Relationship between PSF and Gonio-reflectance Distribution of Specular Reflection

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Abstract

Glossiness is one of the important qualities for printing paper. Glossiness is a specular reflection phenomenon in aspect of optics. Therefore, there are various methods of evaluating specular reflection phenomenon. When a person is evaluating the glossiness of paper, it is quite popular to visually inspect the glossiness by the sharpness of the reflected light image. In this paper, it is shown that this visual inspection can be expressed by a transfer function of specular reflection image.

First, we discuss the possible use of point spread function of specular reflection (SR-PSF). A technique for measuring SR-PSF of paper is proposed. The measurement principle is a collimator method. This method has been used for the PSF measurement of typical transmittance optical system. We have developed the apparatus to measure SR-PSF. The SR-PSFs were measured for paper samples. The experimental results showed that the measured SR-PSF works as a transfer function for specular reflection image.

Second, we show that the apparatus used for measuring SR-PSF also works as a goniophotometer within a narrow solid angle. It is shown that the reflection angle calculated theoretically meets well with that experimentally obtained. That is, a distribution of reflection angle can be calculated using SR-PSF data.

It is thought that the spreading of specular reflection observed on paper samples is caused by the distribution of surface normals. Our results showed that SR-PSF and gonio-reflectance distribution are one phenomenon expressed in two different physical concepts. Our future study will be focused on new reflection model for computer graphics.

Introduction

Glossiness is one of the important qualities for printing paper. For example, coated paper is categorized to glossy or mat. The ISO (International Organization for Standardization) specular gloss is generally used to evaluate glossiness. However it is well known that the ISO specular gloss, in some cases, do not correspond to the feeling of glossiness by the visual inspection. So, many new measurement techniques are developing to estimate gloss of paper [1-3].

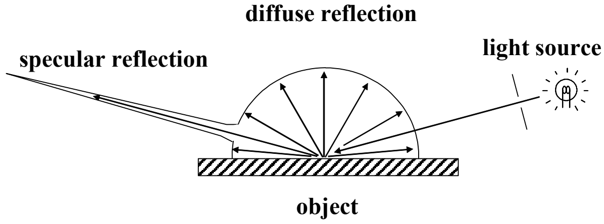

Figure 1. *Schematic diagram of dichromatic reflection model.*

Light reflection phenomenon is explained in the dichromatic reflection model as shown in Figure 1. Glossiness is a specular reflection phenomenon in aspect of optics. Specular reflection is called as mirror reflection in generally.

When a person is evaluating the glossiness of paper, it is quite popular to visually inspect the glossiness by the sharpness of the reflected light image in fig.2. In this paper, it is shown that this visual inspection can be expressed by a transfer function of specular reflection image.

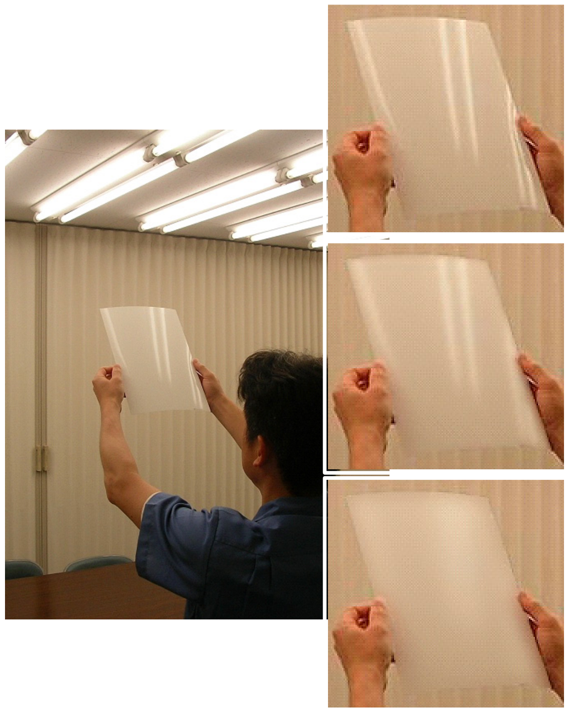

Figure 2. *Photographs showing the visual inspection of paper glossiness. The upper right is high glossy paper, the middle one is glossy and the bottom one is mat, for example.*

Point spread function (PSF) is used for a transfer function in image science [4]. PSF can be calculated from MTF also. There are some reports about MTF of diffuse reflection [5,6]. Authors reported the measurement and analysis of MTF of diffuse reflection [5]. In general, the print (the ink image on paper) is observed as the diffuse reflection light. Specular reflection light image is different from the diffuse reflection light image. However, there are only a few cases which applied PSF to a specular reflection phenomenon.

In this paper, we discuss Point Spread Function of specular reflection (SR-PSF) and introduce an apparatus to measure the SR-PSF. Furthermore, we also found that this apparatus works as a goniophotometer within a narrow solid angle. The reflection angle calculated theoretically meets well with that obtained by an experiment. The angle of reflection is affected by the surface normal. We will discuss the relationship among SR-PSF, gonioreflectance distribution and surface normal distribution.

Experiment 1: Point Spread Function of Specular Reflection

First, we would like to introduce the use of point spread function of specular reflection (SR-PSF) for glossiness measurement.

Theory and measurement apparatus

The point spread function (PSF) describes the response of an imaging system to a point source. The PSF is a system's impulse response in a optical system. Figure 3(a) shows a measurement method of the PSF for the transmission optical system.

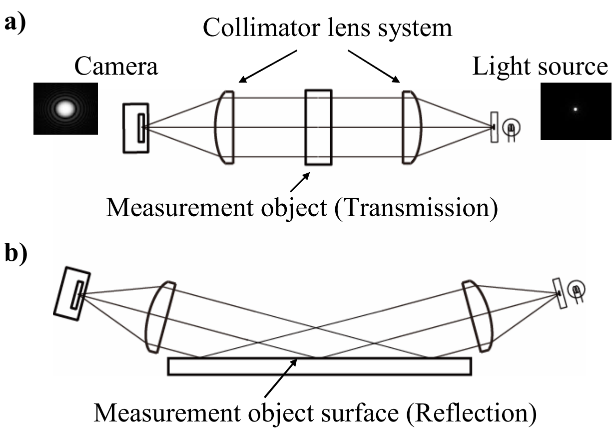

Figure 3. *a) A schematic diagram of the measuring method for conventional PSF. b) The proposed measuring method for SR-PSF.*

We applied this method to measure the SR-PSF as shown in Fig.3(b). A pinhole test pattern is projected to the sample paper, and the intensity distribution of reflection light is measured by the two dimensional CCD camera. The parallel light is reflected on the paper sample surface. The reflected light is inversely collimated as an image of point spread function.

Figure 4 shows the optical setup the actual experiments used in this study. The lighting and viewing angles are set to be 75 degree in the experiments. Figure 5 shows the photograph of the apparatus.

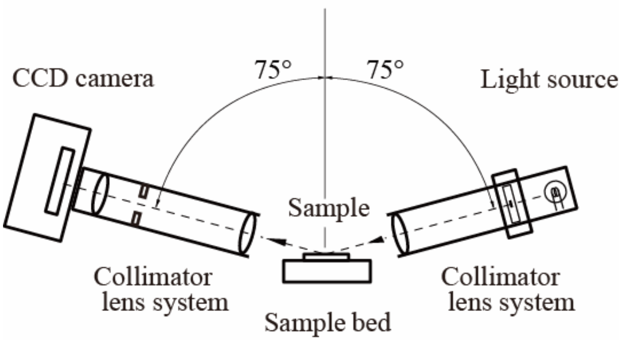

Figure 4. *Apparatus diagram in this study for measuring SR-PSF.*

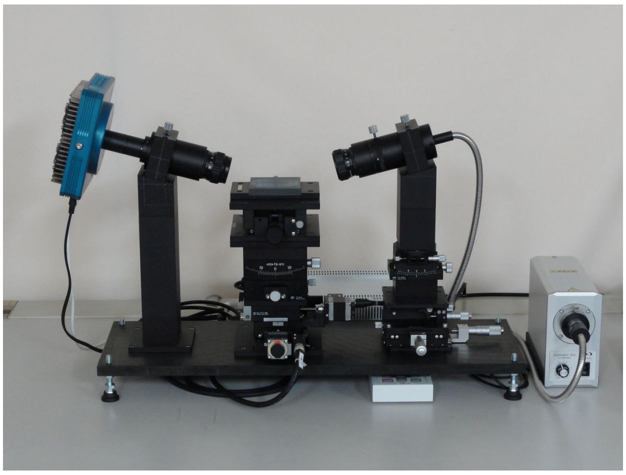

Figure 5. *Photograph of the measurement apparatus for SR-PSF.*

In this experimental system, the LED lamp is used as the light source and is placed behind the metal plate having 100 micrometers diameter pinhole. A CCD camera is 512x512 pixels, and has 16 bits gray levels. We checked the linearity of this camera output (0 ~ 65,535). So the output value was used as light intensity in this study. The paper sample was set on the central sample bed, and they were measured under the darkroom. We prepared the black glass (refractive index is 1.567) as a standard. The measurement condition was set by this standard.

Figure 6 shows the typical measurement results. The SR-PSF of black glass showed the shape which is almost same as the original pinhole. This result shows that this system can measure the SR-PSF at high accuracy. The SR-PSF of a coated paper showed the broad distribution.

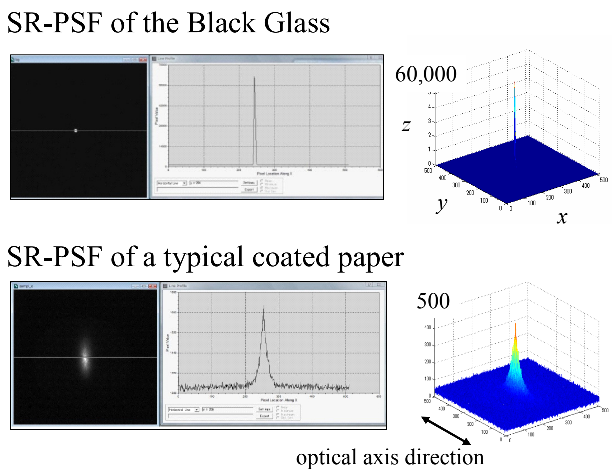

Figure 6. *Typical measurement result of SR-PSF. The figure at left show images, center show cross sections and right show 3D meshes.*

Measurement results

The SR-PSFs were obtained for different type of sample paper. Table 1 shows samples used in this study and those measurement results. Figure 7 shows the SR-PSFs of sample papers. The samples are black glass, ink-jet paper and four coated papers (No.1 to No.4) having different glossiness.

Table 1. Samples used in this study and those measurement results.

Sample	ISO 75° Specular Gloss
BlackGlass	94.6
Inkjet paper	79.4
Coated paper No.1	80.1
Coated paper No.2	64.0
Coated paper No.3	50.5
Coated paper No.4	21.7

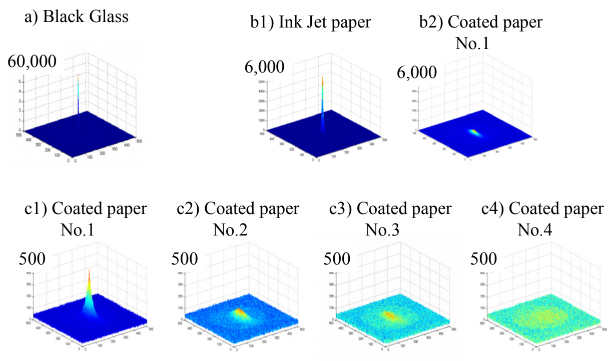

Figure 7. Measurement results of SR-PSFs.

Note: Full scales for a),b) and c) are 60,000, 6,000 and 500 respectively.

Confirmation that SR-PSF is a transfer function of specular reflection image

There is a characteristic shape in all the SR-PSF distribution of samples. The SR-PSF distribution is broad in optical axis direction, and narrow in cross direction. If this SR-PSF is the transfer function of reflection image system, the reflection image is spread wider (i.e. out of focus) in optical axis direction and is spread narrower in cross direction. We checked it by an experiment.

Figure 8 shows the schematic diagram of the experiment. The reflection image on the paper sample is captured by CCD camera. This CCD camera has a normal lens system in this experiment. It will be finely reflected to a CCD camera if the sample surface is like a mirror.

The measurement results of the sinusoidal image are shown in Fig.9. Figure 10 shows the results of Chinese character image.

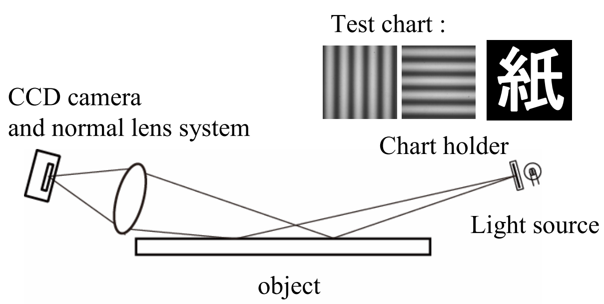

***Figure 8.** The method to capture the specular reflection image in this study.*

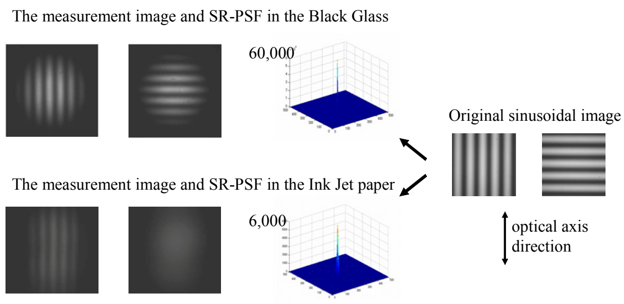

***Figure 9.** The measurement results of the sinusoidal image.*

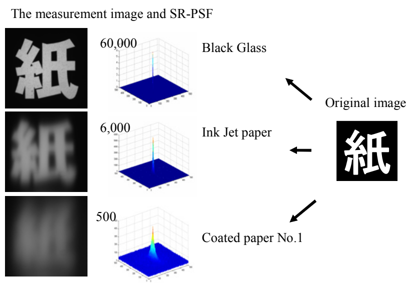

***Figure 10.** The measurement results of the Chinese character image.*

Those experimental results showed that the reflection image had low resolution in optical axis direction, and high resolution in cross direction. These results are consistent with the feature of general PSF. It was confirmed that the SR-PSF works as a transfer function for specular reflection image.

Experiment 2: Gonio-reflectance distribution

Second, we studied that whether the apparatus used for SR-PSF measurement can work also as a goniophotometer.

Goniophotometer and gonioreflectance

The peak of specular reflection is at the specular reflection angle. In general, there is some strong reflection near the specular reflection angle. The reflectance according to angle is called gonioreflectance. For example, it is measured by goniophotometer in Fig.11 [7]. The goniophotometer measures reflectance, moving a detector.

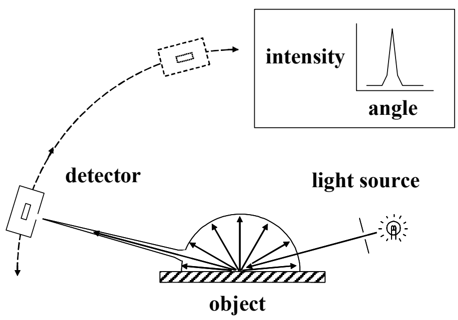

***Figure 11.** Schematic diagram of goniophotometer and gonio-reflectance.*

Gonio-reflectance distribution is an important basic property of optics. Many reflection models in computer graphics use this information as the BRDF. In this study, a collimator optical system was used on the apparatus for SR-PSF measurement as shown in Fig.3 . It is suspected the special property of this collimator optical system may work as a goniophotometer within a narrow solid angle.

Property of collimator optical system

Figure 12 shows the schematic diagram of collimator optical system. Collimator optical system has a focus in one side of a lens, and another side is parallel light. In collimator optical system, the focal position is determined by the angle of parallel light. So the angle of parallel light can be calculated by the pixel position of the CCD camera in this apparatus.

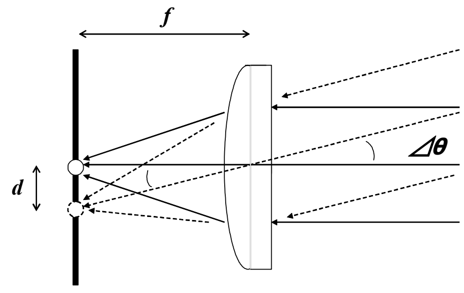

Figure 12. *Schematic diagram of collimator optical system. Focal point distance d can be calculated from focal length f and the difference of angle Δθ.*

Figure 13 shows the coordinate system in this study. The reflected light is observed at the position (x, y, z). The y is optical axis direction, the x is cross direction and the Z is distance from sample. The deviation position of the reflected light by small angles Δθx and Δθy is calculated according to Eq. 1. The CCD camera angle fixed at 75 degree. The CCD camera pixel position (x', y') is calculated by rotation of a vector in Eq. 2.

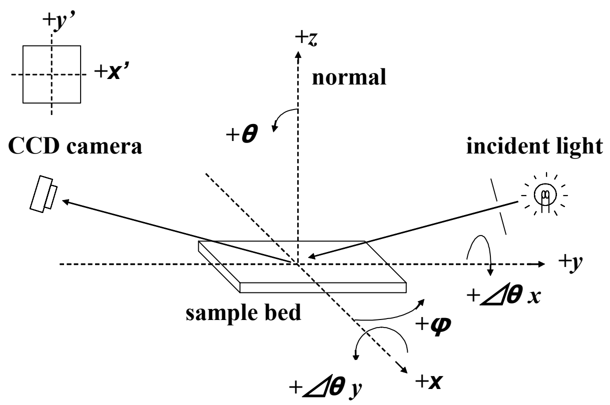

Figure 13. *Coordinate system in this study.*

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = f \begin{pmatrix} \sin(2\Delta\theta_x)\cos(75+2\Delta\theta_y) \\ \sin(75+2\Delta\theta_y) \\ \cos(2\Delta\theta_x)\cos(75+2\Delta\theta_y) \end{pmatrix} \qquad (1)$$

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\Delta\theta_y) & \sin(\Delta\theta_y) \\ 0 & -\sin(\Delta\theta_y) & \cos(\Delta\theta_y) \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} \qquad (2)$$

The observed position corresponding to the deviation angle by experiment

The reflection light angle is changed by the sample bed deviation angle (i.e. surface normal). The observed position corresponding to the sample bed deviation angle was measured by experimentally. The sample bed deviation angle (*Δθx*, *Δθy*) can be changed, because the sample bed can be rotated as in Fig. 14. Black glass was used as sample in this experiment, because the SR-PSF of black glass becomes very small point. Figures 15 shows the measured results of the observed position corresponding to the sample bed deviation angle *Δθx* and *Δθy*. The dot in a figure shows the position corresponding to a deviation angle (*Δθx*, *Δθy*). There are 25 dots in one graph. In the center, the dot shows the deviation (0, 0). The deviation angle was changed of -2,-1, 0, 1, 2 degree respectively. In addition, the change of the reflected light angle is twice the change of the sample bed angle.

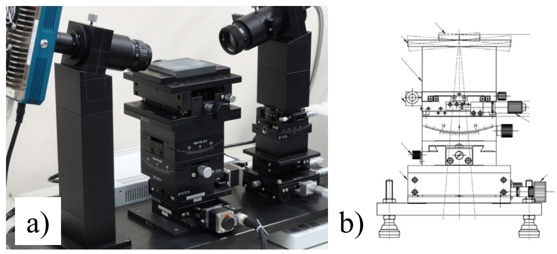

Figure 14. *Photograph shows the sample bed with rotation system (yawing system).*

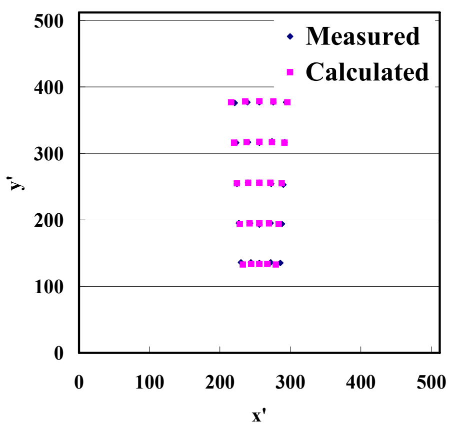

Figure 15. *Measured and calculated results of the observed position corresponding to the changing sample bed deviation angle, Δθx and Δθy. The specular reflection angle is 75 degree.*

The observed position corresponding to the deviation angle by theoretical calculation

Figures 15 and 16 show the calculated results of changing sample bed deviation angle Δθx and Δθy. The experiment was simulated by the theoretical calculation. The experimental results meet well with the calculated results.

We also calculated the case of different specular reflection angle. These showed interesting results. The position corresponding to a deviation angle is non linear. The its distribution is broad in optical axis direction, and narrow in cross direction. It becomes linear when the specular reflection angle is 0 degree especially.

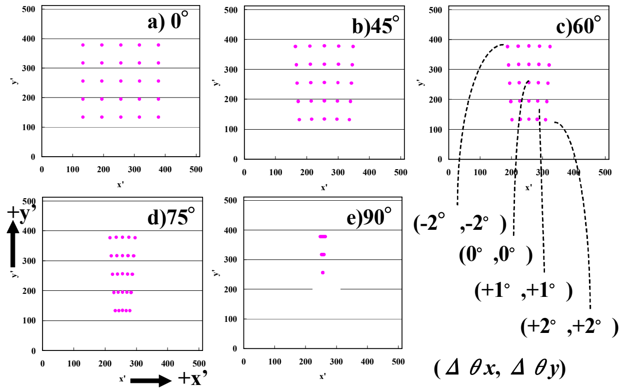

Figure 16. *Calculated results of the observed position corresponding to the changing sample bed deviation angle, Δθx and Δθy. The specular reflection angle (degree) is a)0, b)45, c)60, d)75 and e)90.*

Discussion

Distribution -- what is meant?

This apparatus was developed based on the theory of PSF, in order to measure SR-PSF. The measurement result of SR-PSF of paper shows a certain distribution. On the other hand, the each detected position means the angle of reflected light in this apparatus. We think that the light volume of each position is the quantity of light respectively reflected at a certain angle from the measuring surface. Therefore, the measured distribution is angle ingredient distribution of the light reflected from the surface. It is nothing but a probability density function (PDF) of reflection angle. And it also is a gonio-reflectance distribution.

It is concluded that the measured data of this apparatus is SR-PSF, and is gonio-reflectance distribution at the same time. Our results show that it is one phenomenon expressed by two different physical concepts.

The reason why SR-PSF becomes an oval distribution

In our experiment, the measured SR-PSF became an oval distribution. This can be explained from of reflection angle distribution because both SR-PSF and reflection angle distribution are same in this apparatus. Figure 17 shows the SR-PSF of coated paper No.1 in Fig.6 and the reflection angle distribution in Fig.16. The angle of each position of a measured result is known. This result shows the distribution of surface angle is equal. The distribution of the observed position is an oval.

In general, the PSF of imaging system is isotropy. The SR-PSF is special case. The ratio of deviation depends on the angle of specular reflection in Fig.14.

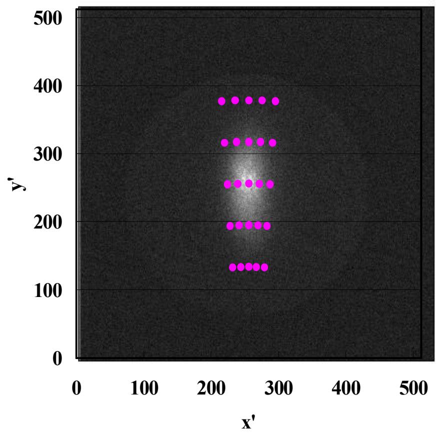

Figure 17. *SR-PSF of coated paper No.1(image) and calculated observed position (dots) corresponding to the changing sample bed deviation angle, Δθx and Δθy, in Fig. 16. The Specular reflection angle is 75 degree.*

Estimation of surface normal distribution

The measured results by this apparatus mean the reflection angles. Therefore the surface normal of part can be estimated by calculation. Figure 18 shows schematic diagram of surface and surface normal. The surface normal distribution can be also measured by this apparatus. It is thought that distribution of specular reflection occurs from surface unevenness.

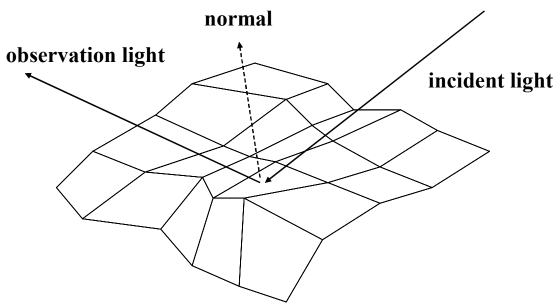

Figure 18. *Schematic diagram of surface and surface normal.*

Applications

SR-PSF, gonio-reflectance distribution and surface normal distribution can be measured at a time using this apparatus. Since they are important basic data, many applications will be considered. Glossiness or feeling of gloss could be estimated by considering an evaluation function. Surface normal distribution is applicable to estimate surface coarseness [8,9]. Surface normal distribution is also applicable to computer graphics [10].

Conclusion

We discussed point spread function of specular reflection (SR-PSF). We have developed the apparatus to measure SR-PSF. The experimental results showed that the measured SR-PSF works as a transfer function for specular reflection image. We also showed that the apparatus works as a goniophotometer within a narrow solid angle.

It is concluded that the measured data of this apparatus is SR-PSF, and is gonio-reflectance distribution. It is thought that the spreading of specular reflection observed on paper samples is caused by the distribution of surface normals. Our results showed that SR-PSF and gonio-reflectance distribution are one phenomenon expressed in two different physical concepts. Our future study will be focused on new reflection model for computer graphics.

Reference

[1] N.J.Elton and J.S.Preston, "Polarized light reflectometry for studies of paper coating structure Part I.", TAPPI J.5 (7) 8 (2006).

[2] N.J.Elton and J.S.Preston, "Polarized light reflectometry for studies of paper coating structure Partb II.", TAPPI J. 5(8) 10 (2006).

[3] M.Juuti, H.Koivula, M.Toivakka and K.Peiponen, "A diffractive gloss meter for local gloss measurements of papers and prints", TAPPI J. (4) 27 (2008).

[4] T.H.James ED.,: The Theory of the Photographic Process, Fourth Edition, Macmillan, 592-635(1977).

[5] S.Inoue, N.Tsumura and Y.Miyake, "Measuring MTF of Paper by Sinusoidal Test Pattern Projection", J. Imaging Sci. Technol. 41 (6) 657 (1997).

[6] G.L Rogers, "Measurement of the modulation transfer function of paper", Appl. Opt. 37(31) 7235-7240(1998)

[7] R.M. Leekley, C. W. Denzer and R.F. Tyler, "Measurement of Surface Reflection From Papers and Prints", TAPPI Journal (4) 615 (1970).

[8] H.Lipshitz, M.Bridger and G.Derman, "On the relationships between topography and gloss", TAPPI J. 73(10) 237 (1990).

[9] E.Caner, R.Farnood and N.Yan, "Relationship between gloss and surface texture of coated papers", TAPPI J. (4) 19 (2008).

[10] K. E. Torrance and E. M. Sparrow, "Theory or Off-Specular Reflection From Roughened Surfaces," J. Opt. Soc. Am, 57(9)1105-1112 (1967).