Evaluation of Bispectral Spectrophotometry for Accurate Colorimetry of Printing Materials

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Abstract

During recent years the need for accurate color measurements has been increasing to achieve proper color management in a number of industries. One of the most wide spread techniques to measure color is based on spectrophotometric measurements.

However, when dealing with hardcopy materials (paper and inks) that contain fluorescent components, the color measurements become questionable. Conventional spectrophotometers measure total radiance factors of fluorescent materials for the light source within the instrument. Such measurements cannot be used to obtain accurate colorimetry for other illuminants or sources. On the other hand using bispectral methods, which measure reflected and fluorescent spectral radiance factors as a function of incident wavelength, produces illuminant independent data and thus more accurate colorimetric calculations.

The main goal of the present work is to determine colorimetric errors created by conventional spectrophotometry compared to bispectral measurements for a collection of printed materials. Another point is to evaluate the significance of these errors in color reproduction applications.

Introduction

As imaging technology advances the need for accurate tools grows. Colorimetry has become an important tool to achieve accuracy on imaging reproduction and color management procedures. Nonetheless, on the workflow of image reproduction many hardcopy materials are involved.
Today most high-end hardcopies will display fluorescent properties. Measured on conventional color measurement instruments (spectrophotometers) these types of materials will produce incorrect color values.

One of the main contributions to these phenomena in the hardcopies is the optical brightneners in the paper to magnify the whiteness as well as some of the natural pigments within the inks employed in different printing technologies, which exhibit fluorescence. Most of these fluorescent components come in very small amounts that are not detectable to the eye but they can be significant enough to affect colorimetric values.

Luminescence is defined as the conversion absorbed energy into emission of light. The energy conversion of interest here usually occurs in the visible or near-visible range and under light excitation.

The total spectral radiance factor of a luminescent (fluorescent) sample is made up of two components the reflected and the luminescent, expressed in *equation 1*. For a sample with no luminescent component the reflected component will be equal to the total spectral radiance. In *figure 1* the spectral radiance of a fluorescent orange golf ball is given as an example to illustrate how the spectral radiance factor of a sample is made up.

Equation 1 Total radiance factor equation

$$\boxed{\beta_T(\lambda) = \beta_S(\lambda) + \beta_F(\lambda)}$$

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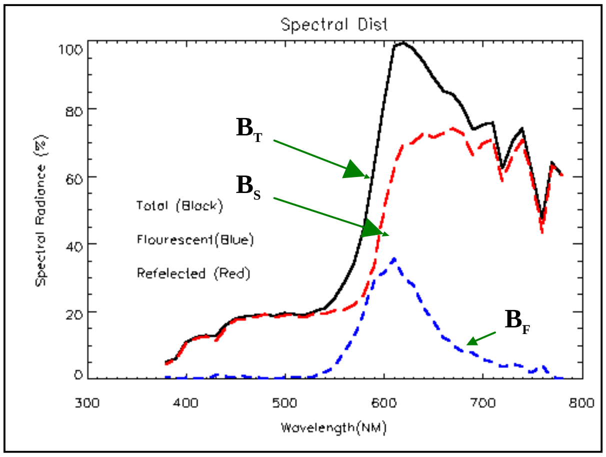
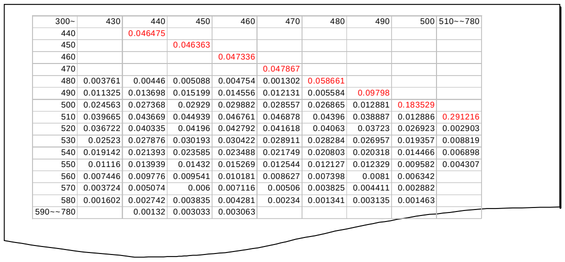
Figure 1 Fluorescent Orange Golf Ball



Conventional spectrophotometers, using polychromatic illumination; only measure the total radiance factor of fluorescent materials for the light source in the particular instrument employed. Frequently, hardcopy materials are specified under CIE illuminant D50. Since there are no instruments with good approximations of D50 as the light source, colorimetry of fluorescent samples on conventional instruments can be considered erroneous.

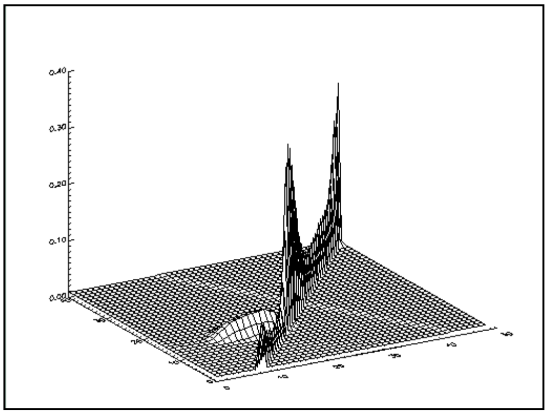
Bispectral spectrophotometric instruments can make colorimetric measurements taking into account the contribution of both the fluorescent and the reflected component to the total radiance of a sample. This way the measurement becomes light-source independent and the full bispectral radiance factor can be obtained in a matrix form as a function of the excited wavelengths. The main difference of the bispectral method from the conventional method is the incorporation of two monochromators into the instrument. For the bispectral method one monochromator is located between the instrument light source and the sample to be measured. The function of this monochromator is to separate the radiation from the instrument's light source into its spectral components before it reaches the sample. The second monochromator is located between the sample and the photodetector, which separates the radiation leaving the sample surface into its spectral components. This way the instrument produces a matrix of all the wavelength contributions of light excitation and emission. The columns in *figure 2* correspond to the excitation while the rows correspond to the emission wavelengths, the values within the diagonal correspond to the reflected component while the values off-diagonal correspond to the fluorescent contribution. *Figure 3* shows the graphical representation of the matrix form. The xy plane corresponds to the excitation and emission wavelengths while the z-axis radiance factor.

Figure 2 Part of Matrix of a bispectral measurement from a green fluorescent sample



300~	430	440	450	460	470	480	490	500	510~~780
440		0.046475							
450			0.046363						
460				0.047336					
470					0.047867				
480	0.003761	0.00446	0.005088	0.004754	0.001302	0.058661			
490	0.011325	0.013698	0.015199	0.014556	0.012131	0.005584	0.09798		
500	0.024563	0.027368	0.02929	0.029882	0.028557	0.026865	0.012881	0.183529	
510	0.039665	0.043669	0.044939	0.046761	0.046878	0.04396	0.038887	0.012886	0.291216
520	0.036722	0.040335	0.04196	0.042792	0.041618	0.04063	0.03723	0.026923	0.002903
530	0.02523	0.027876	0.030193	0.030422	0.028911	0.028284	0.026957	0.019357	0.008819
540	0.019142	0.021393	0.023585	0.023488	0.021749	0.020803	0.020318	0.014466	0.006898
550	0.01116	0.013939	0.01432	0.015269	0.012544	0.012127	0.012329	0.009582	0.004307
560	0.007446	0.009776	0.009541	0.010181	0.008627	0.007398	0.0081	0.006342	
570	0.003724	0.005074	0.006	0.007116	0.00506	0.003825	0.004411	0.002882	
580	0.001602	0.002742	0.003835	0.004281	0.00234	0.001341	0.003135	0.001463	
590~~780		0.00132	0.003033	0.003063					

Figure 3. 3D representation of a bispectralmeasurement from a green fluorescent sample.



Experimentation

The design and sampling of the experiment was constructed to take into account different printing processes under normal reproduction conditions of colors. Throughout the experiment a bispectral-spectrophotometer (BFC-450) manufactured by Labsphere was used to measure the samples. Around 10-12 minutes were taken for each measurement to be completed, since each sample was measured at every excitation wavelength throughout all the emission wavelengths.

The analysis is based on seven prints (paper with color patches of 100% CMYK and 50 % CMYK), one print (paper with patches of 100% CMYK and 40 % CMYK),and one print (paper with patches of 100% CMYK). In total they were76 measurements. They were measured with the intention to analyze the effect of fluorescent component in the color determination.

Among the different printing process used to generate the samples were: two color proofers (3M & Epson), two thermal printers (Kodak XLT 7720 & Fujix Pictography), RIT Lithographic press, and a combinatiof inkjet printers with different quality papers.

Results

The principal objective was quantifying the colorimetric error using typical vs. bispectral techniques. The approach of emulating total radiance method from bispectral measurements was used, since this allows several advantages. First the reduction of noise in colorimetric values due to the use of different instruments. Second the flexibility to choose any instrument as light source for the total radiance emulation. Third avoiding problem of calibration of different instruments and evading quantification of the light source error as well as variations on instrument's light source. This also aids interpretation of the results since only one apparatus was used to make the measurements.

The simulation for total radiance is shown in *eq2*. It consists of the bispectral radiance factor ($\beta_T(\mu,\omega)$ matrix form) which is expressed in function of the excitation (μ) and the emission (ω) wavelengths. Then the $\beta_T(\mu,\omega)$ is multiplied by the specified light source ($\Phi^I_\lambda(\mu,\omega)$) for colorimetric calculations and by the instrument light source ($\Phi^{Ins}_\lambda(\mu,\omega)$) this is the light form which ever instrument was chosen to be simulated. Then the resultant matrix is summed over the excitation wavelength to obtain an array which only is emission dependent. It is divided by the instrument light source ($\Phi^{Ins}_\lambda(\omega)$). This last operation is the point where conventional instruments try to make the measurement light source independent.

Eq. 2 Total Radiance Emulation.

$$\boxed{\tau(\omega)=\frac{\sum\limits_{\mu}\Phi^{I}_{\lambda}(\mu,\omega)\Phi^{Iins}_{\lambda}(\mu,\omega)\beta_{T}(\mu,\omega)}{\Phi^{Iins}_{\lambda}(\omega)}}$$

Once obtaining $\tau(\omega)$, which can be called stimulus function, the XYZ can be obtained with traditional colorimetric approach as shown in *eq 3*. In the present work, the CIE 1931 standard colorimetric observer (2°) color matching functions were employed.

Eq. 3. XYZ calculations

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}=\begin{bmatrix} \mathrm{k}\sum_{\omega}\tau(\omega)\ \bar{x}(\omega) \\ \mathrm{k}\sum_{\omega}\tau(\omega)\ \bar{y}(\omega) \\ \mathrm{k}\sum_{\omega}\tau(\omega)\ \bar{z}(\omega) \end{bmatrix} \qquad \mathrm{k}=\frac{100}{\sum\limits_{\omega}\Phi_{\lambda}(\omega)\bar{y}(\omega)}$$

From XYZ using the CIELAB equations, the L*, a*, b* values were derived. The same approach can be used to obtain colorimetric values by the bispectral method but there is no need to introduce the instrument light source ($\Phi^{Ins}_\lambda(\mu,\omega)$) since the measurements are already light source independent. Then the equation to obtain $\tau(\omega)$ stimulus function would look as *equation 4*, and in the same fashion the XYZ and CIELAB can be obtained.

Eq. 4 Stimulus function from Bi-sprectral measurements

$$\boxed{\tau(\omega)=\sum_{\mu}\Phi^{I}_{\lambda}(\mu,\omega)\beta_{T}(\mu,\omega)}$$

Two different light source power distributions were employed to simulate conventional spectrophotometers. The light sources were a xenon arc lamp (commonly found in many instruments) and a tungsten filtered lamp (simulating daylight D50 from a light booth). The color values obtained by the simulations were compared with the bispectral method twice (with different specified light source). The first time using CIE tables for D50 and the second comparison was using D50 spectral power distribution from daylight simulator. These SPDs were employed for specific light source colorimetric calculations. The metric to evaluate the comparison was the color difference in terms of ΔE_{94} .

Figure 4. ΔE94 Bispectral VS Total Radiance using Xenon lamp (CIE D50)

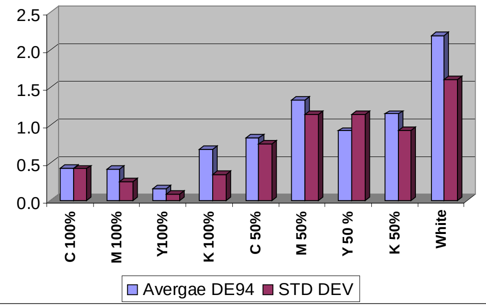


Figure 5. ΔE94 Bispectral VS Total Radiance using Daylight source (tungsten filtered lamp) CIE D50 Tables

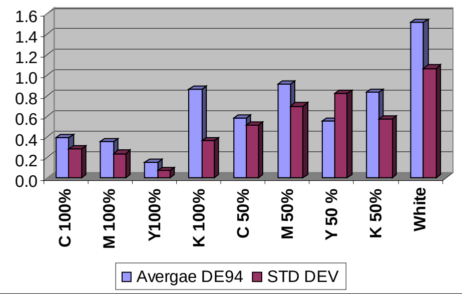


Figure 6. ∆ *E94 Bispectral VS Total Radiance using Xenon lamp & (Mabecth D50)*

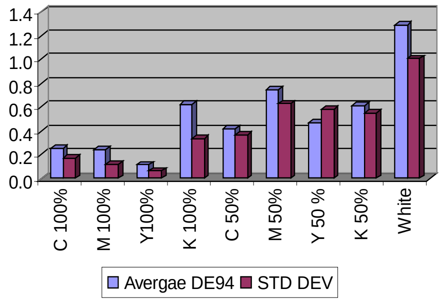
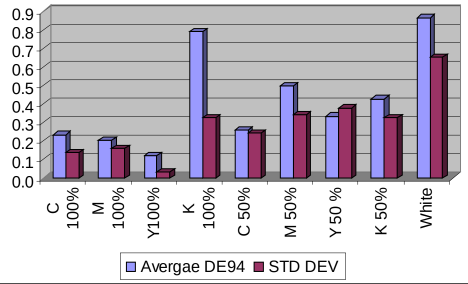


Figure 7. ∆*E94 Bispectral VS Total Radiance using Daylight source made with fltered tungsten lamp (Mabecth D50)*



Figures 4 trough *7* show the average ΔE_{94} of all the printed samples were classified by percentage of area coverage and color patch. Overall the samples with the largest color differences are the papers themselves. This is because most modern high quality manufactured paper contain optical brighteners to enhance the whiteness. On a second level, in terms of color differences, the 50% solids were positioned, which again most of the color difference can be blamed to miscalculation of the fluorescent components coming from the paper. Although in general, the color differences values seem small and not necessarily means that will not affect drastically color reproduction. These overall low values can be associated to the mixture of different ink types and printing process, the non- fluorescent ink samples diminished the overall average from the ones containing fluorescence. The black patches show high color errors mainly because since these measurement took place at low reflectance any fluorescent component will create big difference in the colorimetric values

There is also a significant difference whether to use spectral power distribution (SPD) of CIE D50 tables or daylight simulator SPD to make colorimetric calculations. Altogether the CIE tables created a higher color differences than the daylight simulator source. This difference can also be appreciated in *table 1* where, a summary of the different methods employed to analyzed the samples are express in terms of ΔE_{94}. Also in the last column is shown the color difference from two bispectral methods one using CIE D50 tables and the other using daylight simulator SPD. Note the significant large maximum ΔE_{94} values

In general, with CIE D50 light source about 29% percent of the samples analyzed have a ΔE_{94} above 1.0. In practical terms this color difference would be noticeable if existed. However in this case there is no difference to notice, it is simply a measurement error that would be propagated through the color management chain.

Table 1 ΔE_{94} *Summary of analyzed samples*

Specified source	**CIE D50**		**Daylight from Light booth**		**CIE VS. Light booth**
Instrument. Source	**Tungsten filtered**	**Xenon Lamp**	**Tungsten filtered**	**Xenon Lamp**	
Average ΔE_{94}	0.65	0.90	0.41	0.53	1.10
Max ΔE_{94}	2.98	4.52	1.75	2.85	3.59
Min ΔE_{94}	0.00	0.05	0.00	0.04	0.05
Samples above >1 ΔE_{94}	16	23	9	9	34
Samples above >2 ΔE_{94}	6	9	0	5	10
Std Dev	0.67	1.03	0.41	0.60	0.68

Most likely the averages hide the different substrates contribution, as well as the different types of inks contribution from the different printing processes. Since the samples cover a variety of printing technologies, the averages attenuate the color difference errors. In *table 2* there are some selected samples of different printing technologies. These selected samples exhibit considerable amount of fluorescence (for not being considered fluorescent at normal viewing conditions) and do not necessarily correspond to the maxima found. Choosing CIE D50 as specified and xenon arc lamp as instrument light source was just an arbitrary decision to show some examples.

Table 2. Individual color difference of selected samples using CIE D50 as specified illuminant for colorimetric calculations

	Bispectral Method			**Total Radiance Method using Xenon Arc lamp**			
Samples	**L***	**a***	**b***	**L***	**a***	**b***	**ΔE_{94}**
Fluorescent							
Orange Golf ball	71.4	49.6	32.2	73.3	52.5	35.4	**2.25**
Green Plastic	61.7	-69.4	42.8	62.7	-70.9	44.2	**1.09**
Printed materials							
Xeror White paper for inkjet	93.1	1.4	-6.0	92.9	.29	-1.8	**3.42**
50% Magenta Kodak XLT Thermal printer	64.2	37.0	-1.3	61.1	36.7	0.6	**1.24**
Lithography white paper	91.0	0.4	-.06	91.0	.12	0.9	**1.68**
50% Yellow in Riverside HP870	90.6	-1.6	25.4	90.6	-1.9	28.	**1.08**
50% Cyan Hp paper in HP870	67.0	-18.9	-31.	66.8	-20.3	-27.	**2.24**
100% Cyan HP paper in HP870	53.8	-28.7	-40.	53.6	-30.0	-38.	**1.23**

Conclusions

In the present work most of the color errors in the set of samples occur in the lower percentage of dot coverage mainly due to the paper contribution to fluorescence. These contributions already discussed can be attributed to the manufacturing process of the substrate. The findings may not applied in general to any printed material since they are dependent of ink properties, and there are some ink that by nature contains fluorescent components.

Although not shown here, there weren't any significant vectorial trends in the color difference in the CIELAB coordinates. This is an important point to mention because since there were no specific trends it is harder to find corrections, correlation or conversions factors from the conventional spectrophotometry approach to the bispectral method.

For colorimetric calculations using SPD's of CIE D50 tables compare to actual D50 simulators, they create different levels of color differences but at a point the ΔE_{94} deviation can be considered evenly distributed among the two SPD.

One last thing to mention is that a typical error in a good image characterization is on the order of 2.0 units $\Delta E_{94.}$ The current results show that fluorescence measurement errors can be a big contribution (or perhaps the main contribution) to these errors. So in some critical image reproduction will be necessary to take into account the fluorescence contribution to the color error.

There are several future considerations that can be made including: the evaluation of the instrument precision and accuracy on bispectral measurements, the translation of fluorescent color errors into wrongful color management, and last but not least how significant are the paper fluorescent components vs ink.

The goal of this work has been to evaluate the relative effect of fluorescence and its importance when calculating CIELAB colorimetric values. From this it is important to be aware that this effect might have consequences in the final output (any media) in terms of the overall accuracy of color reproduction. It also highlights a more accurate way to measure color to take into account these phenomena. It has been undoubtedly shown how the ΔE_{94} values are significantly affected due to the way in which the fluorescence is measured.

A final result of this research will be the creation of a database of bispectral measurements of printing, and other materials that will be made freely available on the internet for use by other researchers.

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Biography

Sergio Gonzalez received his B.S. degree in Chemical Engineering from the ITESM at Monterrey, Mexico in 1996 and a MS. in Color Science from Rochester Institute of Technology in 2000. Since 2000 he has worked in the Center of Research and development of Grupo CYDSA SA de CV located in Monterrey Mexico. His work has primarily focused on the development of processes and new technologies for the chemistry and packing division including image quality issues.