

1-1-2006

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Recommended Citation

Journal of Pulp & Paper Science 32N1 (2006) 19-23

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J. Pulp & Paper Sci, in press (2006)

Analysis of Paper Gloss

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Abstract

Standard techniques for the measurement of paper gloss are capable of providing highly repeatable indices of the gloss phenomenon. However, it is well known that the gloss phenomenon involves more than can be represented by a single number. A recently developed instrument called a micro-goniophotometer has been applied to the characterization of paper gloss. The Bi-directional Reflectance Distribution Function (BRDF) plots generated by this device were shown to be related quantitatively and directly to Fresnel's law of specular reflection and to the surface roughness of the sample. Unlike standard gloss meter measurements, the BRDF enables the analyst to distinguish between effects of surface roughness and the Fresnel reflectance factor. Moreover, the analysis provides a way to characterize quantitatively the importance of sub-surface specular reflections to the overall gloss of a coated paper.

Introduction

Standard techniques for the measurement of paper gloss are capable of providing highly repeatable indices of the gloss phenomenon.¹ However, it is well known that the gloss phenomenon involves more than can be represented by a single number. Additional significant information about gloss is contained in the bi-directional reflectance distribution function (BRDF) measured by detecting light reflected at angles beyond the equal/opposite specular angle.² Goniophotometer instruments available commercially and reported in the literature are expensive and complex devices compared to gloss meters and are not commonly used for routine paper characterization. Recently, a simple micro-goniophotometer was described that is based on an inexpensive video camera, simple optics, and digital image capture.^{3,4} Using Non-commercial share-ware software, images captured by this micro-goniophotometer have been shown to produce reproducible BRDF curves that provide significantly more information than is available in standard gloss measurements. The work described below explores the utility of this micro-goniophotometer for the analysis of paper gloss.

The Micro-Goniophotometer

The micro-goniophotometer has been described in technical detail elsewhere,^{3,4} and the following is a brief schematic description of the essentials of the analysis. As shown in Figure 1, the system is based on wrapping the paper sample around a cylinder, then illuminating the sample with a line light source collinear with the cylinder, and capturing a digital image of the gloss band. Use of a cylindrical geometry for the analysis of gloss has been demonstrated to be a generally useful technique by other researchers^{5,6,7,8} and has been adopted for the current work.

The light used to illuminate the sample is polarized in either the s or p direction, and a second polarizer is used in front of the camera lens. Two images are captured; one with the two polarizers in parallel (the bright image) and the second with the polarizers crossed (the dark image). The bright image contains both specular light and bulk diffuse light. The former maintains its polarization, but the latter is randomly polarized. The dark image is subtracted from the bright image to produce an image that contains only the specularly reflected, gloss light.

Figure 1: Schematic diagram of the micro-goniophotometer^{3,4} with specular angle $\theta = 20^\circ$. The cylinder diameter is 10 mm. The camera and illumination distances are sufficiently long to minimize parallax.

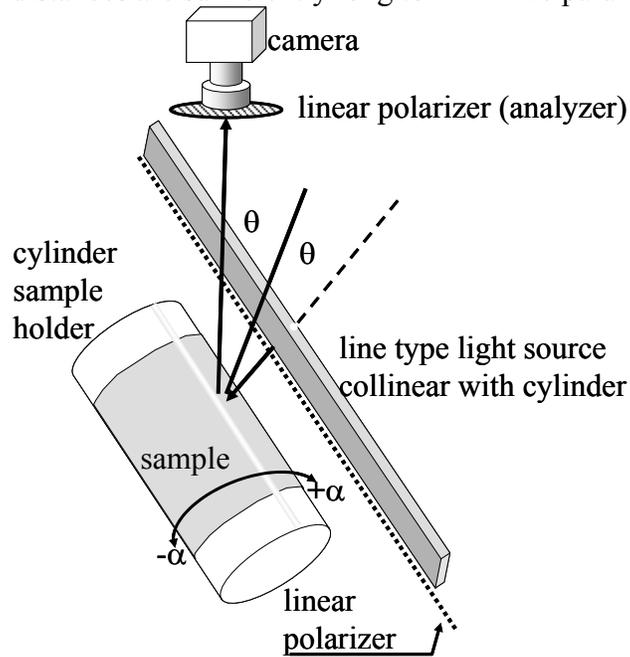
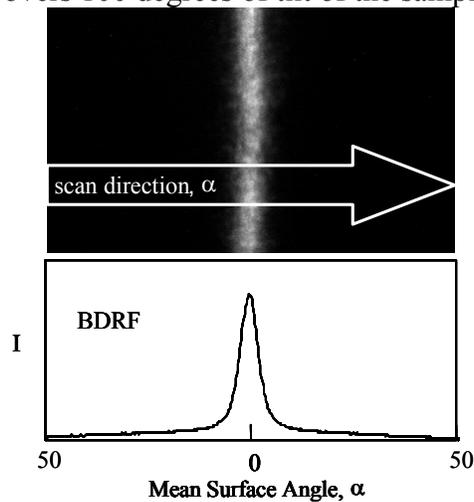


Figure 2: Illustration of an image and a BRDF from the device shown in Fig. 1. The scan direction covers 100 degrees of tilt of the sample.

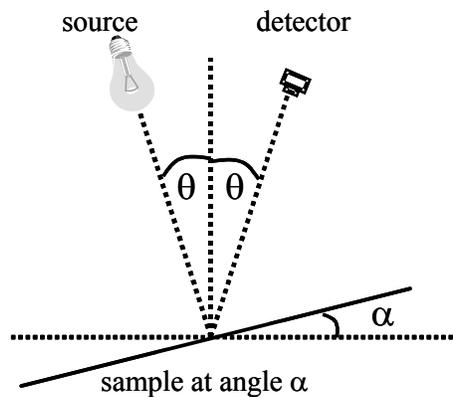


An example of a specular image is shown in Figure 2. The horizontal location in the image corresponds quantitatively to the tilt angle, α , of the sample. This angle is calculated in software for each horizontal location in the specular image. A software scan is done in which each vertical column

of pixel gray values in the image is averaged, and this produces the BRDF for the sample. Spatial and angular resolution can be selected by the experimenter by choosing appropriate microscope optics and cylinder diameter, as described in detail elsewhere.^{3,4} All of these calculations can be performed with readily available, public domain software, and the software scan can be converted into the BRDF graph with a spread sheet program.

The BRDF obtained with the micro-goniophotometer is equivalent to that produced by a traditional goniophotometer in which the tilt angle, α , of the sample is scanned. This is illustrated in Figure 3. The BRDF produced in this way is significantly different from the BRDF produced by scanning the detector or the light source around the sample, as is generally done.¹ The difference is that the light detected by scanning the sample angle, α , maintains the Fresnel gloss angle, θ , as a constant, while scanning the detector or the source also varies θ . The advantage of maintaining θ constant is that the output BRDF can be related more easily to Fresnel's law of specular reflectance.

Figure 3: Goniophotometric Equivalent of the micro-goniophotometer

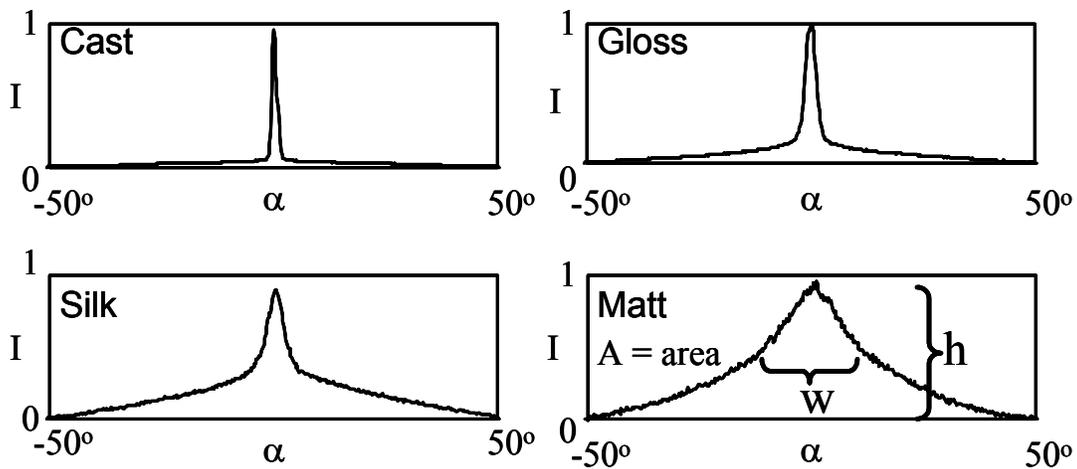


Fresnel's Law and Paper Gloss

Forty five different paper samples were obtained from various commercial sources representing the major manufacturers of both coated and non-coated paper for use in desk top, laser printers. The attempt was to obtain a wide variety of samples covering all of the gloss levels one might find in use in

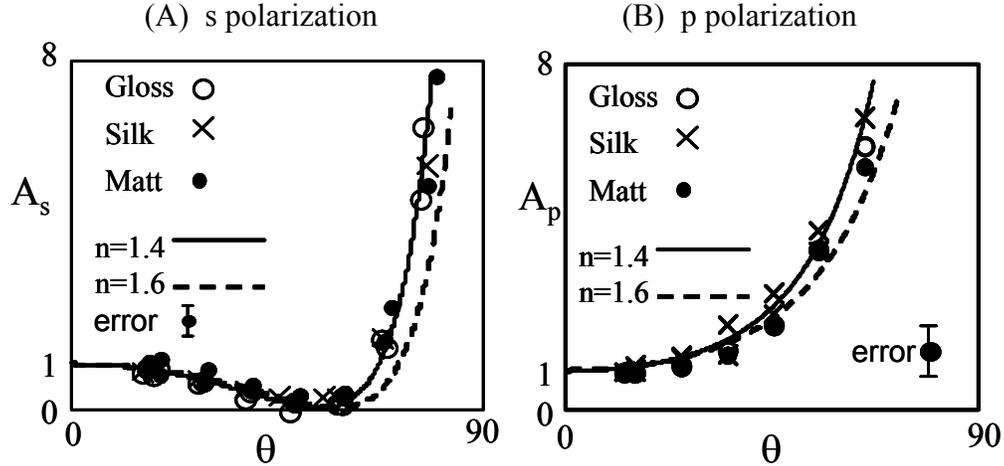
laser printing. These forty five papers were categorized by the manufactures as being either matt (non-coated), silk coated, gloss coated, or cast coated sheets. The number of samples, 45, has no particular significance and represents the authors' best effort at assembling a representative set samples. BRDF graphs were measured for each sample, and examples of each type sheet are shown in Figure 4. From these graphs, measurements of BRDF area, A , peak height, h , and peak width at half height, w , were extracted.

Figure 4: BRDF curves representative of the four classes of paper used in this study. Curves are normalized to unity at their maximum value.



The width of a BRDF is well known to relate to the surface topography of the paper,^{9,10,11,12} and this relationship has been explored and modeled theoretically.^{14,15,16} The area under the BRDF generated by this technique can be compared directly to the angle, θ , used in the measurement. This was done for several of the paper samples using light polarized in both the s and the p directions. The results are shown in Figure 5.

Figure 5: Relative BRDF areas, A_s and A_p , versus specular angle, θ .



The lines shown in Figure 5 were calculated directly from Fresnel's law, shown as equations (1) through (3). The areas predicted by Fresnel's law and measured experimentally are normalized to unity at $\theta = 0$. The calculation was carried out assuming indices of refraction of $n=1.4$ and $n=1.6$, as shown in Figure 5. The experimental BRDF results for both s and p directions of polarization agree within experimental error of the results predicted by Fresnel's law for $n=1.4$, and it can be said that the index of a sheets, coated or non-coated, is approximately 1.4, and significantly less than 1.6. This is in agreement with expectation for most papers. Sheets containing high index minerals such as TiO_2 might contribute to an increased sheet index, but such minerals are generally used to increase bulk scattering rather than to change surface specular reflections. Thus, the agreement between the microgoniophotometer and Fresnel's law lends confidence to the quantitative interpretation of gloss measurements made by this technique.

$$\varphi = \text{Arcsin}\left(\frac{n}{n'} \cdot \sin(\theta)\right) \quad (1)$$

$$\rho_s(\theta) = \left[\frac{\sin(\theta - \varphi)}{\sin(\theta + \varphi)} \right]^2 \quad (2)$$

$$\rho_p(\theta) = \left[\frac{\tan(\theta - \varphi)}{\tan(\theta + \varphi)} \right]^2 \quad (3)$$

$$A_s(\theta) = \rho_s(\theta) / \rho_s(0) \quad \text{and} \quad A_p(\theta) = \rho_p(\theta) / \rho_p(0) \quad (4)$$

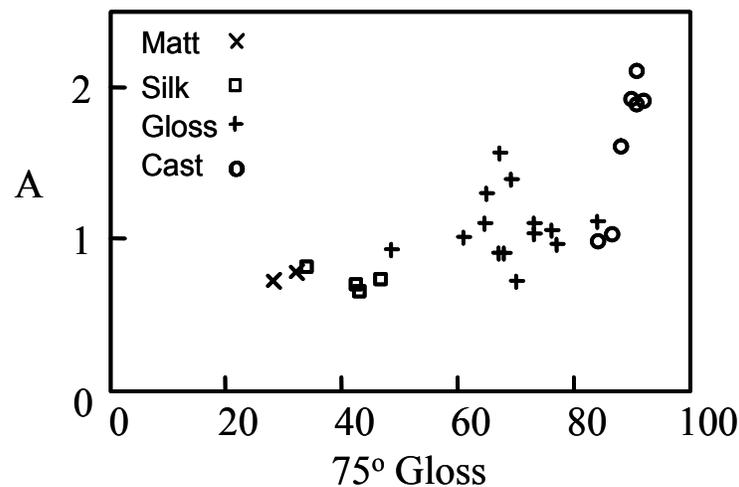
The Meaning of a Gloss Meter Measurement

The experimental metrics extracted from the BRDF provide more information about the sample than is available from a gloss meter. However, the meaning of this additional information is not entirely understood, and the purpose of the project described here was to explore the utility of these BRDF metrics. In the following discussion, all of the BRDF measurements were made at a fixed angle of $\theta=20^\circ$. This was done because at this angle the difference between the Fresnel reflectance factors in the s direction, the p direction, and with random polarization are indistinguishable within experimental error.

The first BRDF metric explored was the area, A, and as described above it is a quantitative index of the Fresnel reflectance factor of the material, ρ . The BRDF areas measured at $\theta=20^\circ$ were compared to gloss measurements made with a BYK-Gardner instrument at $\theta=75^\circ$ that conforms to the TAPPI standard for paper gloss.¹ The results are shown in Figure 6.

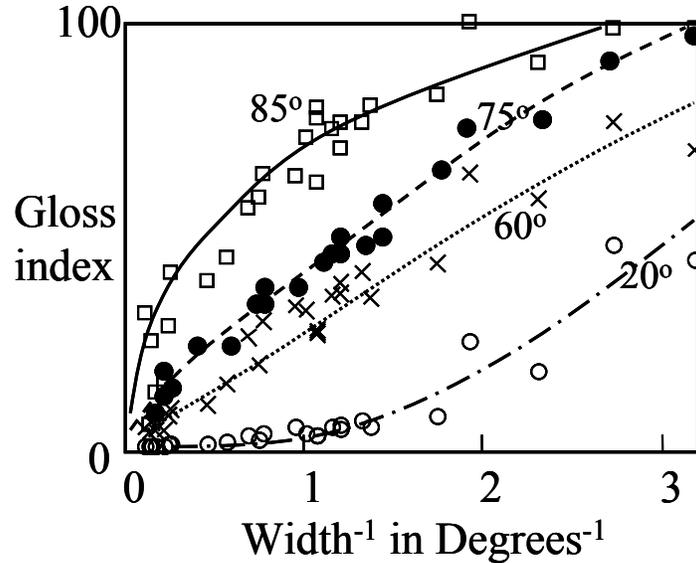
Standard gloss meters are calibrated to provide output as a percentage of the signal from a calibration standard (typically a black glass of $n=1.567$). Therefore, it would seem that a gloss meter measures a reflectance factor. Since the BRDF area is highly correlated with the Fresnel reflectance factor, the poor correlation between the TAPPI standard gloss index and the BRDF area indicates that the gloss index is in fact not highly correlated with the Fresnel reflectance factor.

Figure 6: BRDF area A versus TAPPI standard gloss at 75° .



Gloss index values were measured with another BYK-Gardner instrument at 20°, 60°, and 85°, and none of these gloss indices correlated well with the BRDF area. However, when the gloss indices were compared to 1/w, where w is the width of the BRDF in degrees, the results correlated significantly, as shown in Figure 7.

Figure 7: Gloss indices versus the inverse of the BRDF width. Lines through the data are 4th order polynomial regression lines.



The correlation between gloss index and BRDF width indicates strongly that standard gloss meters are useful indicators of the BRDF width of a material, not the specular reflectance factor. This in turn indicates that a gloss meter reading is primarily governed by the roughness of the sample. This conclusion is in agreement with results published elsewhere.⁹⁻¹⁶

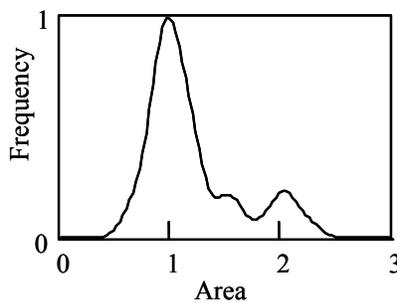
The Meaning of the BRDF Area Measurement

The correlation between Fresnel's law and the relative BRDF areas shown in Figure 5 can be somewhat misleading. The relative areas A_s and A_r are expressed relative to the BRDF area at $\theta = 0$. However, the areas in Figure 6 are expressed relative to an arbitrarily chosen, non-coated, calendered sheet used as our laboratory repeatability standard. It is notable that the BRDF areas vary from sample to sample over more than a factor of two. This would seem to indicate a significant variation in the Fresnel reflectance factors among the samples. However, measurements such as illustrated in Figure 5

indicate that none of the indices of refraction of any of the paper samples differed sufficiently to explain significant differences in the Fresnel reflectance factor. In order to understand this apparent paradox, a histogram analysis of the BRDF areas was carried out.

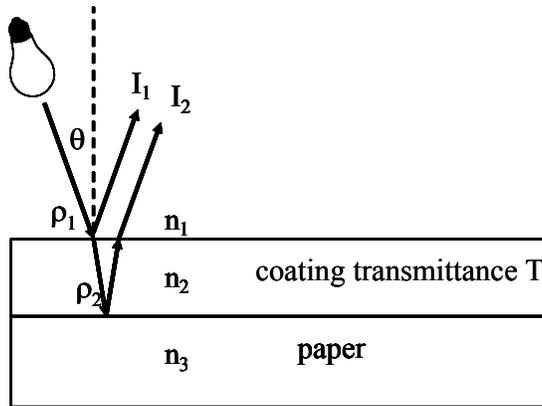
The histogram analysis is a statistical analysis of the frequency of occurrence of an event. In this case, we examined the frequency of occurrence of areas. From the 45 area measurements, we extracted the estimated frequency graph, or histogram, shown in Figure 8.

Figure 8: Histogram of BRDF Area



The histogram analysis shows that the area $A=1$ (relative to the lab standard) is the most frequently expected area of a paper BRDF. However, it is notable that there is a significant probability that a paper will have an area that is twice the reference area. Examination of the individual paper samples resulted in the observation that only cast coated samples have areas above $A=1.8$. Only cast coated and gloss coated samples have areas above $A=1.3$. Based on this observation, the authors would like to suggest that the overall gloss of some coated papers may result from specular reflections that occur at both the front surface and the sub-surface of the coating, as illustrated schematically in Figure 9. Sub-surface specular reflections of this kind have also been reported to occur in printed images and other materials.^{4,17,18}

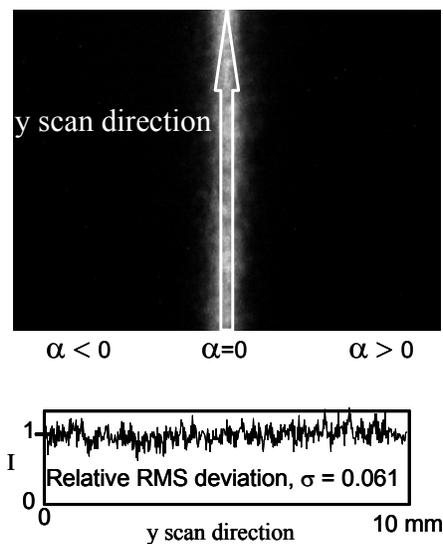
Figure 9: A model of specular reflectance based on reflection from two interfaces



An Index of Gloss Variation

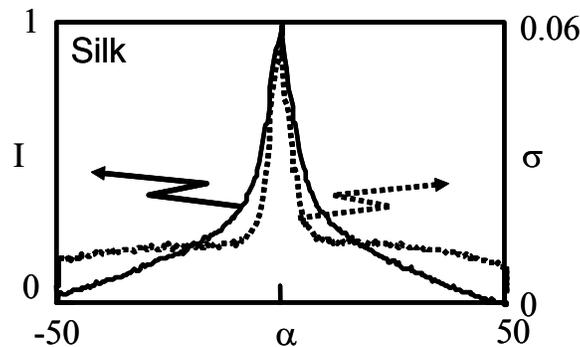
Thus far we have examined the results of scanning the specular image illustrated in Figure 2 only in the horizontal direction to generate the BRDF. One may also scan in the vertical, or y, direction, as illustrated in Figure 10. This direction of scan provides information about the variation in gloss across the sample. With a camera focused on a 10 mm region of the sample, variations resolved to 10 microns can be measured easily with only a 1 megapixel camera. Higher spatial resolution can be achieved with a appropriately magnifying optics.

Figure 10: Illustration of a specular image and a gloss variation graph from the device shown in Fig. 1. The scan direction covers 10 millimeters of the sample.



An index of gloss variation, σ , was defined as the RMS deviation of the light measured in the vertical scan. The value of σ is expressed relative to the mean value of the light. The value of σ was measured for a silk coated sample at all horizontal locations, α , of the BRDF. Figure 11 shows the BRDF of the silk coated sample along with the gloss variation, σ vs α . In addition to measurements of σ and other moments of noise probability, a spatial analysis of correlated statistics can also be performed on the noise scans. Thus, an exhaustive characterization of gloss variation, including both moment and correlated statistics, can be obtained at each angle, α , of the gloss BRDF.

Figure 11: The BRDF (I vs α) and the gloss noise curve (σ vs α) for a silk coated paper.



Conclusion

The intent of this work has been to demonstrate the potential utility of micro-goniophotometric analysis for the characterization of paper gloss. The device used in this project was assembled from readily available, low end components commonly available for routine video microscope inspection. The BRDF plots generated by this device have been shown to be related quantitatively and directly to Fresnel's law of specular reflection, to the surface roughness of the sample, and in some cases to sub-surface effects. Unlike standard gloss meter measurements, the BRDF enables the analyst to distinguish between these effects.

A preliminary examination of the variation in specular reflection across samples resulted in curves of gloss variation, σ , versus BRDF angle. These curves appear to be quite different in character

from the BRDF itself and seem to contain significant additional information about the gloss of samples. However, the significance of this kind of gloss variation analysis has not yet been examined. The intent here is to suggest the potential utility of micro-goniophotometry for providing significantly more insight into paper gloss than is available through standard gloss measurements. Details of the micro-goniophotometry instrument are described in the literature,^{3,4} and the authors would be happy to collaborate with anyone interested in continuing to explore the utility of this analytical technique.

Acknowledgement:

The authors would like to express their appreciation to Per-Åke Johansson, Marie-Claude Béland and the staff at STFI for getting us involved in the gloss problem. We also appreciate the encouragement and help received from Norm Burningham and financial support by Hewlett-Packard.

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