Simulation of Paper Gloss by Point Spread Function of Specular Reflection

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Abstract
We present a method to simulate paper gloss by using Point Spread Function of Specular Reflection (SR-PSF). The SR-PSF is defined as an impulse response of specular reflection that is distribution of light intensity reflected from microscopic facet on the surface of paper. The paper gloss is a combined phenomenon between the specular reflections from microscopic facet and macroscopic facet of paper.

In this study, we measure the SR-PSFs of paper samples that have different levels of specular gloss placed on a flat sample holder. Simulations for gloss of curved paper sample are done by transforming the measured SR-PSFs as a function of angle of macroscopic facet.

In the simulation, we convolve the transformed SR-PSFs with an image of a light source reflected on a cylindrically-curved specular object. Then we add the convolved light source image to an image of a sample paper placed on the curved object. The image of the sample paper is taken with polarizing filter to remove the gloss of the paper.

Our results show that the gloss of the curved paper samples can be simulated depending on the specular gloss with the SR-PSF.

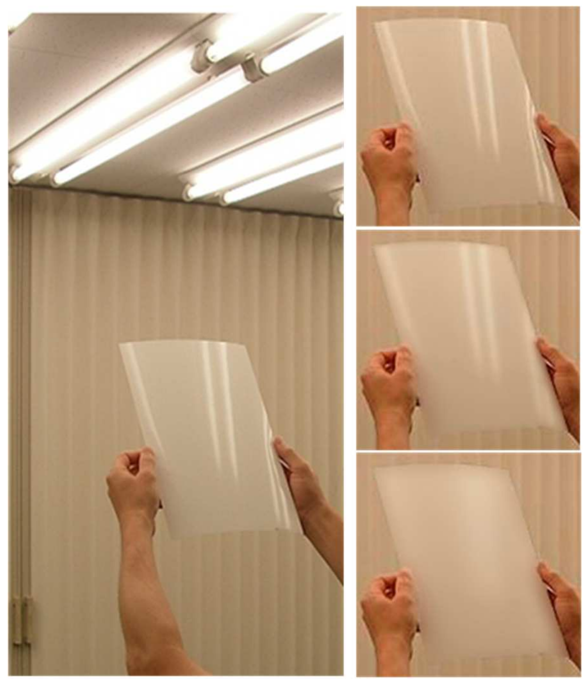

***Figure 1**. Scenes evaluating printing paper. The light sources are reflected on the curved paper. We can see different gloss levels from the images of the reflected light source. The upper right is a high glossy paper, the middle one is glossy and the bottom one is mat.*

Introduction
Gloss is one of the important factors to evaluate quality of printing paper. In the evaluation of the printing paper during paper manufacturing process, sharpness of reflected light source on surface of the curved paper is tested visually as shown in Figure 1. Quality of the paper is evaluated by levels of the sharpness of the reflected light source image on the curved surface.

Point Spread Function of Specular Reflection (SR-PSF) is an expansion of the PSF for specular reflection [1-3]. Fundamental parameter to determine the SR-PSF is angle of facets on surface of paper. Two kinds of facet are considered in this research that are macroscopic and microscopic facets as shown in Figure 2. Because the angle of the macroscopic facet is fixed for flat paper, direction of reflected light is determined by the angles of the microscopic facets. As a result, distribution of reflected light intensity will be a cause of the paper gloss [4, 5]. We define the angles of the macroscopic and microscopic facet as (θ_x, θ_y) and (θ_x', θ_y'), respectively. The distribution of (θ_x', θ_y') and (θ_x, θ_y) determines shape and peak of the SR-PSF, respectively

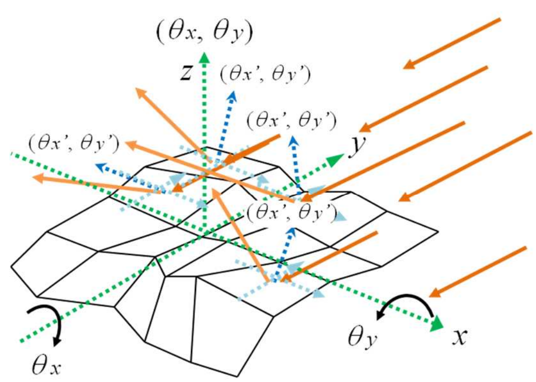

***Figure 2**. Schematic diagram showing macroscopic and microscopic facets on surface of flat paper.*

In the experiment, we measure the SR-PSFs of six paper samples that have different levels of specular gloss. In the measurement, the angle of the macroscopic facet is set to (0°, 0°) that the paper is placed in a flat.

In the simulation, the gloss for the curved paper is calculated from convolution of the measured SR-PSFs with an image of a light source reflected on a cylindrically-curved specular object. In order to simulate the gloss for the curved paper, we transform the measured SR-PSFs as a function of (θ_x, θ_y) determined by the angle of the curved object.

The detailed procedure of our method is described in the following sections.

Measurement of SR-PSF

Measurement method of SR-PSF

The SR-PSF is measured by using the apparatus developed by Inoue *et al*. as shown in Figure 3 and 4 [1]. Light from a pinhole light source is projected onto a sample paper through a collimator lens system. The reflected light on the sample paper is inversely collimated and a two dimensional CCD camera takes the reflected light intensity distribution as an image. The image of the light intensity distribution shows the SR-PSF of the paper sample because it is an impulse response to the pinhole light. The lighting and viewing angles are set to be 75° according to the measuring method for the specular gloss of paper standardized by ISO [6].

In the apparatus, the pinhole is made of a metal plate, and its diameter is 100 μm. The CCD camera has 512×512 pixels resolution, and it has 16 bits output levels per pixel. Resolution of one pixel to the sample paper is 0.029 mm/pixel. The output values can be used as the light intensity because the linearity between the output values and the light intensity is confirmed in advance. The sample paper is set on the sample bed, and the SR-PSF is measured in the darkroom. We prepare a black glass, which refractive index is 1.567, as a standard.

Measurement results of SR-PSF

Six kinds of paper samples that have different levels of the specular gloss were prepared from the same paper material. Figure 5 shows ISO 75° specular gloss measured by the gloss meter, GM-26PRO made by Murakami Color Research Laboratory. Figure 6 shows the measured SR-PSFs by using the apparatus shown in Figure 3 and 4. The *x*’ and *y*’ axis describes the pixel position on the CCD camera. The *z*’ axis describes the output value of the CCD camera. The measured SR-PSFs show different distribution and its peak value in the *z*’ decrease as decreasing of the specular gloss of the sample papers.

Figure 3. *The measurement apparatus for SR-PSF*

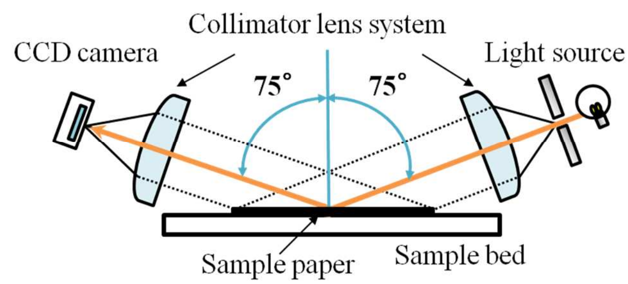

Figure 4. *Apparatus diagram for measuring SR-PSF*

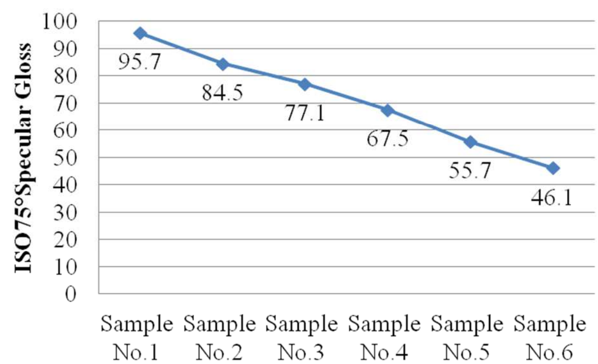

Figure 5. *Specular gloss of the sample papers used in this study.*

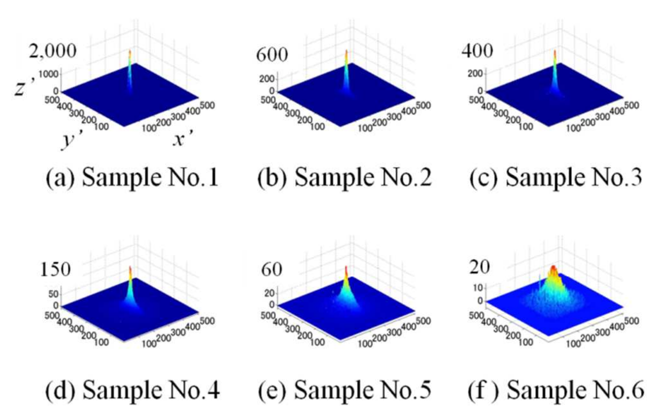

Figure 6. *Measurement results of SR-PSFs. The maximum value of the z’-axis is 2000 in (a), 600 in (b), 400 in (c), 150 in (d), 60 in (e) and 20 in (f)*

Angle dependency in SR-PSF

Relationship between SR-PSF and angle of microscopic facet

Figure 7 shows schematic diagram of a collimator lens system. The collimator lens system focuses incoming parallel light rays into a one point on the CCD. Despite the incoming light rays are parallel, the light rays reach different points on the CCD because the angles of the microscopic facets (θ_x', θ_y') are different.

Figure 8 shows the coordinate system of the measurement apparatus. The y is the optical axis direction, the x is the cross direction and the z is the distance from the sample. The pixel position (x', y') on the CCD is determined by (θ_x', θ_y') and (θ_x, θ_y).

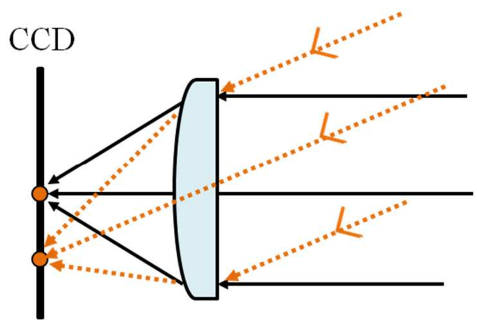

***Figure 7**. Schematic diagram of collimator lens system*

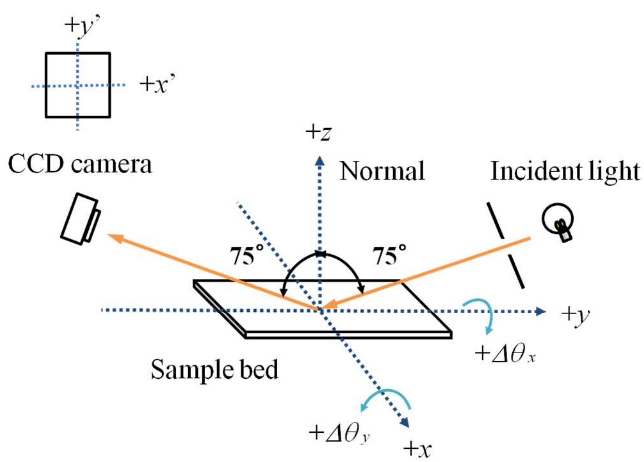

***Figure 8**. Coordinate system of measurement apparatus for SR-PSF.*

Transformation of SR-PSF to correspond angle of macroscopic facets

In the simulation of the gloss for the curved paper, the angle (θ_x, θ_y) and (θ_x', θ_y') are transformed to the focal position (x, y, z) for coordinate system:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = f \begin{pmatrix} \sin(2(\theta_x+\theta_x'))\cos(75^\circ+2(\theta_y+\theta_y')) \\ \sin(75^\circ+2\theta_y) \\ \cos(2(\theta_x+\theta_x'))\cos(75^\circ+2(\theta_y+\theta_y')) \end{pmatrix}, \quad (1)$$

where f is focal length of the collimator lens system. Then the pixel position (x', y') in the CCD camera coordinate is calculated by using a rotation matrix.

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(75^\circ) & \sin(75^\circ) \\ 0 & -\sin(75^\circ) & \cos(75^\circ) \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}. \quad (2)$$

In this study, we consider rotation of θ_x only because the paper is bended in θ_x direction usually in the evaluation of the paper gloss. Figure 9 shows transformed results for the sample No.5 in Figure 6(e) as an example of the transformed SR-PSF. Figure 9(a) shows the SR-PSF at ($\Delta\theta_x$, $\Delta\theta_y$) = (0°, 0°), and from (b) to (e) show the SR-PSFs for ($\Delta\theta_x$, 0°) where -4° ≤ $\Delta\theta_x$ ≤ +4° in every 2°. The white dots plotted in Figure 9 show that (x', y') corresponding to ($\Delta\theta_x+\theta_x$', 0°+θ_y') where -4° ≤ θ_x', θ_y' ≤ +4° in every 2°.

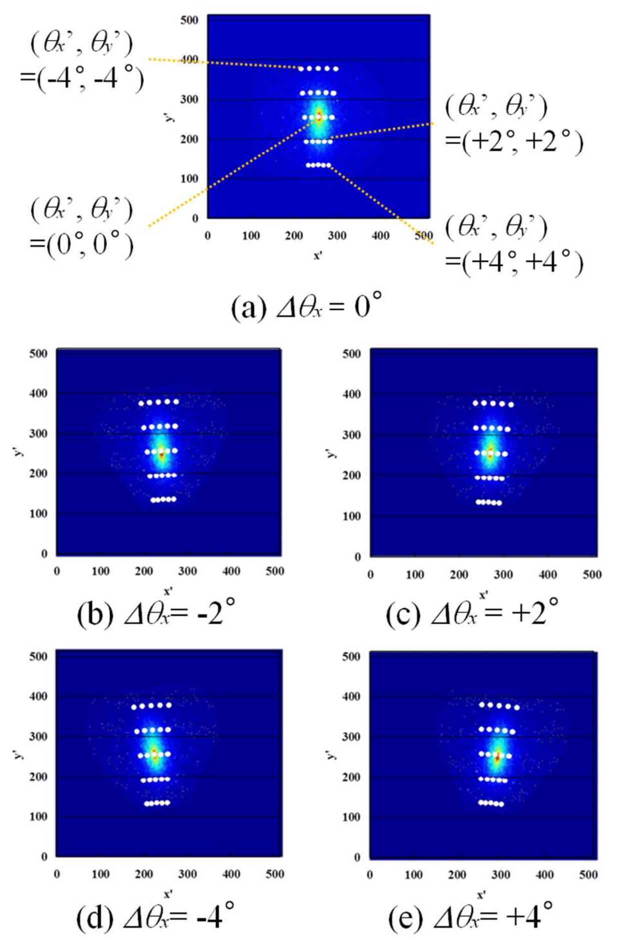

***Figure 9**. The transformed SR-PSFs for the sample No.5. The angle $\Delta\theta_x$ is 0° in (a), -2° in (b), +2° in (c), -4° in (d) and +4° in (e).*

Simulation of paper gloss by SR-PSF

Simulation method

Figure 10 shows a methodology diagram of the paper gloss simulation. Firstly, we project a fluorescent light source onto the cylindrically-curved specular object, and take an image $f_{\text{light}}(x', y')$ of the reflection light source on the object. The size of $f_{\text{light}}(x', y')$ is 1512×1008 pixels, and resolution of the reflection light source to one pixel is 0.029 mm/pixel at the center of the image. Then we convolve the SR-PSF $f_{\text{SR-PSF}}(x', y')$ with this image. The peak value of $f_{\text{SR-PSF}}(x', y')$ is normalized according to ISO75° specular gloss. Equation (3) shows this operation.

$$f_{\text{light}}'(x', y') = f_{\text{light}}(x', y') * f_{\text{SR-PSF}}(x', y'). \quad (3)$$

In this step, we transform $f_{\text{SR-PSF}}(x', y')$ corresponding to the curvature of the object whose diameter is 260 mm. We assume that the displacement of the angle per line of the pixel in $f_{\text{light}}(x', y')$ is constant, and we calculate the displacement by using the diameter of the object.

Secondly, we add $f_{\text{light}}'(x', y')$ to the paper image $f_{\text{paper}}(x', y')$ taken with the polarizing filter to remove gloss component. The paper sample is placed on the cylindrically-curved object. Equation (4) shows this operation.

$$f_{\text{gloss}}(x', y') = f_{\text{light}}'(x', y') + f_{\text{paper}}(x', y'). \quad (4)$$

Figure 11 shows photographing environment. Table 1 summarizes photographing device.

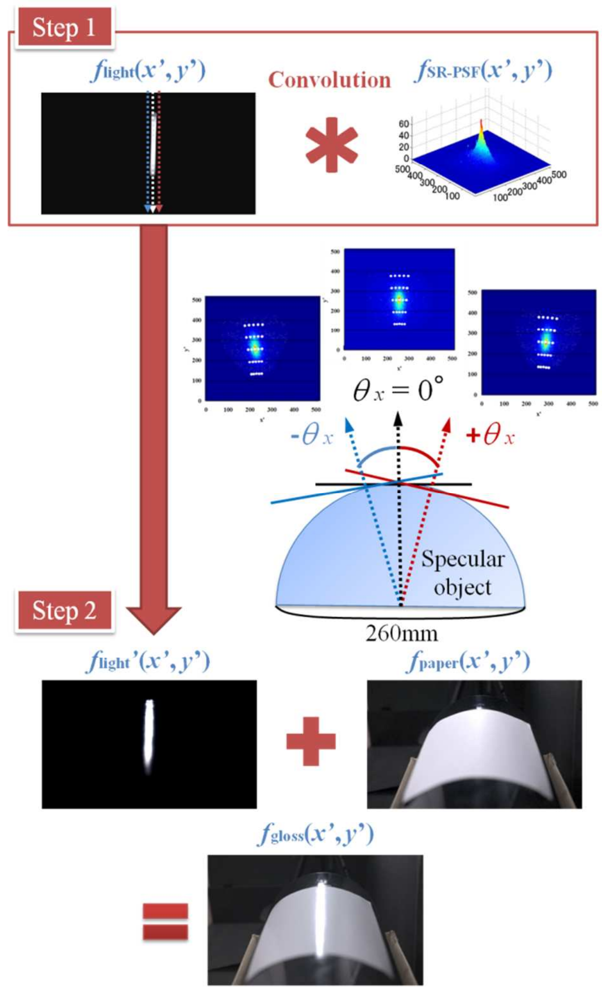

***Figure 10**. Methodology diagram of the paper gloss simulation*

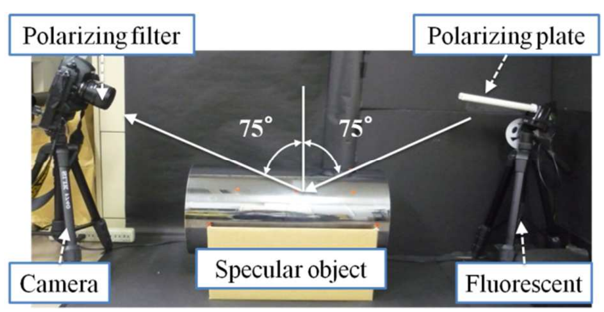

***Figure 11**. The photographing environment for the paper gloss simulation.*

Table 1. Photographing device used in this study.

Camera	Nikon D3X
Lens	Nikon AF MICRO NIKKOR 60mm 1:2.8 D
Polarizing filter	Nikon 62 SPL 2 62mm
Shutter speed (sec)	1.6
F-number	32
ISO speed (sec)	200

Simulation results

In the simulation, two methods are considered. Method 1 regards the macroscopic angle dependency in the SR-PSF, and Method 2 does not regard this dependency. Figure 12 shows resultant images simulating the paper gloss with the same logarithmic conversion as a normalization. The figures at the left side, center and right side show the images of the real paper gloss taken by the camera, the simulated images by Method 1, and the simulated images by Method 2, respectively. It was confirmed that the maximum values in the intensity distributions in Figure 12 were decreased with decreasing of the specular gloss.

Discussion

In the intensity distributions, the sharpness of the light source in each simulated image is more blurred with decreasing of the specular gloss. These results show that the gloss for different levels of the specular gloss can be simulated by using the SR-PSF. However, comparing Method 1 and 2, the intensity distribution in the direction of x' is more accurate than that in the direction of y'. This is because we don't consider the direction of θ_y angle and perspective of the object. As future works, we improve the accuracy in the simulation by considering θ_y angle and the perspective of the object in the captured image.

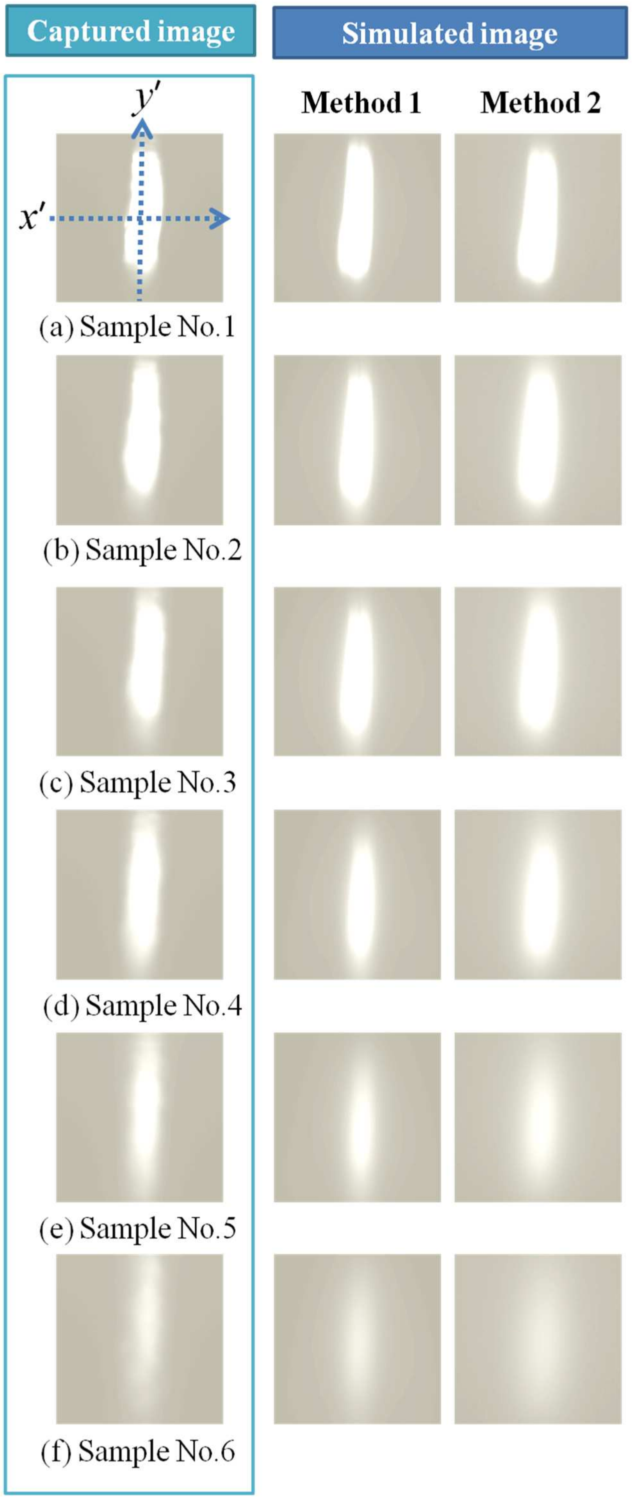

Figure 12*. Simulated results of the paper gloss. From left to right, the figures show the captured images, the simulated images regarded macroscopic angle dependency as Method 1, and the simulated images regardless macroscopic angle dependency as Method 2.*

Conclusion

We measured the SR-PSFs of the paper samples that have different levels of the specular gloss, and simulated the intensity distribution to convolve the SR-PSF with the image of light source. From the simulated results, it was confirmed that the intensity distribution could be simulated depending on the specular gloss with the SR-PSF. In addition, we considered the macroscopic angle dependency in the SR-PSF for the curved paper. As a result, the accuracy in the simulation is improved. As future works, we discuss acceptable range of the error visually.

References

[1] S. Inoue and N. Tsumura, Relationship between PSF and Goniorefreflectance distribution of Specular Reflection, Proc.CGIV, pp. 301-306. (2012).
[2] S. Inoue, Y. Kojima, M. Takishiro, Measurement Method for PSF of Paper on Specular Reflection Phenomenon, Proc.76th Pulp and Paper Research, pp. 67-82. (2012).
[3] T. H. James ED, The Theory of the Photographic Process (Macmillan, NY, 1977) pp. 592-635.
[4] R. Takano, K. Baba, S. Inoue, K. Miyata, N. Tsumura, Reproduction of Gloss Unevenness on Printed Paper by Reflection Model with Consideration of Mesoscopic Facet, Proc.CIC, (2012).
[5] K. E. Torrance and E. M. Sparrow, "Theory or Off-Specular Reflection from Roughened Surfaces," Jour. Opt. Soc. Am., 57, 9, pp.1105-1112. (1967).
[6] ISO 8254-1:2009.

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