Senior Research

Scattering and Depolarization in a Complex System

Final Report

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Scattering and Depolarization in a Complex System

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Abstract

The focus of this research project has been on modeling the effects of scattering and depolarization in mildly turbid media. A turbidometer was designed and constructed to measure the amount of scattering and depolarization caused by various sizes and concentrations of latex particles in aqueous suspension. The relationship between scattering and depolarization was found to have only a small dependence on particle size and/or size distribution. These relationships were used to find the number of scattering events. Two scattering events were found to be sufficient to completely depolarize the incident light for all six latex samples, regardless of the direction in which the light exited the sample. Side-scattered light was found to lose between 25-50% of its polarization, even when nearly zero scattering events take place. These results indicate that the small amount of scattering that may occur within an ink layer may partially depolarize the light. This has significant implications for the interpretation of BRDF measurements using the micro-goniophotometer developed in this laboratory.

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Introduction

An instrumental method of analysis of gloss on both printed and unprinted paper substrates that is consistent with psychometric testing has recently been an actively researched area in our laboratory. Gloss has been traditionally measured using gloss meters, but they only measure specularly reflected light at fixed angles. A better approach involves the use of a microgoniophotometer, which measures the angular distribution of light at a high angular resolution. One such device was developed in our laboratory and is described in detail elsewhere.[1] The focus of the work described in the current report is on the meaning and significance of the experimental technique used in the microgoniophotometer for separating the specular component of the light reflected from the diffuse Lambertian component.

Any instrument designed to measure the specular component of reflected light must separate the specular from the Lambertian diffuse component. The conventional method of isolating the specular component is based on the goniometric difference between specular and diffuse light. Specular light is reflected at an equal/opposite angle, but diffuse light is reflected at all angles between -90° and 90°. As a result, a small solid angle around the specular angle captures specular light with a negligible amount of diffuse, Lambertian light.

The microgoniophotometer developed in our laboratory separates specular from diffuse light by applying a different property of specular reflection. Linearly polarized light is used to illuminate the sample. The specularly reflected light maintains this polarization, but Lambertian diffuse light scrambles the polarization. Polarizers are placed on both the light source and the camera, and images are captured using both crossed and parallel polarizers. The image taken using crossed polarizers, which represents the diffuse component, is subtracted from the parallel polarizer image, which contains both a specular and a diffuse Lambertian component. Nominally, the process of subtraction results in an image that contains only the specular component of the light. However, recent analysis of a variety of printed and non-printed papers strongly suggests that some of the light that is reflected from the samples may contain light that is not clearly either diffuse Lambertian light nor specular light, but may have properties that are between these two extremes. It is quite possible that some of the light may penetrate into the paper or ink, undergo a small number of scattering events, and emerge as reflected light dispersed over a wider angular range, but still maintain some partial degree of polarization. We refer to this component of reflected light as hybrid light, and the intent of the current work has been to examine the behavior of hybrid light in turbid materials in order to judge its possible significance in the use of the microgoniophotometer.

Since hybrid light has properties of both scattered light and polarized light, the experimental design for the project was to measure the degree of de-polarization of linearly polarized light as a function of the amount of scattering. An experimental rather than a theoretical approach was chosen because paper is a complex system, and it is difficult to measure the fundamental physical and optical properties that so many scattering models require. When a layer of ink or toner is applied to the surface of the paper, an added layer of turbid media is added onto an already complex system.

A turbidometer was designed and constructed to perform this experiment. It was used to measure the amount of scattering and depolarization caused by various sizes and concentrations of latex particles in aqueous suspension. The different latex particle samples also had varying size distributions. The goals of the experiment are to develop useful models for the relationships between scattering and depolarization fraction, and to achieve a better understanding of the hybrid light component. The results of this research can expand our understanding of the optical properties of the hybrid component of light that is neither Fresnelian nor Lambertian.

Scattering Theory

Scattering of light has been carefully studied since at least the late nineteenth century, and a vast body of literature has been published on the subject. If we consider our particles to be much larger than the wavelength of light, and that they act as a white surface that follows Lambert's law (as latex should), then according to van de Hulst[2], "it is consistent with this law to postulate that the reflected light is unpolarized, irrespective of the polarization of the incident light." However, the particles used in this experiment are not significantly larger than the wavelength of light. For this experiment, the size of the particles is on the order of the wavelength of visible light. This, according to van de Hulst, makes empirical scattering measurements useful, since it is difficult to model scattering for those particle sizes.[2]

The depolarization behavior of multiple scattered light has been studied by Brosseau, et al[3]. However, the study covered only four unique particle sizes over a range between 0.22μm and 1.05μm. Furthermore, the paper is only concerned with multiple scattered light, which is not always the case for our system. The deviation from the Lambert-Beer law in transmittance of light passing through suspensions of polystyrene latex spheres was studied by Zaccanti and Bruscaglioni[4], but they measured just one angle and did not attempt to measure scattering or the effects of depolarization. Nee and Nee[5] recently published a simulation of the polarization of transmission scattering using a multiple-facets model. They state that a perfectly Lambertian surface perfectly depolarizes incident light, while a perfectly smooth surface maintains the polarization of the incident light. They found that a single-facet model did not depolarize light or change the polarization. A double-facet model also didn't appreciably depolarize light, however, polarization was significantly changed. Depolarization was found to increase appreciably with increasing numbers of facets. However, they did not attempt to derive a relationship between the amount of angular scattering and the amount of depolarization. Rojas-Ochoa, et al[6], published a paper on the depolarization of backscattered linearly polarized light. Their paper focused on particles with sizes between 80nm and 1.5μm, using a diffusing wave spectroscopy technique to measure the depolarization properties. They also did not attempt to derive a relationship between scattering and depolarization. Bicout, et al[7], studied the influence of particle size on the depolarization of multiply scattered light. Their research only covered particles with just three sizes between 0.22μm and 1.05μm, and mainly focused on differences in the characteristic length of depolarization that depend on whether the light is initially linearly or circularly polarized.

The appropriate scattering model depends both on the size and distribution of the scattering centers. For common ink layers, this is not known and may vary significantly among different ink types. However, anecdotal experience appears to suggest the scattering behavior of common inks may not be significantly dependent on the wavelength of light. This suggests so called non-specific scattering, which is reasonably well modeled with a simple random walk or by Kubelka-Munk scattering theory. Thus, Kubelka-Munk was used to model the data collected in this project, and data was collected for a wide range of particle concentrations in latex dispersions with particle sizes over a wide range. As will be shown, the Kubelka-Munk theory adequately described the experimental data.

Experimental Methods

Turbidometer Design

A turbidometer was constructed in order to carry out the experiment. The turbidometer and its individual parts are shown in figure 1. Light is generated by the fiber optic light source and then collimated with a lens. The light then becomes polarized, with the direction of polarization chosen by rotating the mounted polarizer. A neutral density filter (0.5 N.D.) was put in place when the photodiodes became saturated, typically at the lower concentrations. A hot mirror was used because a significant fraction of the fiber light's output is in the infrared, but the linear polarizers only polarize light in the visible portion of the spectrum. This report is concerned only with the behavior of visible light. A light-proof box was constructed and used to hold the cuvette, the analyzing polarizers, and the photodiodes. The box was divided into four chambers so that only light that passes through the cuvette can reach the detectors. The polarizers in front of the photodiodes were oriented with the same polarization axis.

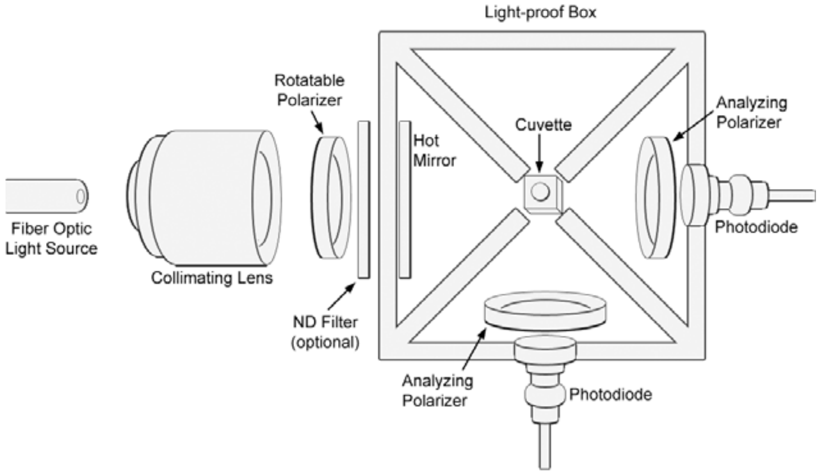

Figure 1. An overview of the turbidometer and its component parts. The photodiode on the right is considered the 0° detector, and the photodiode on the bottom is considered the 90° detector.

The light-proof box was constructed with a light tight cover to allow it to be used under typical room lighting conditions. This was validated by comparing measurements with the room lights on and off. In each case, the difference was significantly less than the noise level of the detector. The response of the photodiodes was tested using neutral density filters and was found to be perfectly linear for the range of irradiance values used in this experiment.

Data Collection and Processing

A syringe was used to measure the amounts of latex and water. The latex samples were provided by a colleague in another laboratory who also provided measurements of particle size distribution. The latex samples were provided as aqueous dispersions and were diluted with distilled water. The concentration was halved for every measurement by using half of the contents in the syringe, replacing the missing half with distilled water, and shaking vigorously to ensure an even dispersion. The samples were injected into a 1cm cuvette, which was then placed in the light-proof box. Particle concentrations, c, are all expressed as fractions of the starting concentration.

Collecting and processing detector data for each sample was straightforward. Voltage was measured at both detectors, with the rotatable polarizer oriented in both crossed and uncrossed orientations. The following four voltages were recorded for each concentration of each latex sample.

$V_{0,\parallel}$ = detector voltage at 0^o with polarizers parallel.
$V_{0,\perp}$ = detector voltage at 0^o with polarizers crossed.
$V_{90,\parallel}$ = detector voltage at 90^o degrees with polarizers parallel.
$V_{90,\perp}$ = detector voltage at 90^o degrees with polarizers crossed.

The limiting values of $V_{0,\parallel}$ at c=0 and c=∞ were also measured and labeled as follows.

$V_{0,\parallel,c=0}$ and $V_{0,\parallel,c=\infty}$

From these voltage signals, the following optical properties were calculated at each concentration.

Turbid Transmittance at 0°:
$$T_{\|} = \frac{V_{0,\|} - V_{0,\|,c=\infty}}{V_{0,\|,c=0} - V_{0,\|,c=\infty}} \tag{1}$$

Irradiance of light scattered at 90°:
$$I_{\|} = \frac{V_{90,\|}}{\max(V_{90,\|})} \tag{2}$$

Figure 2 is a typical example of experimental data for one of the latex samples. The fraction of the light that maintained polarization at both 0^o and 90^o was calculated using equations (3) and (4), and Figure 3 illustrates typical results.

$$P_0 = \frac{V_{0,\|} - V_{0,\perp}}{V_{0,\|}} \tag{3}$$

$$P_{90} = \frac{V_{90,\|} - V_{90,\perp}}{V_{90,\|}} \tag{4}$$

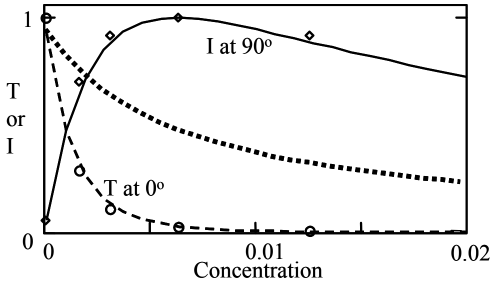

Figure 2: T and I versus concentration for latex sample A. The dotted and dashed and solid lines are models described below.

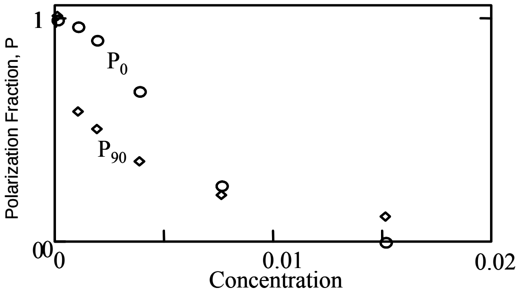

Figure 3: Polarization fraction versus concentration for the latex sample A.

As expected, an increased concentration of latex particles causes an increase in light scattering and a decrease in polarization. To examine the link between scattering and depolarization, the scattering was modeled using Kubelka-Munk theory.

The Scattering Model

The scattering process was modeled using the Kubelka-Munk equations. For the following equations, c is the relative concentration, k is the absorption coefficient per unit of c, k_s is the scattering coefficient per unit of c, L is the length of the cell in cm, $K(c)$ is the absorption coefficient as a function of concentration, and $S(c)$ is the Kubelka-Munk scattering coefficient as a function of concentration. Certain terms that would normally be defined as constants are written here as functions of concentration, since they will be used as such in order to model the scattering process. The following equations were used[8]:

$$K(c) = k \cdot c \tag{5}$$

$$\mathrm{S(c)=k_S \cdot c} \tag{6}$$

$$a(c) = \frac{K(c)}{S(c)} + 1 \tag{7}$$

$$b(c) = \sqrt{a(c)^2 - 1} \tag{8}$$

The Kubelka-Munk turbid transmittance, T_{KM}(c), was then modeled at 0° as a function of concentration using the equation

$$T_{KM}(c) = \frac{b(c)}{a(c)\cdot\sinh[b(c)\cdot S(c)\cdot L] + b(c)\cdot\cosh[b(c)\cdot S(c)\cdot L]}\,. \tag{9}$$

Light scattered in the 90° direction is modeled in terms of the amount of light that is not transmitted through the cell. Since the cuvette is not infinitely wide as assumed by Kubelka and Munk, some of the light comes out of the sides instead of being reflected (back-scattered). Assuming that absorption is negligible (k~0), the fraction of light back-scattered in a Kubelka-Munk system would normally be given by

$$R(c) = 1 - T_{KM}(c) \tag{10}$$

where $R(c)$ is reflectance as a function of concentration. In other words, light that is not transmitted is reflected. However, in the finite cell some of the not-transmitted light emerges as 90° scattered light. This 90° not-transmitted light is also subject to scattering in the lateral direction, and this decreases the amount to light that emerges at 90°. The net effect is that light at 90° is non-transmitted light (1-T) that is attenuated by the turbid transmittance in the 90° direction, T. This is summarized in equation (11),

$$I_{90}(c) = \frac{(1 - T_{KM}(c))\cdot T_{KM}(c)}{0.25} \tag{11}$$

where $I_{90}(c)$ is the side-scattered light. The equation is divided by 0.25 to normalize it to unity at the maximum 90° signal.

Equation (11) was used to model the 90° $I_{||}$, vs c data by assuming zero absorption (k=0) and adjusting the value of the scattering term, k_s. The solid line in Figure (?) is an example, and it is clear that the Kubelka-Munk model provides a good description of scattering in this system.

Although equation (11) fit the data well, equation (10) significantly over estimated the experimental value of T, as shown by the dotted line in Figure (2). This is because the Kubelka-Munk theory models the total light emerging into a hemisphere from the back surface of the sample. Experimentally, only light over a small solid angle around 0° is detected. In order to compensate for this, the model was modified with a power factor, n, as shown in equation (12). By adjusting the value of n, a good fit was achieved between the experimental data and the model, as shown by the dashed line in Figure (2).

$$T_{KM}(c) = \left[\frac{b(c)}{a(c)\cdot\sinh[b(c)\cdot S(c)\cdot L] + b(c)\cdot\cosh[b(c)\cdot S(c)\cdot L]}\right]^{1/n} \tag{12}$$

Relating Scattering to Depolarization

The scattering model was used to explore the degree of light scattering that can be tolerated in a practical ink system. For any given concentration of particles, the scattering power, S_p, is defined in Kubelka-Munk theory as the product of the scattering coefficient, S, and the sample thickness, L, as shown in equation (13).

$$S_p = L \cdot S(c) \tag{13}$$

According to the Kubelka-Munk, scattering power is monotonically related to the turbid transmittance, T, of the material. For inks layers typically useful in color printing, the turbid component of transmittance, T, must not be too low. Otherwise, sub-layers of ink are masked and color reproduction quality is poor. As a rule of thumb, an ink with a turbid transmittance of $T<0.3$ is not useful for color reproduction, and a $T\sim0.5$ may be marginally useful. This corresponds to a scattering power range of $2<S_p<1$. Thus, a latex sample with S_p below 1 is representative of the degree of scattering in high quality inks, and S_p in the range $2<S_p<1$ is characteristic of inks of questionable utility in color printing. Scattering powers greater than 2 are not of importance in this project.

The two graphs in figure (4) show transmittance and depolarization as a function of latex concentration. By combining the data, one could plot depolarization versus T. However, a more general relationship can be obtained by converting T into scattering power, S_p, by applying the scattering model. When this is done, the results shown in Figure 4 are obtained.

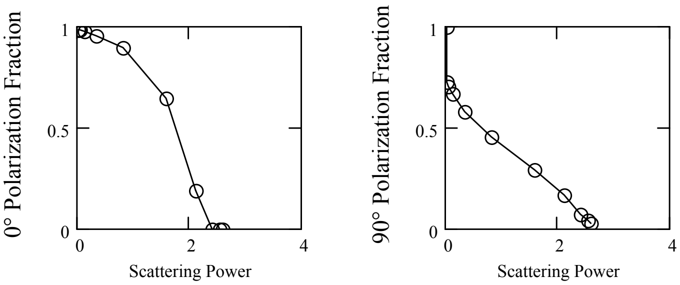

Figure 4. Polarization fraction for latex A plotted as a function of scattering power for *T* (left) and *I* (right).

Results and Conclusions

The analytical procedure and data processing described above was performed on six different acrylic latex samples representing a wide range of particle sizes and distributions, as shown in Table I. All samples were found to fit the scattering model well for turbid transmittance values above 0.3, and by fitting the model to the data values of k_s and n were obtained as described above.

The value of n was used to correct for the geometry of light detection in the 0^o direction and therefore should ideally be a constant characteristic of the instrument geometry. The results shown in Table 1 does show a small variation in n between the latex samples, which is an indication of some deviation from ideal Kubelka-Munk scattering. This is a relatively small deviation, however, and does not significantly alter the general conclusions discussed below.

	Latex A	Latex B	Latex C	Latex D	Latex E	Latex F
mean particle size (μm)	0.1487	0.2237 (98%), 1.039 (2%)	0.0224	0.2664	0.9602 (16%), 0.2311 (84%)	0.676 (25%), 0.0864 (75%)
particle size distribution (μm)	0.0544	0.1269 (98%) 0.554 (2%)	0.0153	0.1224	0.653 (16%), 0.1289 (84%)	0.6024 (25%), 0.0937 (75%)
k_s	310	400	9	350	350	190
n	4	4	5	4	5	5

Table 1. A summary of the *ks* and *n* parameters used in this experiment, along with mean particle size and size distributions given as standard deviations. The samples with two sizes and distributions listed had a bi-modal distribution, and the percentages reflect the percentage of each particle size by volume.

Figure 6 summarizes depolarization versus scattering power in both the 0° and 90° directions for all six latex samples used in the study. Note that if any light at all is detected in the 90o direction, it is because scattering happened, and therefore some depolarization occurred. For this reason, the polarization fraction versus scattering power observed at 90° has a zero intercept less than 1.0.

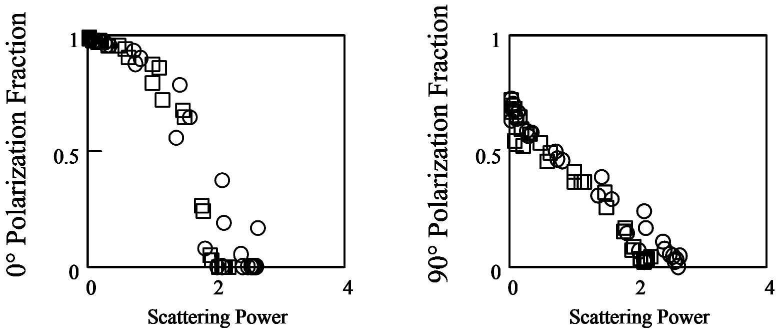

Figure 6. The similarities in depolarization behavior are shown here. The squares represent latex samples with an empirical *n*=5, and the circles represent *n*=4. This difference explains the small difference in behavior between the two sample populations.

It is particularly noteworthy that all latex samples behaved in essentially the same way. Complete depolarization occurs at scattering powers between 2 and 3, which is within the region where Kubelka-Munk is shown to be a good model for the system. The model does not appear to apply for highly scattering materials with low transmittance, but this experiment clearly showed that complete depolarization occurs well before the scattering model fails. Therefore, a new model would not generate any new insights as to the relationship between scattering and depolarization for ink and toner, and a new model does not need to be developed.

As far as using the microgoniophotometer approach to measure gloss is concerned, this experiment shows that light with properties that are a hybrid between Lambertian and Fresnelian can be expected to be part of the experimental BRDF measurement. This conclusion is reached because depolarization is not complete in the range $1<S_p<2$, and practical inks can have scattering powers in this range. This further suggests that gloss, as a visual attribute of printed images, may depend in part on the amount and behavior of this hybrid reflected light. This also suggests that it would be useful to continue developing the micro-goniophotometric instrument to explore means of characterizing hybrid light as well as Lambertian and Fresnelian light.

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