Measuring MTF of Paper by Sinusoidal Test Pattern Projection*

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Image quality of hardcopy is significantly influenced by paper characteristics. Light scattering phenomena in paper produce optical dot gain, which has a large influence on the tone reproduction characteristics of halftone images. Light scattering phenomena in paper can be represented by the modulation transfer function (MTF) of paper. However, little has been reported on techniques for measuring the MTF of paper. In this study, a new technique for measuring MTF of paper is proposed. We have developed a modified microdensitometer to project a sinusoidal test pattern on sample paper. The reflection density distribution of the projected sinusoidal test pattern was measured by the microdensitometer, and the MTFs of various types of papers obtained. The point spread function (PSF) of paper was calculated by the Fourier transform of the measured MTF. The PSF could be expressed by an exponential function. The obtained PSFs were applied to a model to predict reflection density of the halftone image. This result showed that the predicted density is approximately the same as the measured density in the halftone image and the estimated optical dot gain is well correlated to the measured optical dot gain.

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Introduction

Image quality of hardcopy is significantly influenced by paper characteristics. Paper is a well-known turbid medium. Therefore, incident light to paper causes absorption, transmission, reflection, and scattering. Those phenomena produce optical dot gain and have a large influence on image quality, particularly tone reproduction characteristics of halftone print and digital halftone images. The dot gain of halftone patterns were analyzed by using the Yule-Nielsen[1,2] equation defined by Eq. 1,

$$Dr = -n\log(1 - a(1 - 10^{-Ds/n})) \qquad (1)$$

where Dr is reflection density, a is the dot area, Ds is the solid ink density, and n is a factor to give the amount of light diffusion in the recording paper. If the value of n is equal to 1.0, it becomes the Murray-Davies equation. Determining the value of n is important for analyzing the tone reproduction in halftone prints. However, if the factor n is an empirical value, then the value cannot be determined theoretically. Some theoretical models have been studied to predict reflection density in a halftone image.[3–5] The light scattering phenomenon is represented by the point spread function (PSF) of paper in their models. However, little has been reported on techniques for measuring the PSF of paper.

If the light scattering process of paper is assumed isotropic, the imaging properties are specified either by the PSF, the line spread function (LSF), or the MTF in the spatial frequency domain. If one of these functions is determined, the other can be calculated mathematically. Yule et al.[1,2] measured the LSF of paper by the edge projection method. As a result, they suggested that the LSF of paper may be represented as a Gaussian function. Engeldrum and Pridham[6] measured the LSF of paper with the same technique. They pointed out that the noise in this edge projection method is not low enough for accurate (noise-free) determination of paper MTFs using a measurement slit of 1.0 mm length and 0.0254 mm width and the edge gradient method needs to include at least 30 times larger area in the measurement for satisfactory data. They also measured the MTFs of paper using the scattering and absorbing coefficients from the Kubelka-Munk turbid medium theory. They pointed out that the paper MTFs of coated papers are poorly described and the plain papers well described by this theory. Oittinen and Saarelma[7] reported a method whereby an optically sharp edge image of glass is contacted on the paper and this reflection intensity distribution is measured by scanning over the edge with a microdensitometer. Teraoka and Taguchi[8] reported a method whereby rectangular wave patterns on paper are made by an off-press proof system and paper LSFs are measured by this reflection response.

In this article, we propose a new technique for measuring the MTF of paper by sinusoidal test pattern projection. The MTFs of coated and uncoated paper were measured by this method. We also introduce a theoretical model to predict reflection density based on the PSF of paper. Experimentally obtained PSFs are applied to validate the model.

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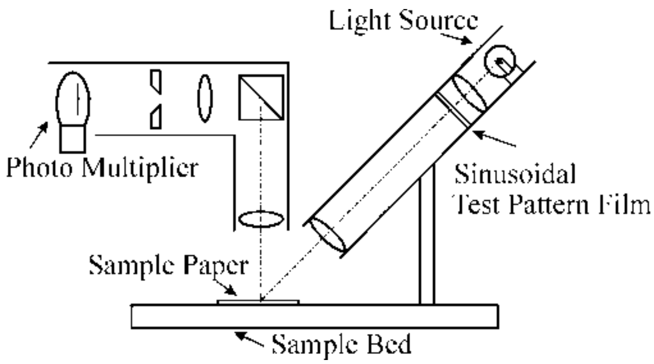

Figure 1. Diagram of modified microdensitometer.

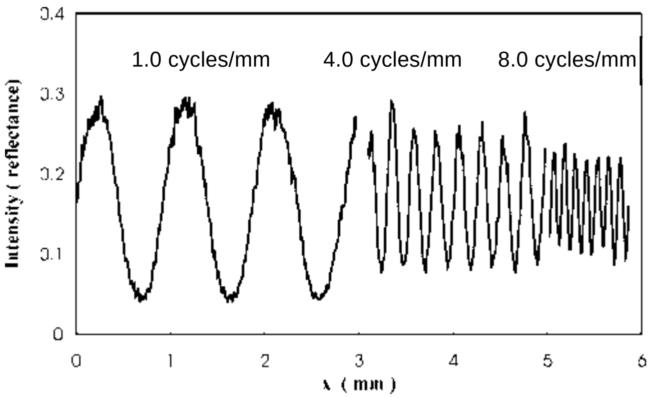

Figure 2. Projected sinusoidal test pattern traces for coated paper.

Measuring MTF of Paper by Sinusoidal Test Pattern Projection

The MTF of paper was measured by a modified sine wave method. Such methods based on the use of spatial sine waves are commonly used in the practical measurement of the MTF.[9–11] An optical system is projected by a one-dimensional distribution $I(x)$ of the form:

$$I(x) = b + c \cdot \cos(2\pi\omega x), \tag{2}$$

where ω denotes the spatial frequency and c/b denotes the modulation. The MTF for the spatial frequency ω is given by the ratio of output to input modulations. In experiments, the modulation M can be expressed by Eq. 3.

$$M = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \tag{3}$$

where I_{max} and I_{min} denote the maximum and minimum light intensity of the recorded sinusoidal curve, respectively.

In this modified sine wave method, a sinusoidal test pattern is projected onto paper and the reflection intensity distribution measured with a modified microdensitometer. The modulation for each spatial frequency can be determined easily using Eq. 3. The microdensitometer used, which is a modified MPM-5 (UNION Optical, Tokyo, Japan), is shown in Fig. 1 and is referred to as Yule's[2] apparatus. The normal illuminating system of the microdensitometer is replaced with a special projection system fixed on the sample bed at an angle of 45°. This projection system consists of a chart holder with a sinusoidal test pattern film and a halogen lamp. The internal projection system is coated black to avoid the flare light. The function of this optical system is to project a uniform image of the sinusoidal test pattern in the chart holder onto the image plane. The projected image is focused only on a line on the sample bed, because the image is projected at an angle of 45°. Therefore, scanning was done on this focused line. The effective measurement aperture of the microdensitometer is 0.01 mm wide and 0.1 mm high.

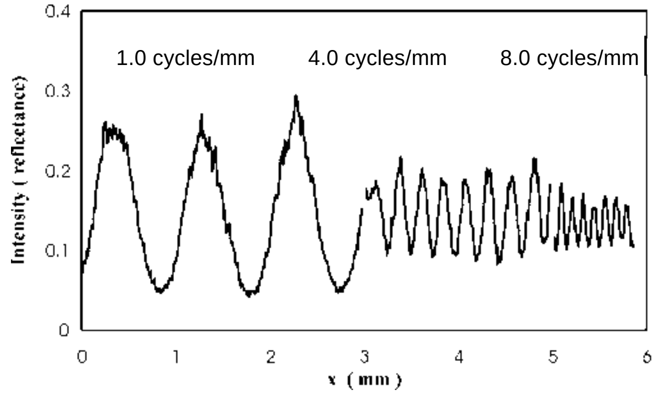

Figure 3. Projected sinusoidal test pattern traces for the uncoated paper.

The sinusoidal test pattern used was Sine Patterns, M-5-60, a variable-transmission-type pattern made on exceptionally high-resolution film. The sinusoidal test pattern arrays contained a set of sinusoidal areas with the spatial frequencies of interest. Each sinusoidal area varied sinusoidally in transmittance. Each modulation (contrast) value was about 60%. The harmonic distortion of these patterns was generally less than 3%. Low-contrast patterns were used to ensure that all intensity values were well within the measurement range of the microdensitometer. Nine sinusoidal test pattern arrays were used for each sample paper, each with a different spatial frequency, 0.375, 1.0, 2.5, 4.0, 6.0, 8.0, and 10.0 cycle/mm.

Two types of paper were measured: uncoated and coated. The uncoated paper was 64.0 g/m^2 for plain paper copier (ppc) and mat. The coated paper was 104.7 g/m^2 for print, coated with 15 g/m^2 pigment on each side, and glossy. The input sinusoidal test pattern projected onto the sample paper was degraded by internal diffusion in the paper, and the resulting degraded image was then reflected onto the slit of the microdensitometer through the scanning optics. Measure- ments were made by driving the sample bed with the sample and the projection system (which remained fixed in relation to one another). Readings were taken at 0.01 mm intervals, namely, values obtained correspond to the output sinusoidal image distribution. Because this was reflection density recording data, reflectance could be obtained by Eq. 4,

$$Ro = 10^{-Dr}, \tag{4}$$

where Ro is reflectance and Dr is reflection density. This reflectance corresponded to the intensity of the output sinusoidal image. The modulation was calculated from the maximum and minimum intensity, reflectance, of the output sinusoidal image using Eq. 3.

The output sinusoidal images measured for sample papers in this way are shown in Figs. 2 and 3. These results

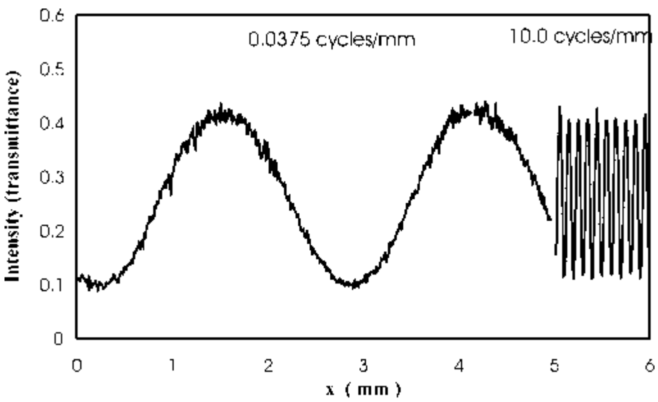

Figure 4. Sinusoidal test pattern film traces.

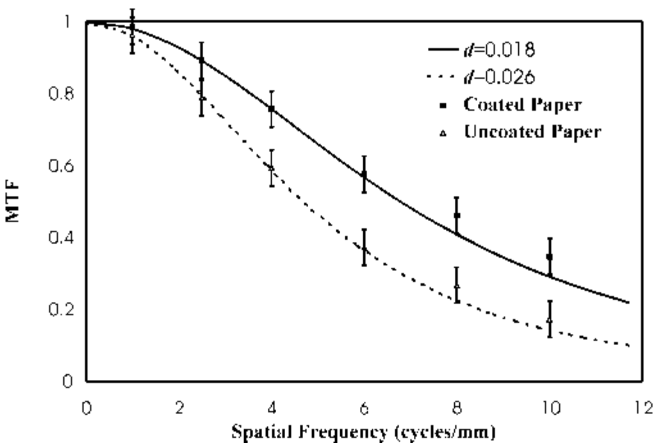

Figure 5. MTF curves in Eq. 5 and measured MTFs. The error bars show the standard deviation for the measurement noise.

include the spreading of light by the instrument itself, and a correction was made for this by use of the measuring system MTF, which was, in turn, measured by transmittance of the sinusoidal test pattern film shown in Fig. 4. The resulting MTF of paper was corrected using this system MTF. The MTFs of the coated and uncoated papers are shown in Fig. 5.

Empirical MTF Models

From Fig. 5, it is apparent that the MTF of the coated paper was higher than for the uncoated. Both MTFs decreased with increasing spatial frequency; furthermore, the MTF had a finite value at spatial frequencies greater than 12.0 cycle/mm. However, determining an accurate MTF is difficult in the high spatial frequency owing to noise.

Various curves have been proposed to interpret the observed nature of the photographic MTF:[6] Equations 5 through 7 show three representative MTF expressions.

$$MTF(\omega) = \frac{1}{[1+(2\pi d\omega)^2]^{\frac{3}{2}}}, \tag{5}$$

$$MTF(\omega) = e^{-2\pi k_2|\omega|}, \tag{6}$$

$$MTF(\omega) = e^{-2\pi k_3|\omega|^2}. \tag{7}$$

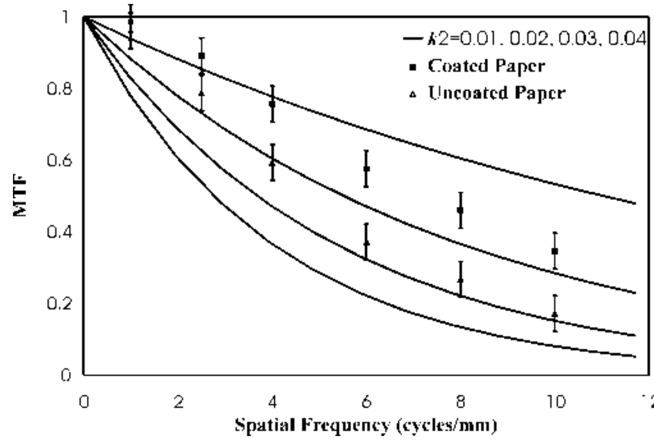

Figure 6. MTF curves in Eq. 6 and measured MTFs. The error bars show the standard deviation for the measurement noise.

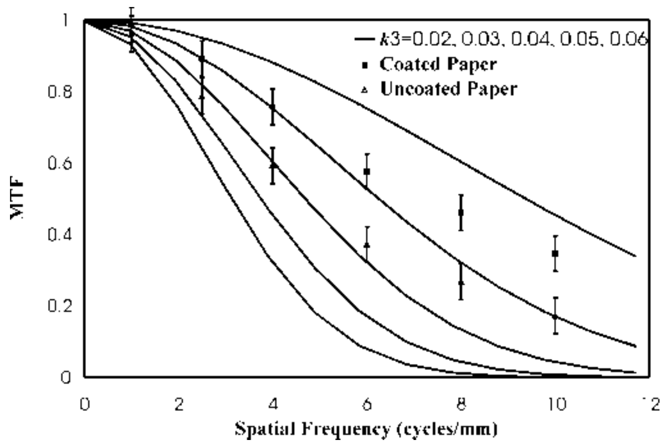

Figure 7. MTF curves in Eq. 7 and measured MTFs. The error bars show the standard deviation for the measurement noise.

Figures 5 through 7 show the measured MTF data (dots) and the MTF fitting curves using each expression (lines). The MTF of paper can be approximately expressed by Eq. 5. The coefficient d was calculated as 0.018 for the coated paper and 0.026 for the uncoated, respectively.

Prediction of Reflection Density using MTF of Paper

Some models have been proposed to predict reflection density of halftone images. The light scattering phenomenon in paper is represented by the PSF of paper in these models.[3,4] We introduce a model to predict reflection density based on PSF of paper[5] as follows:

We assume that the print image on paper comprises two layers: transparent image and diffuse reflection. Figure 8 shows the diagram of this model where the transparent image layer is ink and the diffuse reflection layer paper. Steps in this model

Step 1: Incident light $Ii(x,y)$ at coordinate x, y is projected to the transparent image layer.

Step 2: The transparent image layer absorbs incident light.

Step 3: Incident light is scattered and diffused in the diffuse reflection layer, and this phenomenon is represented as PSF.

Step 4: The scattered and reflected light in the diffuse reflection layer is absorbed in the transparent image layer again.

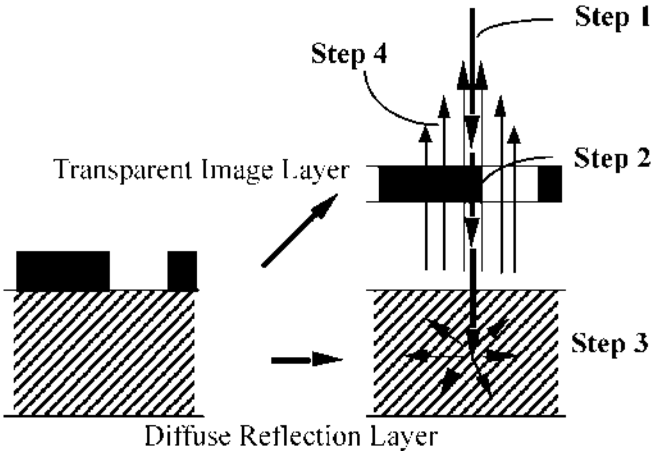

Figure 8. Diagram of reflection density model.

These steps can be expressed as the following equation:

$$Ir(x,y) = \{[Ii(x,y)T(x,y)] * h(x,y)\}T(x,y), \qquad (8)$$

where $Ir(x,y)$ is reflection light intensity, namely, the observed image; $T(x,y)$ is transmittance of the transparent image layer; $h(x,y)$ is the PSF of the diffuse reflection layer; and * indicates the convolution integral.

In general, hardcopy has been analyzed by using reflection density. According to the definition of reflection density, the value of $h(x,y)$ should be reflection relative to the perfect reflection diffuser. In the measuring geometry, the illuminating angle should be 45° and the measuring angle should be 0°. We defined this $h(x,y)$ as reflectance PSF. We assumed the reflectance of the diffuse reflection layer was uniform, then the reflectance PSF could be divided into reflectance ratio Rr and normalized reflectance PSF $Rpsf(x,y)$. Therefore reflection density $Dr(x,y)$ can be expressed by Eq. 9.

$$Dr(x,y) = -\log \{[T(x,y)*[Rpsf(x,y)Rr]]\ T(x,y)\}. \qquad (9)$$

Eq. 9 is modified to Eq. 10.

$$Dr(x,y) = -\log \{[T(x,y)*Rpsf(x,y)]T(x,y)\} - \log(Rr), \qquad (10)$$

where $-\log(Rr)$ means reflection density of the diffuse reflection layer itself, namely, the reflection density of paper. Normalized reflectance PSF, $Rpsf(x,y)$, is obtained mathematically as another form of paper MTF.

Measured and Predicted Reflection Densities

An experiment was performed to compare the measured density with the predicted density in the model. Figure 9 shows a method to measure the reflection density. The density of each sample paper was measured through a transparent test chart film. The transparent test chart film used was "The System Brunner Print Control Strip" (Dupont, Delaware, USA). This test chart film had four kinds of halftone patterns: screen ruling at 25 lpi with dot area of 50% and screen rulings at 150 lpi with dot areas of 25%, 50%, and 75%. The halftone dot shape of 25 lpi is a diamond. The halftone dot shape of 150 lpi is a circle. The dot area in the System Brunner Print Control Strip was nearly perfect, so it was not necessary to consider mechanical dot gain in this method. The reflection densitometer (RD-918 Macbeth, New York, USA) was used to measure the reflection density.

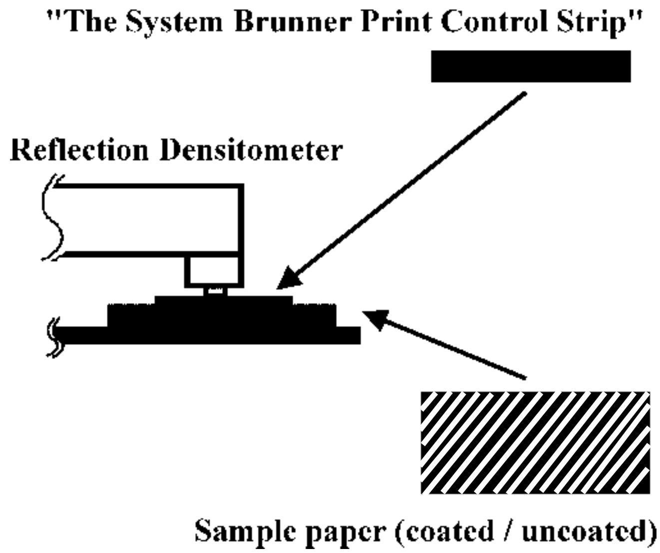

Figure 9. A schematic diagram of the macro-density measuring method.

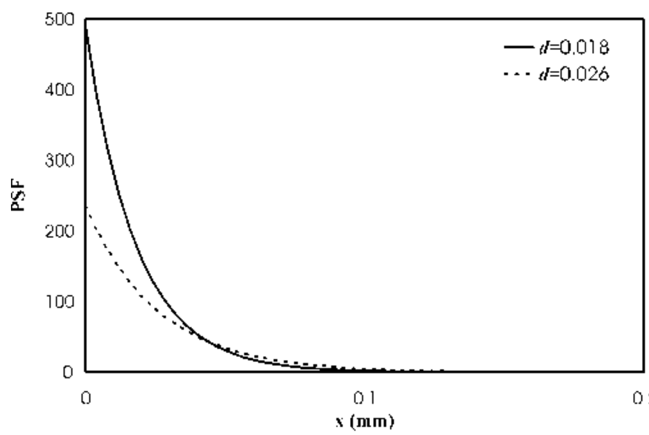

Figure 10. The PSF $Rp(x,y)$ curves of the coated and uncoated paper when y = 0.0.

The prediction was obtained from Eq. 10. The normalized reflectance PSF $Rpsf(x,y)$ was calculated mathematically as the other form of the paper MTF represented by Eq. 5. The exponential expression is

$$Rpsf(x,y) = \frac{1}{2\pi d^2} e^{\frac{-\sqrt{x^2+y^2}}{d}}, \qquad (11)$$

where d is the same coefficient as in Eq. 5. According to the measurement results, the coefficient d was 0.018 for coated and 0.026 for uncoated paper. The integral of $Rpsf(x,y)$ was normalized to be 1.0. Figure 10 shows $Rpsf(x,y)$. The transmittance $T(x,y)$ of the dot domain in the transparent test chart film was less than 0.0001 as measured by the transmission densitometer (TD-904 Macbeth).

Table I shows measured and predicted densities for eight samples, two types of papers, and four halftone images. Each density in Table I was corrected for base density $\log(Rr)$. Predicted and measured densities were approximately the same under each condition.

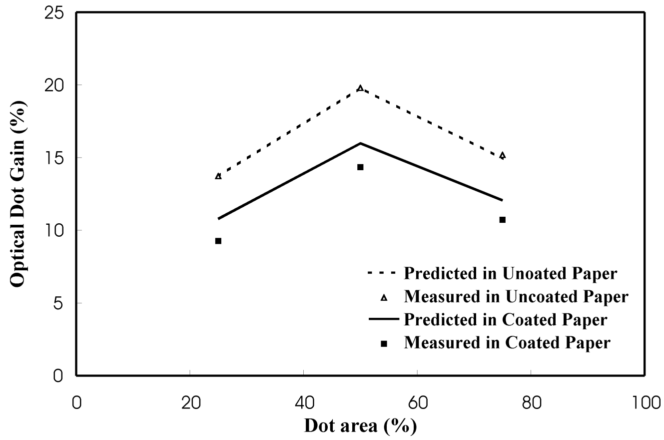

Figure 11. Measured and predicted optical dot gain.

TABLE I. Measured and Predicted Macro Densities of the System Brunner Print Control Strip on Sample Papers

Condition		Coated Paper		Uncoated Paper	
Screen	[%]	Measured	Predicted	Measured	Predicted
25 lpi	50	0.32	0.33	0.36	0.34
150 lpi	25	0.18	0.19	0.21	0.21
150 lpi	50	0.44	0.46	0.51	0.51
150 lpi	75	0.82	0.86	0.97	0.96

Figure 11 shows the measured and predicted optical dot gains for 150-lpi samples, which are approximately the same for the uncoated paper. Predicted optical dot gains were only 1.5% larger than the measured results for coated paper. This result suggests that the MTF of the coated paper may be slightly higher. If the coefficient d is assumed 0.016 in the coated paper, the predicted and measured densities are almost the same.

Conclusions

Measuring MTFs of papers by the sinusoidal test pattern projection method was proposed. This method allows direct measurement of the MTF of any type of paper without special preparation. The results obtained by this measuring technique were stable. As a result, it was shown that the PSFs of coated and uncoated papers are expressed by an exponential function. Furthermore, we introduced a model to predict reflection density based on the PSF of paper. By using the experimental PSFs of paper, we validated this model. The result demonstrated that the predicted density in this model was approximately the same as the measured density in halftone printing.

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