Paper Substrate Spread Function and the MTF of Photographic Paper

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Abstract

For about half a century, the effect of light diffusion in paper, as captured in the optical point spread function or its Fourier Transform (MTF), on halftone reproduction has been known. That light diffusion or scattering processes have some effect on the microstructure of an image on a diffusing-scattering substrate has not been widely studied, particularly with respect to photographic prints. The purpose of this study is to construct a simple model of photographic printing paper that specifically includes the effect of the paper spread function or MTF. The paper substrate spread function influences the overall MTF at two different stages in the process of exposing and measuring the print MTF. The first influence is during the exposing stage, where the MTF acts in a linear manner. In the second stage, the paper substrate spread function is nonlinear, causing a reduction in modulation during the measurement of the print image. Because of this nonlinear stage, a Contrast Transfer Function (CTF) is developed that is a function of all relevant, and measurable, parameters. Model predictions show that the paper substrate spread function, and not the MTF of the photographic emulsion forming the image, dominates the normalized CTF of the print. Results from the model are compared with published data and show good agreement.

Introduction

Flatbed desktop scanners connected to personal computers are common, and they are used to scan all sorts of photographs. One area of increasing interest is scanning old photos from early photographic processes. It is not uncommon to find photographs that are in excess of 120 years old in family collections.

Although it is practically difficult to determine the image quality characteristics of the early cameras (e.g. the MTF of the system), there is another element of the photographic process that can be considered limiting; the photographic paper. Once the limiting factor, or upper bound, of the spatial properties of the photographic print is identified, the "maximal" scanning parameters can be readily calculated.

Although photographic papers have been manufactured for longer than film has been made, there is little in the literature on their image microstructure properties. One of the earliest comprehensive experimental investigations of the "sharpness" (really the MTF) of photographic papers is that reported by Ruth Stapleton.[1] One of the general conclusions of her work was that the Modulation Transfer Factors of photographic paper, as measured by edge gradient analysis, was never as high as that produced by the paper photographic emulsion (film) by itself. The cited cause of this was the "multiple internal reflexions in the gelatine layer." Although this is, perhaps, a contributing factor, it does not appear to be the one of consequence. Present knowledge suggests that the most significant factor is the spread of light within the paper base.

The problem of light spreading within the bulk of a paper image substrate was identified by Yule and Nielsen[2] over 50 years ago. They termed this phenomenon "optical dot gain" referring to the apparent increase in dot area due to the paper. Substantial research work has been reported in the literature on the topic of dot gain and the spread or diffusion of light in paper. Much of the effort has centered on predicting the mean spectral reflectance or colorimetric values of halftone patterns[2-15] and estimating or measuring the paper optical spread function or its Fourier transform.[4,15-23] Generally speaking, there has been little work done on examining the effect of the paper optical spread function on the microstructure of images, but there are some exceptions.[1,23] So far as this author can determine, Stapleton's report[1] is the only work directed towards photographic paper.

The exposing and measurement process of sinusoidal images on photographic paper is far more complex than its photographic film counterpart. The roots of this complexity can be traced to the paper optical spread function (POSF). The POSF contributes to image degradation at both the exposure and measurement or viewing stages. At the measurement stage, the system is also inherently nonlinear.

The goal of this investigation is to formulate a simple model of the exposure of a sinusoidal image that includes the MTFs of both the photographic emulsion layer and the paper MTF. What is presented in this paper is a "small-signal" model of the exposing and measurement of sinusoidal exposure distributions of photographic paper.

Modulation Transfer Function Models

The problem of measuring the MTF of photographic paper is divided into two steps: 1) exposing, and, 2) measurement. In this section, a model for step each is developed.

Exposure MTF Model

Typically, silver halide, AgX emulsion is coated on a high-quality coated-paper or polymer stock. In addition to the AgX coating, a baryta layer coats the paper, which results in a substrate that includes high scattering among its properties. The coatings contribute to light scattering, as does the substrate itself.

The exposure model consists of a one-dimensional normally incident sinusoidal irradiance of the form in equation (1).

$$E_I(x) = a_e \bar{I}\left[1 + T_f(u_0) M_e \cos(2\pi u_0 x)\right] \tag{1}$$

where a_e = the fraction of light absorbed by the AgX layer, I is the average irradiance, M_e = the sinusoidal esposure modulation = (max-min)/(max+min), $T_f(u_0)$ = the MTF of the AgX layer, x = distance, mm, and u_o = the spatial frequency, cy/mm, of the sinusoidal exposure. For simplicity, only the irradiance is considered in this model. A simple scaling by exposure time gives the units of exposure. In practice, the model parameters are all functions of wavelength, λ. Wavelength notation is not explicitly carried in the model, but in some situations it may be crucially important and should be incorporated.

During the initial exposure, the light is channeled three ways: some of the light is absorbed by the AgX coating (emulsion), some is transmitted, t_e, and some is reflected by the emulsion surface. The reflected component is ignored in this model. The sinusoidal light distribution gets scattered by the emulsion coating as it passes through the layer. It is assumed that this scattering is represented by the well-known modulation transfer function of the film, $T_f(u_o)$. for both the absorbed light, exposure, and the transmitted light. If the primary mechanism is light scattering by the AgX coating, then this seems to be a reasonable assumption. The spatial distribution of the light after passing through the emulsion layer and before encountering the paper substrate is still a cosine.

At this point, the cosinusoid has been reduced in modulation by the modulation transfer factor, $T_f(u_o)$, of the AgX layer at spatial frequency u_o. This transmitted sinusoidal image is then incident on the paper substrate. Again, the overall amount of reflected light is reduced by the paper reflectance factor, r_p, and the modulation of the reflected light is reduced by the paper MTF, $T_p(u_o)$. It is assumed that the diffusion of light within the paper is a linear system. Although this assumption does not seem to have been explicitly tested, the measured data to date[18-23] suggests that this is quite reasonable.

The reflected light, the light that is coming from the direction of the paper substrate, constitutes a second exposure to the AgX layer. If we now simply assume that the two exposure distributions E_I and E_{II} add, then the total relative exposure distribution for the photographic layer is just the sum of the two exposure distributions in each direction.

The exposure modulation is computed by taking the difference between the maximum and minimum exposures and dividing that by the sum of the maximum and minimum. Since we assume the scattering is isotropic, then there is no particular reason to assume any phase shifts of the exposure distribution. In this case, the maximum occurs at $x=0$ and the minimum at $x = 1/2\ u_o$. Dividing the exposure modulation by the input modulation, M_e, yields the exposure MTF, $T_{fe}(u)$, of the photographic paper. The exposure MTF incorporates the paper MTF, the emulsion layer MTF, the reflectance of the paper, and the transmittance of the AgX layer. Equation (2) shows this result.

$$T_{fe}(u) = \frac{T_f(u)\left[1 + r_p t_e T_f(u) T_p(u)\right]}{1 + r_p t_e} \tag{2}$$

Equation (2) shows that the exposure MTF of the photographic paper is not simply the MTF of the emulsion layer, $T_f(u_o)$. This “intrinsic” MTF is reduced by a function that depends on the transmittance of the emulsion layer, the reflectance of the paper, and the paper MTF. For very low spatial frequencies, the exposure MTF is approximately equal to the MTF of the AgX layer. At spatial frequencies where the paper MTF is zero, the exposure MTF is the AgX emulsion layer MTF reduced by a factor equal to $1/(1 + r_p t_e)$. This factor lies in the interval of one to two, so, at most, the reduction in the inherent emulsion MTF is only a factor of two.

Note that since $T_f(u_o)$ *and* $T_p(u_o)$ are typically less than one, the photographic paper exposure MTF is always less than the AgX emulsion layer alone. From a photographic paper design point of view, the exposure MTF can be maximized by reducing either the paper reflectance, the emulsion transmittance, or both. Figure 1 shows percent absorptance versus wavelength for some representative silver halide emulsions.[27] Note that these spectral absorptance curves are strong functions of wavelength. Reducing the emulsion transmittance by incorporating a dye, say, is a well-known tactic for increasing spectral sensitivity and improving the spatial frequency response by reducing halation.[23b]

AgX Layer Sensitometric Assumptions

The latent, or exposure, image is inaccessible to measurement before the conversion to a silver image via development. Common practice for determining the MTF of photographic materials is to incorporate various levels of exposure in the form of large–area gray patches. These patches serve to characterize the nonlinear emulsion (film) response to light, and to determine the effective exposure of the sinusoidal patterns.[24] To avoid this model complexity, an approximation can be developed by assuming a small modulation signal.

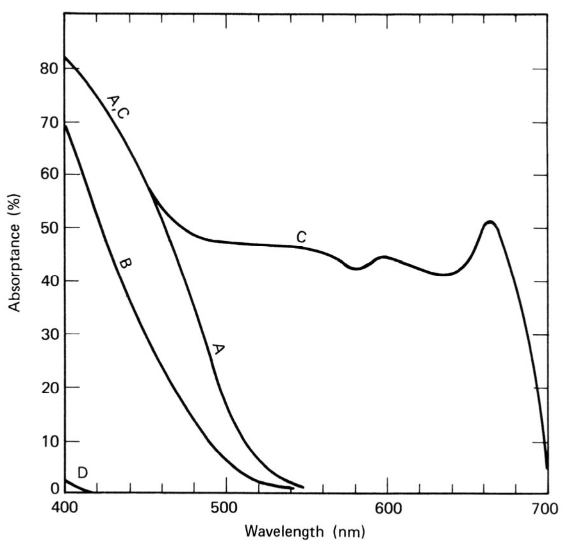

Figure 1. Absorptance spectra for several different silver halide emulsions. A = undyed negative type, B = extremely fined grain type, C = A with sensitizing dye, and D = pure silver chloride. From Ref. (26)

In order to develop a closed-form solution, and in the interest of simplicity, the small signal approximation for the developed sinusoidal transmittance image is used, which is given by equation (3). This equation can be developed by using the first term of the binomial expansion of equation (1).

$$t_I(x) = \left(a_e \bar{I}\right)^{-\gamma}\left[1 - \gamma T_f(u_0) M_e \cos(2\pi u_0 x)\right] \quad (3)$$

This equation is a good approximation for modulations < 0.15 and gamma values < 2.5. For these cases, the amplitude of the second harmonic is typically < 0.01.

Measurement MTF Model

Once the exposed photographic paper is developed, a low-modulation sinusoidal transmittance image exists on the paper substrate.

The measurement model assumes the same layered structure as the exposure model, with the exception that the illumination is constant and is modulated by the transmittance image in the photographic emulsion layer.

After passing through the exposed and developed photographic image, the uniform-intensity illumination is incident on the paper surface as a sinusoidal image, which is reduced in modulation by the same paper spread function (MTF) that reduced the modulation of the exposure image. Again, it is assumed that this is a linear process. The reflected image must now pass back through the transmittance image before the measuring instrument can detect it. This multiplication step gives rise to a nonlinear system that generates a frequency of twice the frequency of the transmittance pattern.

The measurement instrument does not have perfect spatial frequency response, hence the detected sinusoidal image is reduced in modulation by the MTF of the measuring instrument $T_m(u)$.

Since this measurement process is inherently nonlinear, it is not correct to formulate a linear system modulation transfer function. Instead, a Contrast Transfer Function, CTF, is defined via the minimum and maximum of the reflectance distribution. This CTF is defined by equation (4), which is more detailed than previously reported.[22]

$$CTF(u) = \frac{M_i T_m(u)\left[1 + T_p(u)\right]}{1 + \dfrac{M_i^2 T_m(u) T_p(u)}{2}\left[1 + \dfrac{T_m(2u)}{T_m(u)}\right]} \quad (4)$$

If the spatial frequencies are low enough, or the measurement instrument has sufficient high MTF, then the ratio of the two MTF's in the denominator of equation (4) is approximately 1.0 and we can rewrite it in a simpler form as equation (5).

$$CTF(u) = \frac{M_i T_m(u)\left[1 + T_p(u)\right]}{1 + M_i^2 T_m(u) T_p(u)} \quad (5)$$

Careful perusal of equation (5) will reveal that there is a "gain" associated with the transmittance image on paper. For low modulations, M, $CTF(0)$ approaches $2M_i$, but as M_i approaches *1.0*, $CTF(0)$ approaches M_i. Thus there is an interesting low-contrast gain factor of two that enhances the contrast (modulation) of low-contrast imagery.

If we are willing to assume that the measurement instrument has a high MTF compared to the optical MTF of the paper, and use low-modulation sinusoids, then equation (5) can be further simplified to yield a simple equation for the paper MTF. When using small M_i and when using a measurement instrument that is assumed to be of high spatial quality, $T_m(u)$. *1.0,* and the numerator in equation (5) becomes equation (6). Solving for the paper MTF, $T_p(u)$, yields equation (7), which is an estimator for the paper MTF.

$$CTF(u) \approx M_i\left[1 + T_p(u)\right] \quad (6)$$

$$T_p(u) \approx \left[\frac{CTF(u)}{M_i} - 1\right] \quad (7)$$

The two variables in equation (7)–the modulation of the sinusoidal transmittance image and the measured contrast transfer function–are either known or readily measured, and thus can be used to estimate the paper MTF.

Combined Model CTF

The complete relationship for the combined exposure MTF and measurement CTF, including the measurement-device MTF, is shown in equation (8).

$$CTF(u) = \frac{\dfrac{\gamma M_e T_f(u) T_m(u)}{1 + r_p t_e}\left[1 + r_p t_e T_f(u) T_p(u)\right]\left[1 + T_p(u)\right]}{1 + \dfrac{1}{2}\left\{\dfrac{\gamma M_e T_f(u)}{1 + r_p t_e}\left[1 + r_p t_e T_f(u) T_p(u)\right]\right\}^2 T_p(u) T_m(u)\left[1 + \dfrac{T_m(2u)}{T_m(u)}\right]} \qquad (8)$$

Experiment

Since it is quite easy to generate models, the real test occurs when they are applied. Unfortunately, there is a dearth of data in the literature on the model parameters of interest, so comparison experiments are necessarily limited. Because of limited data, the objective in testing the model is limited in scope to obtaining “order of magnitude” results.

Model-Data Comparison

The experiment consisted of a comparison of the photographic paper contrast transfer function, CTF, model to published data. This presented a significant challenge because the key model parameters are not generally known.

The strategy was to use published data, notably Ref. (1), fix a small number of parameters, and estimate the paper MTF parameters that best fit the data in a least-squares sense. It turns out that only one parameter, the AgX layer transmittance can be arbitrarily fixed. The paper reflectance, assumed to be *R-infinity* in Kubelka-Munk theory, is a parameter of the paper MTF model,[18] so was not independently variable. For the paper MTF model equation (A3) was used.[18]

Stapleton’s film MTF data curve B (Figure 3 of Ref. (1)) was used for model value of $T_f(u)$. Using raw, noisy data points can make the interpretation of the result almost impossible, so a least-squares fit of the film MTF data was used for the calculations.

It is not entirely clear from Ref. (1) whether all the published MTF curves were corrected for the measurement MTF, a 9µm slit. For this reason, a slit-width parameter, *w*, was added to the least-squares calculation, which represents the measurement MTF, the well-known Sinc function, $\sin(\pi uw)/(\pi uw)$.

Preliminary computations suggested that excellent least-squares fits to the measured paper MTF could be obtained by varying *R-infinity*, the scattering coefficient, *S*, and *w*. However, the estimated parameter values of *R-infinity* and *S* for the paper were unrealistic when compared to published data for typical papers.[18,19] Considering these preliminary results, the computational strategy was altered to keep a fixed value of *R-infinity* and solve for *S* and *w*. Both *S* [see equation (A3)] and *w* control the roll-off rate of the measured CTF and thus provide CTF shaping.

The computational procedure consisted of selecting the two parameters–the emulsion transmittance, t_e, and *R-infinity*–and solving for the paper scattering coefficient, *S*, equation (A3), and slit width, *w*. The *S* and *w* estimates minimized the mean-squared difference between the model CTF, equation (8), normalized so CTF(0) = 1, and curve C from Stapleton's Figure 3 of Ref. (1). This yields a comparison of Stapleton’s data with the model.

Model Results

A number of good fits were obtained over a wide range of *S*, t_e and R-infinity. But not all of these solutions were particularly realistic. A decision was made to restrict the range of the free parameter R-infinity to the interval of 0.6 to 0.95. Published data for coated non-photographic paper suggested that reasonable values of the scattering coefficient, *S*, lie in the range from 5 to 150mm^{-1}.[18,19] The absorption coefficient, *K*, *S*, and *R-infinity* are locked together. Therefore, given any two, the other can be determined.[28]

The transmittance of the photographic paper AgX layer is completely unknown except for the guidance provided by Stapleton's Figure 3. Using a fixed emulsion transmittance for each of the least-squares fits covering the range of 0.1 to 0.5 gave reasonable values of *S*. Curiously, almost all computations gave 9µm as the estimate for the slit width, and suggesting, perhaps, that the data from Reference (1) did not have any measurement MTF correction.

Figure 2 shows some typical model results and the measured data for *R-infinity* = 0.80, *S* = 143 and t_e = 0.5. The RMS error about the fit is 0.0.024. Figure 3 shows additional results for this set of parameters. The top curve is the function fit to the measured film MTF from Ref. (1). The next closest, lower, curve is the exposure MTF from equation (2), and the third curve from the top is the model fit to the data shown in Figure 2. Finally, the bottom curve is the paper MTF according to equation (A3) using the estimated model parameters.

Discussion

The proposed model seems quite reasonable in its general characteristics. In particular it models the “break point” in the MTF/CTF curves for photographic paper[1] with reasonable parameter values for the paper and AgX layer. Further testing is required to see how well the model performs with a greater variety of photographic papers.

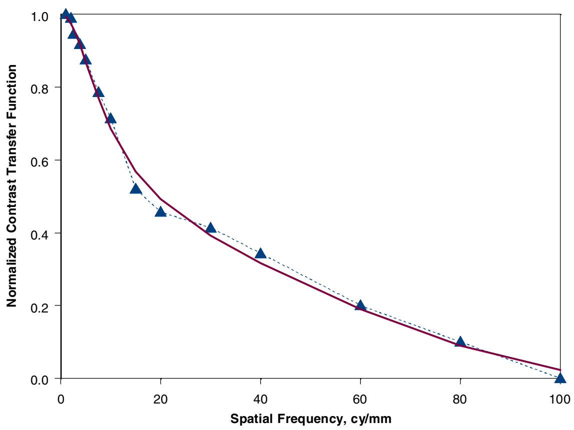

Figure 2. Comparison of CTF Model, solid line, and data, filled triangles, from Ref. (1). See text for model parameters

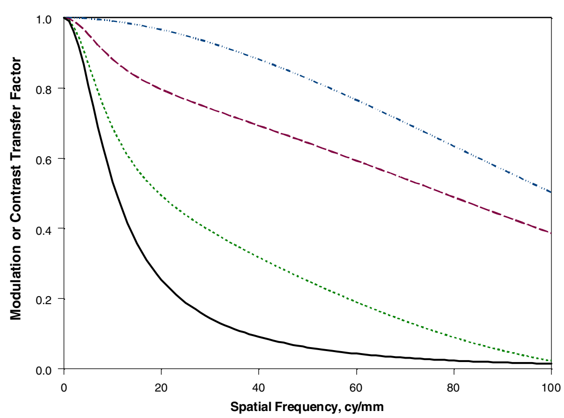

Figure 3. MTF and CTF model curves. Top curve, dot-dash is the emulsion layer MTF, next lowest curve, dashed is the photographic paper exposure MTF, the dotted curve is the paper CTF, and the bottom, solid, curve is the paper substrate MTF.

According to this model, equation (8), the recovery of the photographic paper exposure MTF is not simple. It does not appear that the standard practice of dividing the measured MTF/CTF, or SRF, by the input pattern/target modulation is completely adequate to recover the exposure MTF, $T_{fe}(u)$, under all circumstances. The recovery process is complicated by having several unknown quantities, the most troublesome the paper MTF.

The model shows that there are no practical circumstances where the photographic paper MTF/CTF can be equal to the exposure MTF of the silver halide layer. The CTF is typically degraded toward the paper MTF, but remains higher over most of the spatial frequency bandwidth. Without exhaustive calculations, it appears that the bounds on the CTF are the inaccessible exposure MTF of the AgX emulsion coating and the MTF of the paper itself. Both of these factors give some insight into *why* it is difficult to produce high frequency test patterns of high modulation using conventional photographic processes.

It is important to note that all of the functions and parameters in the model are wavelength dependent, although not explicitly formulated as such. Photographic emulsion absorptances, and paper scattering and absorptance are generally wavelength dependent. This dependence, particularly in the short wavelengths, is responsible for yellow appearance of papers and photographic emulsions. For color imaging applications this can become critically important.

Conclusions

A model has been constructed of the exposing and measuring components of a sinusoidal test pattern exposure of photographic paper to estimate the modulation transfer function, MTF, of the paper. Under suitable assumptions, the exposing part is linear, and yields an MTF for exposure. However, the measurement part is non-linear and is characterized by a contrast transfer function, CTF.

A test of the complete model using least-squares-fit to published data showed good agreement, and provided estimates of parameter values that seemed reasonable. However, more work is needed in developing reliable, practical, estimators for paper substrate MTFs from the model.

The complexity of the model has implications for using photographic paper reflectance patterns in testing of imaging systems (e.g. desktop scanners). In the first instance, the Fourier spectrum of the pattern will be limited by the paper or other scattering substrate, not the photographic emulsion itself. This makes it extremely difficult to make high modulation patterns at high spatial frequencies. Since the test patterns are not "perfect" the correction for the pattern is more complicated than has been assumed. In practice, the image fluctuations, noise, make a more exact correction extremely difficult. More work needs to be done to improve the estimators before this model can be widely applied.

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Appendix

Equations for paper reflectance point spread function, PSF, line spread function, LSF, and MTF from Ref. (18). These expressions are based on Kubelka-Munk Theory for a homogeneous absorbing and scattering layer.[28]

Point Spread Function, *s(r),* equation (A1)

$$s(r) = \frac{S(1-R_\infty)^2 e^{-2bSr}}{\left(1-R^2{}_\infty e^{-2bSr}\right)^2} \qquad \text{(A1)}$$

where r = distance, mm, S = the K-M scattering coefficient, mm^{-1}, R_∞ = the reflectance factor of an infinitely thick "pile" of paper, 2b = (1/ R_∞ - R_∞).

Line Spread Function, *l(x),* equation (A2).

$$l(x) = \frac{2bS}{\pi \ln\left[\frac{1}{1-R^2{}_\infty}\right]} \sum_{j=1}^{\infty} R_\infty{}^{2j} \left(j2bS|x|\right) K_1\left(j2bS|x|\right) \qquad \text{(A2)}$$

where $K_1()$ = modified Bessel function of the first kind and order one and x = distance, mm.

$$T(u) = \frac{1}{\ln\left[\frac{1}{1-R^2{}_\infty}\right]} \sum_{k=1}^{\infty} \frac{R_\infty{}^{2k}}{k} \left[1+\left(\frac{2\pi u}{kS\left(\frac{1}{R_\infty}-R_\infty\right)}\right)^2\right]^{-\frac{3}{2}} \qquad \text{(A3)}$$

Fourier Transform of equation (A1), the paper "MTF", *T(u)*. Where u = spatial frequency, cy/mm.

Biography

Peter Engeldrum, the president and founder of Imcotek, a consulting firm, has over 35 years experience in the imaging field. Image quality and image microstructure have been consistent threads throughout Peter's professional career. His interest in image quality began when he developed and printed his first roll of black and white film and wondered why the pictures were grainy and fuzzy. He is still trying to figure it out.

Peter has degrees in Imaging Science from the Rochester Institute of Technology (RIT), where he served as a faculty member in the Center for Imaging Science for six years. He has published a book, entitled *Psychometric Scaling: A Toolkit for Imaging Systems Development*, and numerous technical papers on a variety of imaging topics. Peter holds several issued patents, and has patents pending, in Internet imaging and display calibration.

He is a Fellow of IS&T. Since his undergraduate days at RIT, he has served in a variety of capacities for the Society and in three IS&T Chapters. Most recently he was the IS&T Visiting Lecturer for 2000-2001. Peter is also a member of the Optical Society of America and the Technical Association of the Graphic Arts.