

New method for measuring colorimetric properties of FWA-treated paper

KENJI IMURA

ABSTRACT: A new method is proposed for measuring the total spectral radiance factor $B(\lambda)$, from which all colorimetric values are derived, of paper treated by FWA (fluorescent whitening agent) illuminated by a specific standard illuminant. The method replaces unstable real fluorescent standards by bi-spectral luminescent radiance factor data that works as virtual fluorescent standards. This method was used to measure total spectral radiance factors by two illuminants for fluorescent standard paper supplied by STFI, and the ISO brightness and CIE whiteness were derived from them. The values agreed with values assigned by STFI well enough to prove the validity of the method. Total spectral radiance factors of four FWA-treated papers with fluorescence eliminated or suppressed were also measured by the method and those colorimetric values were derived from them.

Application: Papermakers can use the new method to improve accuracy, flexibility, and efficiency in measuring colorimetric properties of FWA-treated paper.

Colorimetric properties of an illuminated object are recognized in relation to a white object identically illuminated and observed. For a fluorescent object, total radiation fluoresced and reflected from the object is related to the radiation reflected from the white object. In Eq. 1, the total spectral radiance factor (SRF) $B(\lambda)$, from which all colorimetric values are derived, is given as the sum of the reflection SRF $R(\lambda)$ and the fluorescent SRF $F(\lambda)$. These are the ratios of the radiance from the object due to reflection and fluorescence respectively to the radiance from the perfect reflecting diffuser identically illuminated and received [1, 2].

$$B(\lambda) = R(\lambda) + F(\lambda) \quad (1)$$

Fluorescence depends on the spectral power distribution (SPD) $I(\mu)$ of the illumination and the bi-spectral characteristics of the object such as the bi-spectral luminescent radiance factor (BLRF) $F(\mu, \lambda)$. This is the ratio of radiance at wavelength λ due to the fluorescence of the object illuminated by monochromatic light at wavelength μ , to the radiance from the perfect reflecting diffuser identically illuminated and received. BLRF is generally measured by a sophisticated bi-spectro-fluorimeter.

The perfect reflecting diffuser has neither spectral dependence nor fluorescence. Equation 2 determines the fluorescent spectral radiance factor $F(\lambda)$ of the BLRF $F(\mu, \lambda)$ illuminated by the SPD $I(\mu)$, where the proportional coefficient is neglected [1, 2].

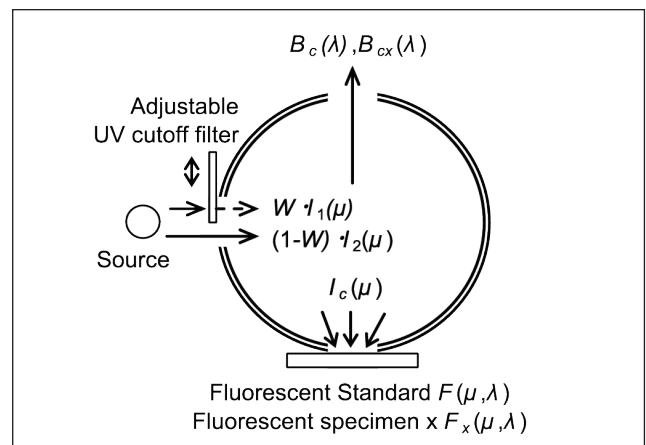
$$F(\lambda) = \int F(\mu, \lambda) \cdot I(\mu) d\mu / I(\lambda) \quad (2)$$

Eq. 1 and Eq. 2 indicate that the total SRF $B(\lambda)$ and, accordingly, the appearance of the fluorescent object depend on the SPD of the illumination, especially on the relative SPD between

the excitation and fluorescence regions of the object. For FWA (fluorescent whitening agent)-treated paper, these are the UV and blue regions. Therefore, ISO 2470 and ISO 11475, respectively, specify the standard illuminants for measuring specific colorimetric values of paper (e.g., Illuminant C for ISO brightness [3] and Illuminant D65 for CIE whiteness [4]).

Because it is not realistic to materialize such standard illuminants defined by SPD data, FWA-treated paper is generally measured approximately by Gaertner and Griesser's method, which adjusts the UV content in the illumination. Several methods for calculating the total SRF by a standard illuminant from the total SRF(s) measured by the illumination of the instrument are not in practical use due to their complexity or inaccuracy [5].

Figure 1 illustrates the Gaertner and Griesser method. The UV cutoff filter is adjusted and inserted in the flux from the UV-rich source to the integrating sphere [6–8]. The degree of insertion (the insertion ratio W) is adjusted by repeatedly positioning the filter and measuring the fluorescent standard



1. Gaertner and Griesser's method.

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until the measured specific colorimetric value (e.g., ISO brightness) agrees with the value assigned to the standard. At the adjusted insertion ratio W , the fluorescent standard is illuminated by composite illumination I_c of the SPD $I_c(\mu)$ given by Eq. 3 where $I_1(\mu)$ and $I_2(\mu)$ are the SPDs of the illuminations by the fluxes without and with the UV content.

$$I_c(\mu) = W \cdot I_1(\mu) + (1-W) \cdot I_2(\mu) \quad (3)$$

ISO brightness of a fluorescent specimen x of the BLRF relatively close to that of the fluorescent standard is derived from the total SRF $B_{cx}(\lambda)$ measured at the same filter position. ISO 2469 defines the procedure for the UV content adjustment and the photometric calibration. The UV adjustment procedure is based on fluorescent standard paper with the assigned colorimetric value that is traced up to the BLRF $F(\mu, \lambda)$ of the same-type paper as the fluorescent standard paper measured by the bi-spectro-fluorimeter at the NRC (National Research Council of Canada).

The new calculation method is more practical than previous methods because it uses two illuminations of the different SPDs; it is based on the same hypothesis as Gaertner-Griesser's method, in which the specimen is close to the fluorescent standard in the relative BLRF.

The new VFS method introduces a virtual instrument in parallel with a real instrument [9-11]. With the real instrument the illuminations I_1 and I_2 have SPDs $I_1(\lambda)$ and $I_2(\lambda)$ that differ in their relative intensities between the excitation and fluorescence regions of general FWA; the instrument measures the total SRFs $B_{1x}(\lambda)$ and $B_{2x}(\lambda)$ of the fluorescent specimen x by the illuminations I_1 and I_2 , respectively. The virtual instrument has the same illuminations as I_1 and I_2 of the real instrument and the target illumination I_p though as the SPD data $I_1(\lambda)$, $I_2(\lambda)$, and $I_p(\lambda)$ and virtually measures according to Eq. 4, Eq. 5, and Eq. 6 the fluorescent SRFs $F_1(\lambda)$, $F_2(\lambda)$, and $F_i(\lambda)$ of the virtual fluorescent standard (VFS) by $I_1(\lambda)$, $I_2(\lambda)$, and $I_p(\lambda)$, where the VFS is given as the BLRF $F(\mu, \lambda)$ data relatively close to $F_x(\mu, \lambda)$ of the real fluorescent specimen x .

$$F_1(\lambda) = \int F(\mu, \lambda) \cdot I_1(\mu) d\mu / I_1(\lambda) \quad (4)$$

$$F_2(\lambda) = \int F(\mu, \lambda) \cdot I_2(\mu) d\mu / I_2(\lambda) \quad (5)$$

$$F_i(\lambda) = \int F(\mu, \lambda) \cdot I_i(\mu) d\mu / I_i(\lambda) \quad (6)$$

The current work introduces a composite fluorescent SRF $F_c(\lambda)$ as a linear combination of $F_1(\lambda)$ and $F_2(\lambda)$ with weighting factors W_λ and $1-W_\lambda$. (Eq. 7):

$$F_c(\lambda) = W_\lambda \cdot F_1(\lambda) + (1-W_\lambda) \cdot F_2(\lambda) \quad (7)$$

Here, the weighting factor W_λ specific to each fluorescence wavelength λ is so determined that $F_c(\lambda)$ calculated using Eq. 7 agrees with $F_i(\lambda)$ at wavelength λ .

Since the reflection SRF $R(\lambda)$ doesn't depend on the SPD

of the illumination, the composite total SRF $B_c(\lambda)$ given by linearly combining the total SRFs $B_1(\lambda)$ and $B_2(\lambda)$ of the VFS by the illuminations I_1 and I_2 , respectively, with the same W_λ and $1-W_\lambda$ agrees with $B_i(\lambda)$ under the target illumination I_i . (Eq. 8):

$$B_i(\lambda) = B_c(\lambda) = W_\lambda \cdot B_1(\lambda) + (1-W_\lambda) \cdot B_2(\lambda) \quad (8)$$

The BLRF $F_x(\mu, \lambda)$ of the fluorescent specimen x relatively close to $F(\mu, \lambda)$ of the VFS is expressed by Eq. 9 with a constant K_c depending on the effective concentrations of the FWA in the specimen.

$$F_x(\mu, \lambda) \approx K_c \cdot F(\mu, \lambda) \quad (9)$$

The constant K_c doesn't change W_λ in Eq. 7 when substituting Eq. 9 for Eq. 4, Eq. 5, and Eq. 6. Accordingly, Eq. 7 is valid enough for the fluorescent specimen x regardless of the effective FWA concentration. The composite total SRF $B_{cx}(\lambda)$ given by linearly combining the total SRFs $B_{1x}(\lambda)$ and $B_{2x}(\lambda)$ measured by the real instrument with the same weighting factors W_λ and $1-W_\lambda$ is a good approximation of $B_{ix}(\lambda)$ of the specimen under the target illumination I_i . (Eq. 10):

$$B_{cx}(\lambda) = W_\lambda \cdot B_{1x}(\lambda) + (1-W_\lambda) \cdot B_{2x}(\lambda) \quad (10)$$

Multiple composite total SRFs of the specimen under different target illuminations can be calculated from the single set of $I_1(\lambda)$, $I_2(\lambda)$, $B_{1x}(\lambda)$, and $B_{2x}(\lambda)$ measured by the real instrument by respectively substituting the SPDs $I_i(\mu)$ of the target illuminations in Eq. 6.

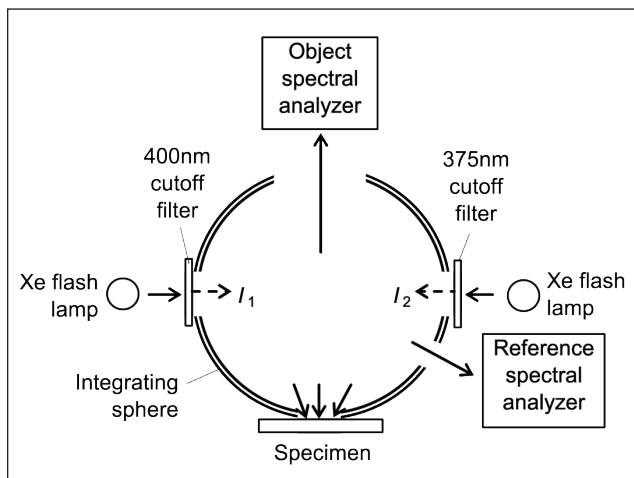
As Eq. 7 indicates, $F_1(\lambda)$ and $F_2(\lambda)$ need to be different at each fluorescence wavelength λ for determining the weighting factor W_λ . This condition is fulfilled when SPDs $I_1(\mu)$ and $I_2(\mu)$ differ in their relative SPDs between the excitation and fluorescence regions of the VFS method.

The virtual instrument integrates hard-to-materialize target illuminations I_i such as Illuminant D65 as the SPD data $I_i(\mu)$ together with the measured SPD data $I_1(\mu)$ and $I_2(\mu)$ and measures the VFS for determining W_λ . Equation 7 enables the weighting factors W_λ to be determined directly for a target fluorescent SRF $F_i(\lambda)$, not for a target illumination. As the special case, Eq. 7 with the target fluorescent SRF $F_i(\lambda) = 0$ gives the weighting factors for the total SRF of the fluorescent specimen with fluorescence virtually eliminated (Eq. 11):

$$W_\lambda \cdot F_1(\lambda) + (1-W_\lambda) \cdot F_2(\lambda) = 0 \quad (11)$$

The composite total SRF $B_{cxf}(\lambda)$ with fluorescence eliminated is calculated by Eq. 10 with the weighting factors W_λ determined by Eq. 11.

The VFS method calculates instantaneously the composite total SRF of the specimen with the weighting factors determined for all of 22 fluorescent wavelengths from 400–610 nm



2. Modified CM-3630 spectrophotometer.

of FWA, for example. This corresponds to as many as 22 measurements at the different filter positions respectively adjusted in the conventional method. In the remainder of this paper, where total SRFs are measured only for specimens, symbolic expressions for total SRFs have subscripts x deleted for simplicity (e.g., $B_c(\lambda)$ instead of $B_{cx}(\lambda)$).

EXPERIMENTAL

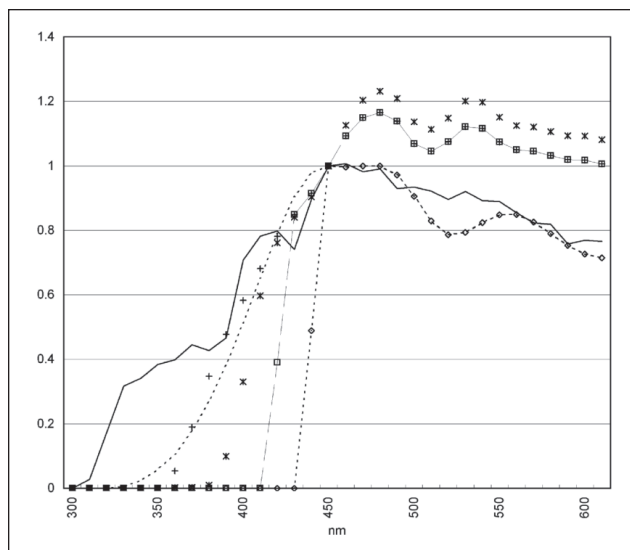
Instrument for VFS method

A Konica Minolta CM-3630 spectrophotometer conforming to ISO 2469 was modified for the VFS method. As **Fig. 2** shows, two illuminators for the illuminations I_1 and I_2 with the 400nm and 375nm cutoff filters, respectively, were integrated in the fluxes from UV-rich xenon flash lamps. With this modification, the SPDs $I_1(\mu)$ and $I_2(\mu)$ of I_1 and I_2 differ in the relative SPDs between the excitation and fluorescence regions of general FWA and can be thoroughly detected by the spectral analyzers in CM-3630 ranged from 360–740 nm.

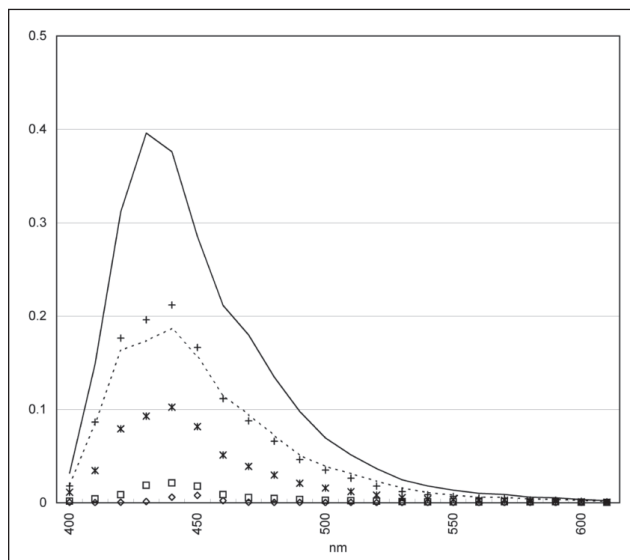
The relative spectral sensitivity was calibrated using a reference incandescent source of the known SPD. Further, the correlations between the spectral outputs from the object and reference spectral analyzers were calibrated for the illuminations I_1 and I_2 respectively, based on the outputs of both spectral analyzers when illuminating the white plate of the known reflectance SRF as specimen by I_1 and I_2 . Those calibrations allowed the SPDs $I_1(\mu)$ and $I_2(\mu)$ to be detected from the outputs of the reference spectral analyzer at each measurement including re-illumination by fluoresced radiation after reiterated reflections in the integrating sphere. By using those SPDs, the errors due to illumination fluctuation and integrating sphere effect [12] are reduced.

Figure 3 shows the measured relative SPDs $I_1(\mu)$ and $I_2(\mu)$ in 300–610 nm range. Also shown are the $I_C(\mu)$ and $I_D(\mu)$ of Illuminants C and D65, respectively, and $I_{42}(\mu)$ and $I_{44}(\mu)$ of the virtual 420 nm and 440 nm cutoff illuminations, respectively. Each SPD is normalized by the intensity at 450 nm near the fluorescence peak of general FWA.

FWA-treated paper under standard illuminants
STFI-Packforsk supplied IR3 fluorescent standard paper (#FB) with the assigned ISO brightness under Illuminant C and CIE



3. Relative SPDs $I_1(\mu)$ (asterisks), $I_2(\mu)$ (crosses), $I_C(\mu)$ (dotted line), $I_D(\mu)$ (solid line), $I_{42}(\mu)$ (squares + broken line), and $I_{44}(\mu)$ (diamonds + dotted line) of real and virtual illuminations.



4. Calculated fluorescent spectral radiance factors $F_1(\lambda)$ (asterisks), $F_2(\lambda)$ (crosses), $F_C(\lambda)$ (dotted line), $F_D(\lambda)$ (solid line), $F_{42}(\lambda)$ (squares), and $F_{44}(\lambda)$ (diamonds) of VFS by I_1 , I_2 , C, D65, I_{42} , and I_{44} , respectively.

whiteness under Illuminant D65 and served as the specimen for evaluating the validity of the VFS method. The BLRF $F(\mu, \lambda)$ data assigned by NRC to the same-type but not identical paper was also supplied by STFI. Prior to measurements by the VFS method, the photometric calibration was performed with the IR3 non-fluorescent standard supplied by STFI with the assigned reflectance SRF, which allowed for comparisons between values determined by the VFS method and those assigned without the influence of the photometric scale difference.

Figure 4 illustrates the fluorescent SRFs $F_1(\lambda)$, $F_2(\lambda)$, $F_C(\lambda)$, and $F_D(\lambda)$ of the VFS calculated using the relative SPDs of I_1 and I_2 at the measurement and Illuminants C and D65,

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respectively, and the BLRF of the VFS. In Fig. 4, $F_c(\lambda)$ is between $F_1(\lambda)$ and $F_2(\lambda)$, while $F_D(\lambda)$ is beyond $F_2(\lambda)$ in the fluorescence region (400–610nm). It indicates that I_2 excites more than C but less than D65 and accordingly the weighting factor $1-W_\lambda$ for I_2 is between 0 and 1 for C while it is larger than 1 for D65 (W_λ for I_1 is necessarily negative).

FWA-treated paper with fluorescence eliminated

Four different FWA-treated papers, aged fluorescent standard paper (#FB'), copy paper (#CP), thick printing paper (#TP), and glossy photographic papers (#PH) were measured by the VFS method. The method was used to calculate the composite total SRFs $B_{cc}(\lambda)$ with fluorescence eliminated as well as $B_{cc}(\lambda)$ and $B_{cd}(\lambda)$ by Illuminants C and D65. The composite total SRF $B_{c42}(\lambda)$ and $B_{c44}(\lambda)$ with fluorescence suppressed by the virtual 420-nm and 440-nm cutoff illuminations I_{42} and I_{44} , respectively, were also calculated using the SPDs $I_{42}(\mu)$ and $I_{44}(\mu)$ as the target illumination.

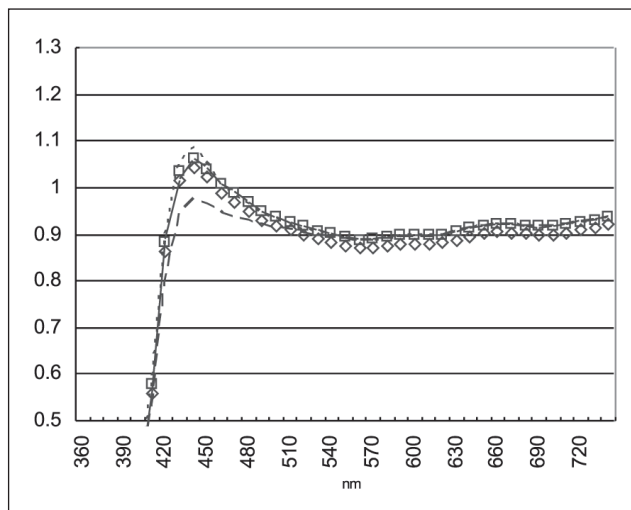
The BLRF $F(\mu, \lambda)$ data of the same-type paper as #FB was again used as the VFS for all four papers. Here, the SPD $I_{42}(\mu)$ was given as the product of the $I_2(\mu)$ and the spectral transmittance $T_{42}(\mu)$ (0.5 at 420 nm, 0 at 410 nm, and 1 at 430 nm) of the virtual 420-nm cutoff filter, while the SPD data $I_{44}(\mu)$ was given as the product of the SPD $I_C(\mu)$ of Illuminant C and the spectral transmittance $T_{44}(\mu)$ (0.5 at 440 nm, 0 at 430 nm, and 1 at 450 nm) of the virtual 440-nm cutoff filter. Total SRFs $B_{42}(\lambda)$ of each paper was conventionally measured by the real 420-nm cutoff illumination. For each paper, we compared the total SRFs $B_{42}(\lambda)$ and $B_{c42}(\lambda)$ by the real and virtual 420-nm cutoff illuminations having SPDs close to each other.

RESULTS AND DISCUSSION

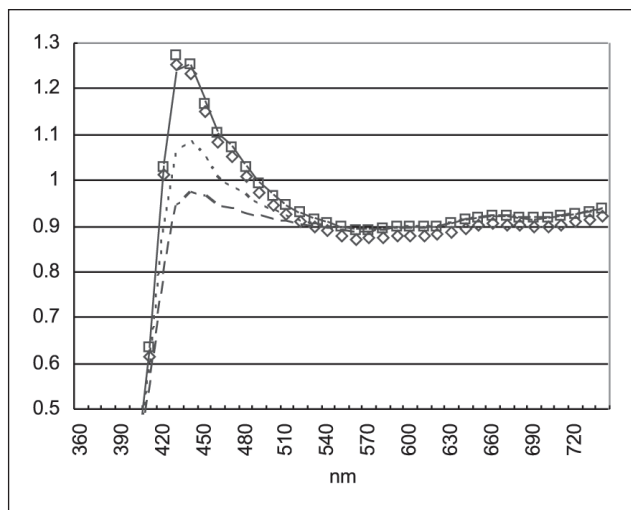
FWA-treated paper under standard illuminants

Figure 5 shows the composite total SRF $B_{cc}(\lambda)$ of #FB under Illuminant C obtained by the VFS method and $B_{cc}(\lambda)$ compensated from $B_{cc}(\lambda)$ together with the reference $B_{ac}(\lambda)$ assigned by NRC to the same-type paper as #FB. Figure 5 also shows $B_1(\lambda)$ and $B_2(\lambda)$ actually measured by the illumination I_1 and I_2 . An 0.018 constant discrepancy exists between $B_{cc}(\lambda)$ and $B_{ac}(\lambda)$ over the whole wavelength range. Since the same discrepancy exists in the range longer than 610 nm where no fluorescence exists, it seems to be caused by the geometric difference between the modified CM-3630 (d:0) and the bispectro-fluorimeter (45a:0) in NRC. Therefore, $B_{cc}(\lambda)$ is compensated to $B_{cc}(\lambda)$ by the averaged discrepancy 0.0182 (i.e., $B_{cc}(\lambda) = B_{cc}(\lambda) + 0.0182$). **Figure 6** shows the composite total SRFs $B_{cd}(\lambda)$ and $B_{cd}(\lambda)$ under D65, the reference $B_{ad}(\lambda)$, and $B_1(\lambda)$ and $B_2(\lambda)$ measured. The compensated total SRFs $B_{cc}(\lambda)$ and $B_{cd}(\lambda)$ agree well with the respective references $B_{ac}(\lambda)$ and $B_{ad}(\lambda)$ in the whole range.

The composite total SRFs $B_{cc}(\lambda)$ and $B_{cd}(\lambda)$ of #FB under Illuminants C and D65, respectively, were measured 10 times by the VFS method and 10 values of ISO brightness and CIE whiteness were respectively derived from them. ISO brightness



5. Composite total SRF $B_{cc}(\lambda)$ (diamonds) of #FB under Illuminant C, compensated $B_{cc}(\lambda)$ (squares), and assigned $B_{ac}(\lambda)$ (solid line) as well as measured $B_1(\lambda)$ (broken line) and $B_2(\lambda)$ (dotted line).



6. Composite total SRF $B_{cd}(\lambda)$ (diamonds) of #FB under Illuminant D65, compensated $B'_{cd}(\lambda)$ (squares), and assigned $B_{ad}(\lambda)$ (solid line) as well as measured $B_1(\lambda)$ (broken line) and $B_2(\lambda)$ (dotted line).

and CIE whiteness of #FB were also measured nine times by the conventional method using the same CM-3630, where the UV content in the illumination was adjusted prior to the measurements using the same #FB with the assigned ISO brightness and CIE whiteness, respectively, as the fluorescent standard.

Table I shows the averages and standard deviations of the ISO brightness and CIE whiteness values obtained by the VFS and conventional methods together with the values and uncertainties assigned by STFI.

For Illuminant C, the average 97.9 ISO brightness by the VFS method agrees well with both the average by the conventional method and the assigned value. The value by the conventional method necessarily agrees with the assigned value as the UV adjustment in the conventional method was performed to ensure agreement. The standard deviations of the VFS and conventional methods are 0.019 and 0.021, respectively, and are small

	ISO brightness		CIE whiteness	
	AVRG	STDV	AVRG	STDV
VFS method (A)	97.9	0.019	148.0	0.053
Conventional method	97.9	0.021	146.4	0.089
Assigned value (B)	97.9		146.3	
A-B	0.043		1.71	
Uncertainty (95%)		±1.4		±3.9

I. Averages (AVRG) and standard deviations (STDV) of ISO brightness and CIE whiteness of #FB by VFS method and conventional method.

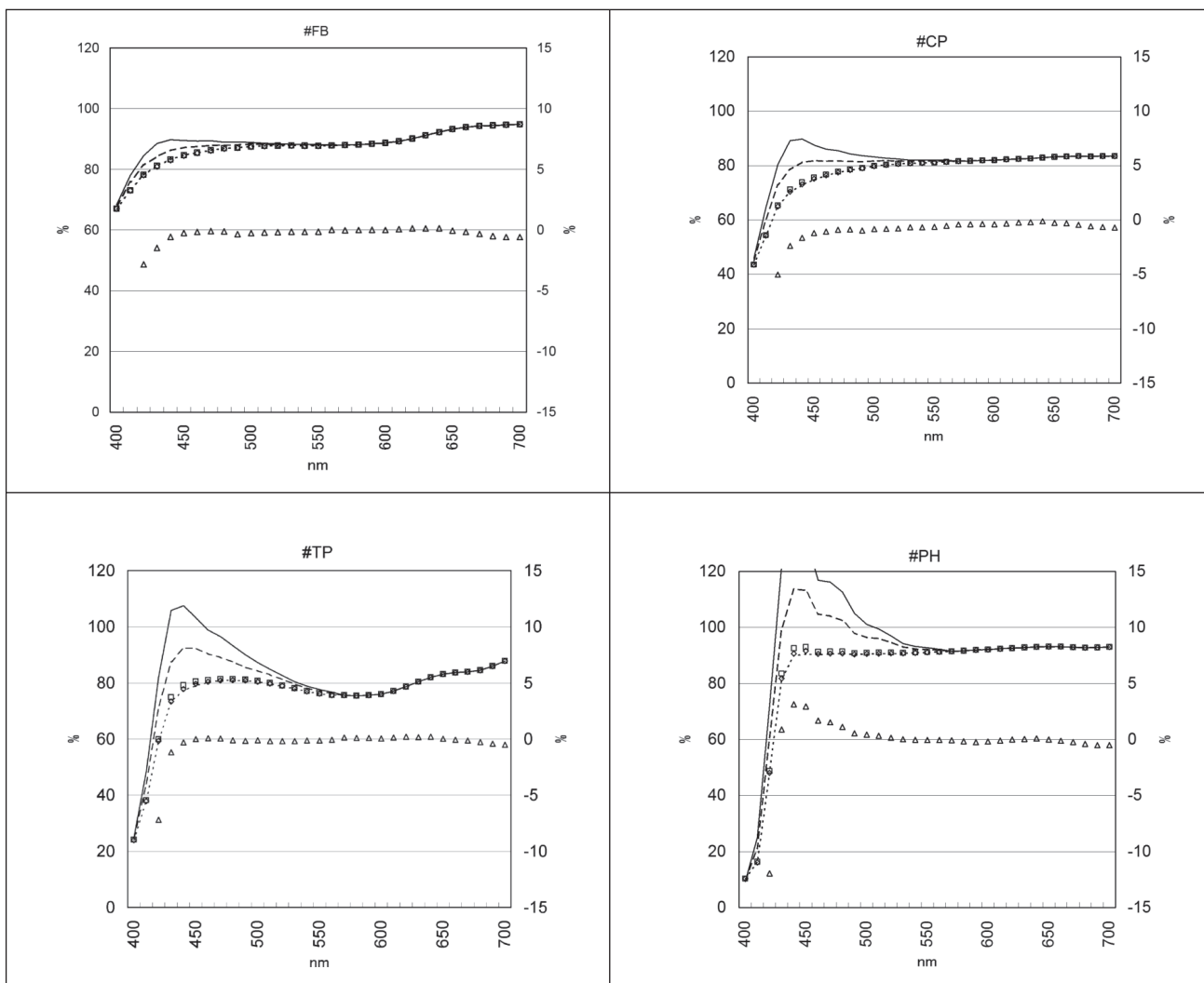
enough when compared with the assigned uncertainty ± 1.4 . The good agreement and low standard deviations are due to the low contribution of fluorescence in Illuminant C.

For Illuminant D65, the average 148.0 CIE whiteness by the VFS method is slightly higher than the assigned 146.3 and the

average 146.4 by the conventional method. The difference, 1.7, is little less than a half of the assigned uncertainty ± 3.9 . The standard deviation 0.053 by the VFS method is better than 0.089 by the conventional method, probably because the SPD of the illumination at each measurement is detected in the VFS method. The bigger differences between the VFS and conventional methods in the average and standard deviation of CIE whiteness than those of ISO brightness are primarily due to the higher contribution of fluorescence in Illuminant D65 than that in Illuminant C.

FWA-treated paper with fluorescence eliminated

Figure 7 shows the composite total SRFs $B_{c42}(\lambda)$, $B_{c44}(\lambda)$, $B_{ce}(\lambda)$, $B_{cc}(\lambda)$, and $B_{cd}(\lambda)$ of #FB', #CP, #TP, and #PH and the differences of $B_{c42}(\lambda)$ from $B_{42}(\lambda)$ measured by the real 420-nm cutoff illumination. As shown, the composite total SRFs $B_{c42}(\lambda)$, $B_{c44}(\lambda)$, and $B_{ce}(\lambda)$ have no data loss in the 400–700



7. Composite total SRFs $B_{c42}(\lambda)$ (squares), $B_{c44}(\lambda)$ (diamonds), $B_{ce}(\lambda)$ (dotted lines), $B_{cc}(\lambda)$ (broken lines), and $B_{cd}(\lambda)$ (solid lines), scaled on the left axis, and the difference (triangles) of $B_{c42}(\lambda)$ from conventional $B_{42}(\lambda)$, scaled on the right axis, of #FB', #CP, #TP, and #PH.

Brightness	B_{c42}	B_{c44}	B_{cE}	B_{cD}	B_{cC}	B_{42}	B'_{42}
#FB'	84.7	84.5	84.5	88.9	86.8	83.9	85.2
#CP	75.5	75.1	75.0	86.0	80.7	75.9	77.1
#TP	78.8	78.1	77.8	98.1	88.4	78.6	79.7
#PH	88.3	87.3	86.9	117.9	103.1	86.7	87.7

II. ISO brightness values of each paper derived from $B_{c42}(\lambda)$, $B_{c44}(\lambda)$, $B_{cE}(\lambda)$, $B_{cD}(\lambda)$, $B_{cC}(\lambda)$, $B_{42}(\lambda)$, and $B'_{42}(\lambda)$.

Whiteness	B_{c42}	B_{c44}	B_{cE}	B_{cD}	B_{cC}	B_{42}	B'_{42}
#FB'	74.0	73.5	73.3	88.1	80.9	67.2	76.8
#CP	56.2	54.8	54.2	93.4	74.8	53.6	62.8
#TP	74.6	72.0	71.1	136.0	105.9	72.4	81.0
#PH	71.5	68.2	66.8	151.4	113.1	67.0	74.1

III. CIE whiteness values of each paper derived from $B_{c42}(\lambda)$, $B_{c44}(\lambda)$, $B_{cE}(\lambda)$, $B_{cD}(\lambda)$, $B_{cC}(\lambda)$, $B_{42}(\lambda)$, and $B'_{42}(\lambda)$.

nm range. The differences of $B_{c42}(\lambda)$ from $B_{42}(\lambda)$ in #FB', #CP, and #TP are fairly small above 420 nm. Those papers don't differ much from the VFS in their BLRFs in the range above 370 nm. Rather large differences at 420 nm are most likely due to the difference in the cutoff characteristics between the virtual and real 420-nm cutoff illuminations, which likely results in the considerable difference in the SPD and accordingly in the total SRFs around 420 nm.

Highly fluorescent papers such as #EN and #PH emphasize this error. The highly fluorescent and glossy #PH shows as much as 3% differences at 440 nm and 450 nm, probably because #PH differs from the VFS in the BLRF even above 370 nm due to the absorption of the coated material. Due to the FWA absorption in the excitation region, all composite total SRFs of those papers with fluorescence eliminated or suppressed will be lower in the range below 430 nm than those expected from the same paper but containing no FWA. The absorption is stronger in highly fluorescent paper such as #TP or #PH, as shown in Fig. 7.

Table II and **Table III**, respectively, show the ISO brightness and CIE whiteness values of each paper derived from the total SRFs $B_{c42}(\lambda)$, $B_{c44}(\lambda)$, $B_{cE}(\lambda)$, $B_{cD}(\lambda)$, $B_{cC}(\lambda)$, and $B_{42}(\lambda)$ and $B_{42}(\lambda)$ modified from $B_{42}(\lambda)$ to have $B_{42}(420)$ repeated at 400 nm and 410 nm following ISO 2469. All values from $B_{c42}(\lambda)$ are expected to be between those from $B_{42}(\lambda)$ and $B_{42}(\lambda)$ except ISO brightness of #CP and #PH. ISO brightness from $B_{c42}(\lambda)$ is lower than that from $B_{42}(\lambda)$ in #CP and higher than that from $B_{42}(\lambda)$ in #PH as expected from the corresponding total SRFs in the fluorescence region, on which ISO brightness strongly depends, shown in Fig 7.

CONCLUSION

Validity of the new method

The agreements between the ISO brightness and CIE whiteness values of the fluorescent standard paper (#FB) by the new and conventional methods as well as the agreement between the total SRFs of #FB by the new method and those as-

signed to the same-type paper prove the validity of the method. The closeness of those values of the four different papers (#FB', #CP, #TP, #PH) by the virtual and real 420 nm cutoff illuminations supports this conclusion. Since both methods stand on the same hypothesis, that the specimen is close to the real or virtual fluorescent standard in the relative BLRF, they are equivalent to each other in principle except the measurement by the 420-nm cutoff illumination.

Traceability in measuring fluorescent paper

The reflection SRF of the non-fluorescent standard for the photometric calibration, the SPD of the standard source for the relative spectral sensitivity calibration of the spectral analyzer, and the BLRF of the VFS establish the traceability of the new method.

The new method will be compatible with the conventional method when the photometric calibration is based on the IR3 non-fluorescent standard, and the SPD of the standard source and the BLRF of the VFS are traceable to the bi-spectrofluorimeter of NRC.

Advantages and disadvantages of the new method

The method requires neither fluorescent standard nor UV adjustment prior to measurements. Thus, the FWA-treated paper like non-fluorescent paper can be measured just by performing photometric calibration in advance as long as the spectral analyzer maintains the relative spectral sensitivity. Recalibration is needed far less frequently than the conventional method which requires UV adjustments.

The method can be used to calculate the total SRFs by different standard illuminants and to derive most of colorimetric values for evaluating FWA-treated paper. The calculations take negligible time owing to computation power. The calculated values with fluorescence eliminated differ from those of same-type paper but they contain no FWA; their applicability remains to be studied.

The instabilities of the light source and the real fluorescent standard in the conventional method are replaced by the much lower instability of the spectral analyzer detecting the SPDs of the illuminations, which will improve the measurement repeatability.

The BLRF data of the VFS is free from deterioration and can be supplied directly from the origin of traceability without any intermediate standard or measurement. Accordingly, the method is free from uncertainty caused by the intermediates.

The error caused by having different relative BLRF from the VFS can be reduced by storing multiple BLRF data and selecting one for the paper to be measured from them. The method's primary disadvantage is that it cannot be applied with existing instruments for the conventional method with the single illumination of the unknown SPD. **TJ**

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INSIGHTS FROM THE AUTHOR

In colorimetric measurement of paper, UV adjustment is an obstacle between fluorescent and non-fluorescent paper and results in relatively low accuracy for the measurement of fluorescent paper. The method I proposed computationally performs UV adjustment using two illuminations and is easier to use. The method introduces the bi-spectral luminescent radiance factor data of the standard paper as the virtual fluorescent standard.



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The key challenge in the research was establishment of the algorithm. It was interesting to discover that fluorescence is a phenomenon that follows theory well. This work describes the method that could improve the quality of paper and production efficiency. For future study, the method will be applied to printed colors on FWA-treated paper.

Imura is on the advisory staff, Research and Development, Konica Minolta Sensing, Inc. in Osaka, Japan. Email Imura at kenji.imura@konicaminolta.jp.

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