the paper samples under testing. The focus of the CCD was then adjusted on the surface of each paper. The recorded image is a direct measure of the PSF (x, y). Its gray value representation corresponds to the light intensity distribution across the paper. A column summation of the intensity values in the image was performed and the resulting LSF(x) recorded (refer to Eq.2). A Gaussian fit to the data profile was used to obtain an appropriate normalization factor (free from noise).

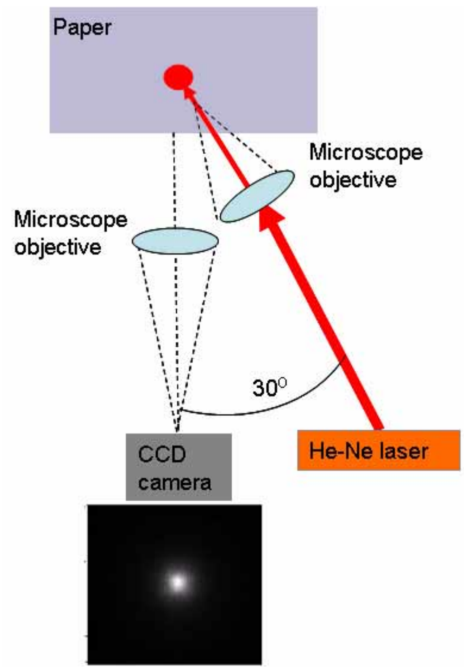

Figure 1. *Laser Pencil Method Scheme.*

It has to be mentioned that in conventional optical systems one has to be careful with the inherent image degradation due to the optical element used in a setup a.k.a. Instrument Signature (IS). It is a common practice to correct for IS by recording the light distribution without the sample under test and then to "de-convolve" this data as IS from the measured data on the samples. In cases of the printing substrates such a step is not necessary since the IS of the experimental setup is small in comparison to the lateral light spread of the printing substrates. We therefore did not explicitly correct for the laser spot contribution to the measured light spread. The same argument holds for the ellipsoidal deformation of the beam shape due to the 30 degree incident direction.

In order to translate the light spread into a contrast response one has to work in the spatial frequency domain (i.e. MTF). The conversion from measured LSF to MTF is performed according to Eq. 3 by using the Fourier Transform tool provided in Microsoft Excel, where the spatial sampling frequency is simply taken as an inverse of the pixel size of the CCD and called "lp/mm" throughout this paper. The MTF is a measure of contrast of an image in comparison to the original object. If the peaks and valleys in the test signal have the intensities I_{max} and I_{min}, respectively, the contrast of that signal is defined as:

$$C_i = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \tag{4}$$

The ratio of the image contrast C_i to the original object contrast C_o is defined as the Modulation Transfer Function – MTF:

$$MTF(\omega) = \frac{C_i}{C_o} \tag{5}$$

where ω is usually expressed in line pairs per mm or cycles per mm. Obviously, the higher the MTF the better the image contrast. The MTF is mathematically related to the PSF as shown earlier (Eq. 3). The corresponding MTFs of all 4 paper samples are shown on Figure 2.

As can be seen from the graph, the glossy paper "M" shows best performance (i.e. contrast) since it gives the highest MTF. The experiment agrees with the expected assumption that vinyl printing substrate will exhibit weaker primary and subsurface scattering and stronger specular reflection. PE coated paper "P" shows a stronger light scattering (lower MTF) compared to vinyl "M". When PE coated paper "P" is over coated with a micro-porous receiver layer, it forms paper that we call here "P micro". One can see increasing of the lateral light spread due to additional scattering and multiple reflections that are caused by the thin micro-porous top coating. This effect can be seen from the lowest MTF for the paper "P micro" which has the worst performance. .Paper "A" is a non coated paper that usually has lower quality and is highly scattering – as can be seen from its MTF.

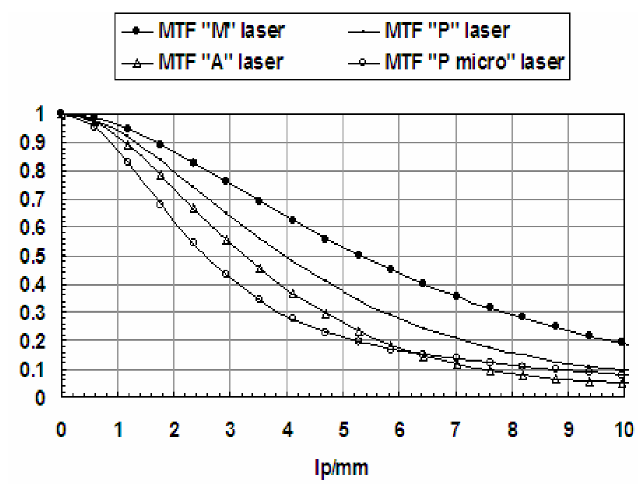

Figure 2*. Modulation Transfer Functions, using LPM for 4 different paper substrates: "M" - glossy paper, "P" - high quality paper, "A" – newspaper paper, "P micro" - high quality paper with micro-porous top coating*

PSF measurements by Projected Edge Method

The second method developed for measuring the lateral light spreading of diffuse surfaces was the Projected Edge Method (PEM). This method is well known for MTF measurement in the context of transmission geometry. The challenge here is again the experimental realization of appropriate reflective measurement geometry. The experimental setup is sketched in Figure 3: Light from a Halogen lamp is collimated using a bi-telecentric objective (Opto-Engineering) with a divergence of < 0.5 deg and then directed at 30 degree wrt. to the paper surface normal onto a very sharp edge. The edge was placed with a customizable distance of 200 – 600 micron above the paper surface. The part of the paper surface that was illuminated by half of the spot is reflected with maximum brightness but as the shadow area beneath the knife edge is approached the illumination intensity gradually attenuates until it drops to zero (in the dark shadow of the projected edge).

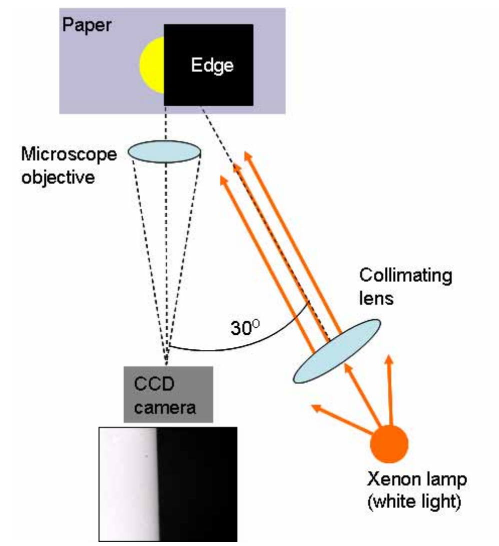

Figure 3*. Projected Edge Method Scheme*

Due to the 30 degree incident angle of the directed light the center of the shadow is shifted away from the normal position of the edge by the corresponding cosine component of the distance edge vs. paper which enables observation of a meaningful shadow region with the CCD camera. It is crucial to carefully exclude all stray light from the shadow region below the knife edge: several light baffles were used to shield parasitic illumination and all mechanical components in the neighborhood of the edge knife were coated with a matte black paint. At low enough stray light and noise levels (from CCD and surface structure of the paper) the intensity attenuation in the shadow region depends on the lateral light spread due to the subsurface scattering only and represents a direct measure the intrinsic paper edge spread function.

The image of the illuminated paper with the corresponding shadow of the edge is captured by a CCD camera (AVT *Dolphin*) with a microscope objective (20x *Mitutoyo*) and tube elongations resulting in an addressability of 0.96 microns per pixel. The intensity distribution across the edge is then obtained in terms of gray values as provided by the camera. As expected, the Signal to

Noise Ratio (SNR) of the image obtained with the large area collimated light source was quite low, which could partially overcome by an additional condenser lens between light source and bi-telecentric objective. Further improvements would require usage of a (cooled) low noise CCD camera. By image analysis a line profile of the intensity distribution across the edge was obtained (i.e. the Edge Response Function). The derivative of the ERF results into a noisy LSF (refer to Eq.1), especially at the low SNR levels. Therefore, additional numerical (adjacent) smoothing operation was used before the derivation, carefully checking that the average signal shape was not altered.

In addition, the PEM had to be corrected for the instrument signature (IS), which was mainly caused by two effects, namely:
1) for the image degradation due to optical elements used in the setup (i.e. detection optics and slightly divergent illumination) and 2) for the additional broadening of the shadow projected under non orthogonal conditions. In order to measure the IS in the non-directed measurement geometry proposed here an appropriate sample was prepared, which should not reveal any subsurface scattering but at the same time should provide enough diffuse surface reflections to allow observation under the non-directed geometry (30/0). Standard measurement of the IS in directed geometry (black glass) might otherwise introduce geometrical uncertainties. A black glass with a small amount of soot particles (smoke) deposited on the surface turned out to be a suitable reference sample for the IS measurement (superior to slightly roughened metal mirror). The low SNR in the shadow region provided a noisy LSF which in turn required even more additional smoothing of the ERF. With this in mind we expected some deviations from the result obtained by the LPM and the PEM.

In order to perform the IS correction, the following mathematical considerations were used. From Fourier analysis it is known that convolution (de-convolution) in space domain is equivalent to multiplication (division) in the spatial frequency domain [8].

$$LSF_1 \otimes LSF_2 = OTF_1 . OTF_2 \tag{6}$$

$\otimes$ denotes convolution.
Knowing that, the correction for the IS was made in terms of the corresponding OTFs as follows:

$$\Im\{LSF_P(x)\} = OTF_P \tag{7}$$

$$\Im\{LSF_G(x)\} = OTF_G \tag{8}$$

$$OTF_{Pc} = \frac{OTF_P}{OTF_G} \tag{9}$$

$$MTF_{Pc} = \left|OTF_{Pc}\right| = OTF_{Pc} . OTF^*_{Pc} \tag{10}$$

where P, G and Pc denote “Paper as measured”, “Glass with soot (IS measurement) and “Paper corrected for IS” respectively and the asterisk – complex conjugate.

The MTF’s of the same paper samples used in the PEM method are shown in Figure 4:

To obtain the IS-corrected LSF, an Inverse Fourier Transform of the IS-corrected OTF has to be performed. To overcome known numerical problems arising from Fourier transform performed on low SNR data, the measured data were first parameterized with an analytical function. A suitable analytical least square fit was obtained by the convex linear combination of a Gaussian and a Lorentz term. The analytical fit was limited to the frequency range from 0 to 30 lp/mm in order to avoid numerical instability of the procedure that was encountered for frequencies beyond 30 lp/mm. This high frequency range, however, is not relevant for the diffuse reflective display materials under investigation.

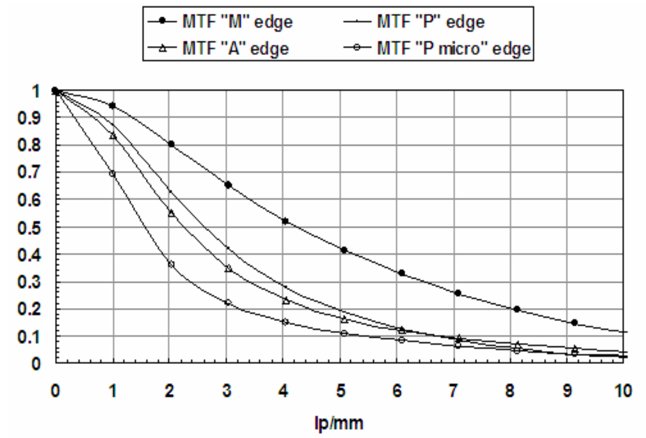

***Figure 4**. Modulation Transfer Functions, using PEM for 4 different paper substrates: “M” - vinyl, “P” - high quality PE coated paper, “A” – newspaper paper, “P micro” - high quality paper with micro-porous top coating*

Comparison of the resulting MTFs from LPM and PEM methods

As mentioned in the previous section, there are differences expected between the results from both measuring methods. The reasons are the following:

1) The difficulty of measuring the IS of the non-directional edge projection method (PEM) with good enough SNR leaves us with an uncertainty in the de-convolution of the IS. This mainly affects the sharpest paper (“M”) since lateral spread is considerably larger for the other substrates, thus making IS correction less important.

2) Both methods use different spectral distribution of illuminating light. This might result into differences in sub-surface scattering and thus to other average light spread within the paper.

3) The temporal coherence of the illuminating light sources is different in both methods and affects the resulting MTF. A complete discussion of the coherence issue is out of the scope of this paper and only general considerations are discussed here (see also ref. [9, 10] for details). The LPM uses monochromatic, highly coherent radiation of a laser, whereas the PEM is based on polychromatic radiation with low coherence. Differences between monochromatic and polychromatic radiation mostly appear in highly scattering media. The coherent illumination (LPM) creates high intensity interference peaks (i.e. speckles), whereas the low coherent light (PEM) creates peaks with much lower intensity and somewhat smeared speckles (since all the wavelengths in the spectrum contribute differently). The interference pattern is governed by the coherence length of the radiation which in the case of low coherence is much shorter compared to the coherent

case. The limited temporal coherence acts as band pass filter in the optical path length and reduces interference phenomena in multiple scattering media.

Assume a two identical electric fields impinging on a detector at point Q, where one of the fields has been delayed by τ . The total detected electric field is then:

$$E(Q,t) = E_1(t) + E_2(t+\tau) \tag{11}$$

The measured intensity is the temporal average of the total field:

$$I = \left\langle E(t).E^*(t) \right\rangle \tag{12}$$

From (8) and (9) follows that:

$$I(\tau) = \left\langle \left|E_1\right|^2 \right\rangle + \left\langle \left|E_2(t+\tau)\right|^2 \right\rangle + \left\langle \left|E_1.E_2^*(t+\tau)\right| \right\rangle$$

$$+ \left\langle \left|E_1^*.E_2(t+\tau)\right| \right\rangle =$$

$$= I_1 + I_2 + 2\,\mathrm{Re}\{\Gamma(\tau)\} \tag{13}$$

where $\Gamma(\tau) = \left\langle E_1(t).E_2^*(t+\tau) \right\rangle$ (14)

$\Gamma(\tau)$ denotes the autocorrelation function of the fields (a.k.a. *mutual coherence function*) and $\gamma(\tau) = \Gamma(\tau)/\Gamma(0)$, measures the normalized degree of coherence with values between 0 (no coherence) and 1 (fully coherent) [9,10].

Considering the differences between the two PSF measuring methods in terms of coherence, one has to be careful when comparing the resulting MTFs. Although in highly scattering medium one would expect that coherence is most probably lost immediately after the light hits its surface, it is possible that the coherence is maintained within the first few scattering events. Locally this higher degree of coherence will add up to the intensity in a manner expressed by Eq. 13. The degree of coherence will decrease after multiple scattering events (e.g. in the tail of the PSF), resulting in more "localized" intensity in the center of the PSF. This mechanism is expected mainly in the LPM giving rise to differences in the resulting PSFs/MTFs of the two methods. A comparison of the MTFs obtained with both methods is shown in Figures 5, 6, 7 and 8. The higher MTFs obtained by the LPM correspond to the more "localized" light distribution of the PSFs when measured with light of higher degree of coherence.

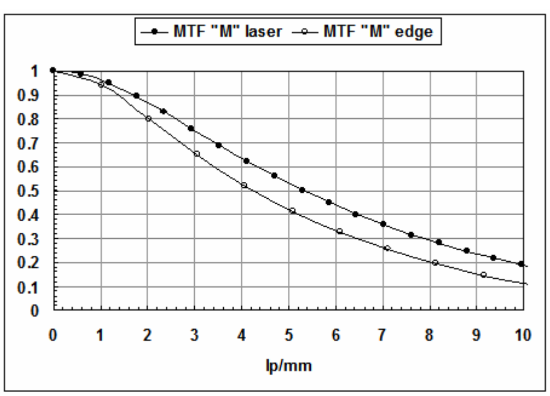

Figure 5. *MTF of glossy vinyl substrate "M" for LPM and PEM*

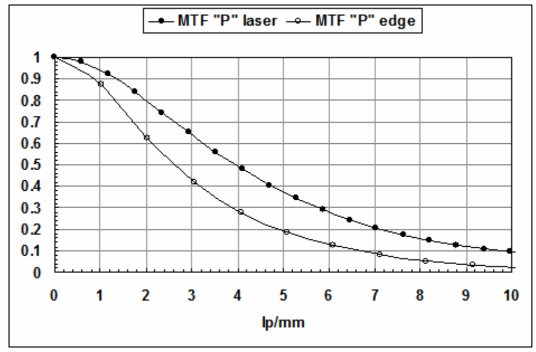

Figure 6. *MTF of PE coated paper "P" for LPM and PEM*

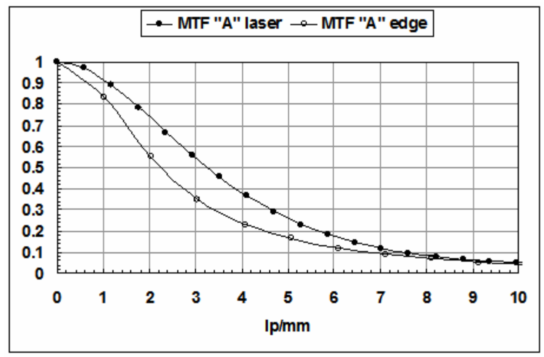

Figure 7. *MTF of non-coated paper "A" for LPM and PEM*

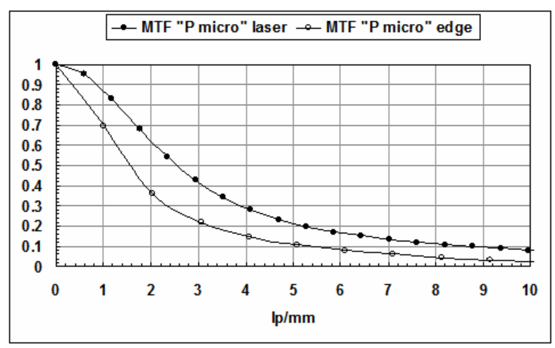

Figure 8. *MTF of PE paper with μ–porous coating "Pmicro" for LPM and PEM*

As can be seen from the figures above, the functional shape of the MTF curves from both methods is more or less maintained. PEM shows lower level of the MTFs resulting from the various reasons described earlier. This doesn't necessarily mean that there is not a unique method which will provide unambiguous results, but rather tell us the following: 1) the PSF method has to be chosen in view of the application 2) if comparison between two methods is really needed the coherence of the illuminating light has to be either identical or appropriate compensation has to be applied.

In particular, since our interest is focused on diffuse materials inspected under non-coherent white light illumination, we find that the PEM is more relevant for our future investigations.

Applications

The PSF methods described in this work are useful for the characterization of printing substrates in graphics industry, where effects of lateral light spread are important in view of perceived sharpness of image details and color formation in the context of halftone printing, an effect known as "(optical) dot gain": a printed dot appear optically bigger than its physical size. The measuring techniques do not only provide an estimate of the optical quality of the printed paper substrate but also allow quantitative analysis of the image display performance in terms of reflection MTF. An experimental example of the dot gain effect is shown on Figure 9, which shows a scanned image of dots produced with water based pigment ink on micro-porous paper: the dark halo around the printed dot is due to the lateral light transport through the paper substrate.

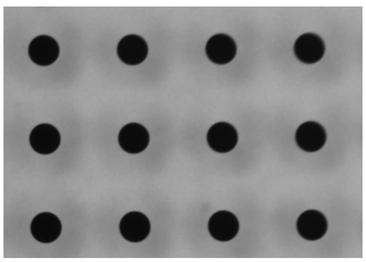

Figure 9*. Optical Dot Gain effect –dots appear bigger then their physical size due to lateral light transport*

The MTF data of the papers are used to quantitatively introduce optical dot gain effects in simulations of the halftone printing process. A virtual image chain of the inkjet printing process developed recently [1] allows to calculate microscopic images comparable to Figure 9. This way, the relative importance of physical and optical spread mechanisms can be studied.

The described PSF methods are useful as experimental benchmarks for detailed Monte Carlo studies of the volumetric light transport in the diffusely reflecting printing substrates, especially in the presence of (partially penetrating) printed dots.

The described PSF methods may also be useful for the optical characterization of projection screens. The quality of the projected image on a white diffuse screen will depend on the degree of sub-scattering. In addition, projection methods with different degree of coherence have been discussed in literature (DMD's and light valves vs. laser projection techniques).

Summary

In this article we have shown two experimental methods for measuring the degree of lateral light transport within diffuse materials. Its quantitative measure - the MTF is a valuable comparison figure of merit. In addition the measured MTF can be easily included in simulation tools as image quality parameter and help in the design/optimization of appropriate diffuse substrates. We have described in details the two methods – the Laser Pencil Method and the Projected Edge Method. The obtained MTFs for four different paper substrates were compared with each other; comparison between the two measuring methods was shown as well. Coherence effects have shown to be quite of importance. Detailed analyses suggest that for consistency when certain method is adopted care has to be taken of maintaining the coherence of the illuminating light source. Suitable applications where including the measured MTF is of importance are also suggested in the *applications* section of this article.

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