

Color Management with OBAs – Theory and Practice

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Abstract

Optical brightening agents (OBAs) are widely used in the printing industry to alter the appearance of papers and other printing medias. The bluish fluorescence of OBAs has caused color management problems since the early days. There are various remedies, but OBAs remain an unpredictable nuisance to color management practitioners.

The technology for measuring fluorescent samples has existed for a long time. But the equipment required is too big, too expensive and too slow to be practical for color management work.

In 2009, the ISO standards for color measurement and viewing were updated to more clearly specify the illumination. These changes were intended to solve the OBA problem for D50 illumination, which is the standard in graphic arts and color management. This spurred the development of new measuring instruments that unexpectedly provide the information needed to solve the general problem of color management with OBAs.

This paper explains some techniques we developed to utilize this information. By measuring the relative UV excitation of the viewing environment, it is fairly simple to compute correct colorimetry for any illuminant. This work suggests possible improvements to standard data sets. We also make recommendations for future updates of the ISO standards.

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Introduction

Many printing substrates contain optical brightening agents (OBAs), also known as fluorescent whitening agents (FWAs). These compounds convert UV energy, from the viewing or measurement source, to emitted blue visible light. This fluorescence caused problems for color management practitioners early on. Various remedies, including UV-cut filters, OBA-free medias, and software adjustments were tried. But these Band-Aid measures only reinforced the sense that something was fundamentally wrong.

ISO TC-130, the international standards group for graphic arts, took on the OBA problem. In 2009, the standards for color measurements (ISO 13655:2009) and viewing conditions (ISO 3664:2009) were modified to specify the same amount of UV excitation for the measuring and viewing illumination (equivalent to D50). Four measurement conditions were defined, M0, M1, M2, and M3.

The introduction of these measurement conditions spurred the development of devices able to capture M1 and M2 data in a single session (X-Rite, 2016). We imagine the manufacturer³ was just trying to implement the updated standard. But, serendipitously, they gave us a tool that helped solve the OBA problem.

Measuring Fluorescent Samples

Spectrophotometers used in the graphics arts typically illuminate the samples with white light, and analyze the spectrum of the reflected light. When the samples contain fluorescent compounds (OBAs or inks), the illumination may activate them, and affect the measurements. That limits the use of the measurements to the particular illumination used in that instrument.

In 1953, R. Donaldson wrote a seminal paper describing a spectrophotometer with dual monochromators, one to filter the illumination and one to analyze the reflected light (Donaldson, 1954). This type of instrument produces a table of spectral reflectance curves made from a sequence of illumination wavelengths. These are called bi-spectral measurements, and the table containing them is called a Donaldson matrix.

With bi-spectral measurements, the reflected light from a sample may be computed for any illumination source by multiplying its SPD by the Donaldson matrix. This elegant solution works with any sample (fluorescent or not), and any illumination (assuming the matrix includes activating wavelengths). The spectral product from this multiplication is then used to compute standard colorimetry.

³ *The authors have no connection to X-Rite, Inc. other than owning and using their equipment.*

Bi-spectral technology has been available for many decades, but there are some drawbacks. The equipment is big and expensive. It is also quite slow, and requires a large sized sample. It would be a major task to measure a single profiling chart. Instruments for measuring the viewing illumination over the UV+visible range are also very expensive. So, while bi-spectral measurements solve the OBA problem in theory, they are not practical for color management work.

A typical Donaldson matrix consists of about 50 individual measurements, each for a different wavelength of illumination. That compares to a single measurement when we use D50 illumination. So, the idea of standardizing the illumination for measuring and viewing makes sense, when you realize how cumbersome the bi-spectral alternative is.

There is a middle ground between these two extremes. If you measure each sample twice with well-chosen illuminants, you can estimate the OBA aspects of a Donaldson matrix with reasonable accuracy (Ehbets, 2008), (Tominaga, Hirai, and Horiuchi, 2015). This is possible because fluorescent compounds have some favorable properties, which we will discuss shortly. The illuminants are chosen to separate the fluorescence of the OBAs from the normal reflectance. This technology was first used in 2006, in the X-Rite EyeOne iSis.

Today, in 2016, the X-Rite i1Pro 2 and X-Rite iSis 2 use this two-sample method. There may be similar devices from other manufacturers. These newer instruments will operate in the so-called ‘dual-scan’ mode, which yields a single measurement file containing the M0, M1, and M2 measuring conditions, all in a single session. It is possible, but less convenient, to obtain M1 and M2 data by measuring charts twice with two different instruments, or by changing the mode of a single instrument.

At this point, let’s review exactly what the M1 and M2 measuring conditions are. M1 measurements are made with the equivalent of D50 illumination, including the UV component. M2 measurements are made with the illumination passed through a UV-cut filter to suppress the OBA fluorescence.

$$\text{OBA effect}(\lambda) = (M1(\lambda) - M2(\lambda)) * D50(\lambda)$$

where λ is the wavelength, and D50 is the spectral power distribution (SPD).

It is important to understand that the OBA effect is actually a spectral power distribution, whereas the M1/M2 data is reflectance. The OBA effect is emitted light and is “rolled into” these reflectance measurements. We multiply by the D50 SPD to extract it. This may be difficult to comprehend at first, because we are so used to seeing the OBA effect as a change in reflectance.

Another useful measure is the ‘OBA index’ of the media,

$Z1$ = Z-value of bare media, M1 condition

$Z2$ = Z-value of bare media, M2 condition

$$\text{OBA index} = (Z1 - Z2)/Z(D50) = (Z1 - Z2)/82.49$$

The OBA index describes the intensity of the brightening effect, which primarily affects the Z-value. Typical values are between 0% and 20%.

The OBA effect can be visualized using color management tools. We printed an IT874 chart on media containing OBAs. We measured the chart with an i1Pro 2 instrument and ran the measurements through a software program to compute the M1 - M2 difference. These differences are small, so we multiplied them by a factor of 10 to improve visibility. Figure 1 shows the M1 data, and the M1 - M2 difference (OBA effect).

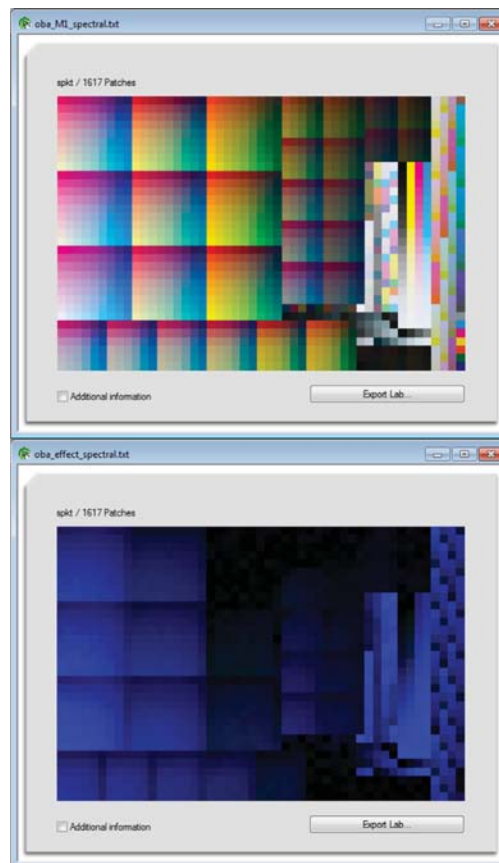


Figure 1- M1 spectral data (top) and OBA effect (x10) (bottom)

The OBA effect has a fairly uniform blue color, which is diminished by the CMYK inks. The yellow and black inks show greater attenuation (darker areas) than the cyan and magenta inks. This can be seen in the CMYK ramps, near the right side of chart. Some of the darker areas have a slightly different hue. The shape of the spectral distribution is similar for all samples.

OBA Properties

Optical brighteners are a group of organic compounds with fluorescent properties. They convert UV light to visible blue light. Typically, the spectral range of the emitted blue light is 400 to 500 nm, with a peak at 430 nm. (Shi, et al, 2012) This added blue light counteracts the normal yellowness of the bleached cellulose and other paper components. These added OBA compounds can increase the CIE whiteness from the mid-90's to well into the 130's. (Blum, Linhart, Frenzel, 2010) In the CIE whiteness index, measures above 100 indicate a bluish brightened white. Values below 100 appear yellowish. (CIE, 2004) Fluorescent compounds have certain properties that help to simplify color management with OBAs.

1. Additivity – The luminescence of a sample, illuminated by a combination of two light sources, is the sum of the luminescence from each individual light source. (Donaldson, 1954)
2. Linearity – The magnitude of the luminescence is proportional to the magnitude of the illumination. This is a corollary to the additivity rule. (Donaldson, 1954)
3. Kasha–Vavilov rule – The quantum yield of luminescence is independent of the wavelength of exciting radiation. (Kasha, 1950)
4. Mirror image rule – For many fluorescent compounds, the absorption spectrum is a mirror image of the emission spectrum. (Lakowicz, 2006)

Our treatment of the OBA effect relies on these rules, which allow us to extract the OBA effect from the normally reflected light, and model it as a onedimensional quantity.

Modeling the OBA Effect

The OBA effect can be measured directly. Because it is a fluorescent emission, it should have the properties we just discussed. The utility of the OBA effect as a concept depends in many ways on these properties. So, let's look at how well our measured data conforms.

The first thing to examine is the chromaticity of the OBA effect. According to the Kasha–Vavilov rule, the spectral content of a fluorescent emission is largely independent of the excitation. Although the intensity of the OBA effect is attenuated by the inks, the chromaticity coordinates should be constant. The following figures show the chromaticity of the data we viewed earlier. Figure 2 shows the x-y coordinates in two dimensions, and a three dimensional view including the Y-value.

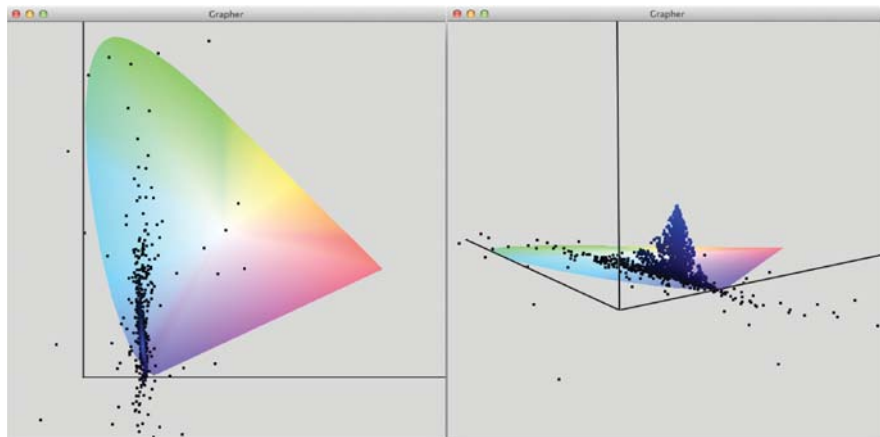


Figure 2 - OBA effect chromaticity (2-D and 3-D)

From this figure, it appears that the chromaticity of the more intense samples is fairly constant. As the intensity diminishes, the y-chromaticity spreads out in both directions. If we plot the yellow-only samples, we see the y-chromaticity increase with the yellow ink. If we plot the magenta-only samples we see the chromaticity decreases with magenta ink.

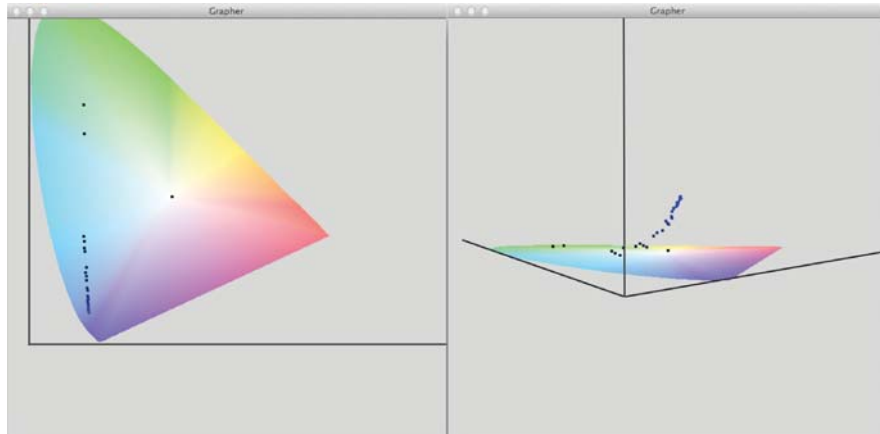


Figure 3 – OBA effect chromaticity – yellow samples (2-D and 3-D)

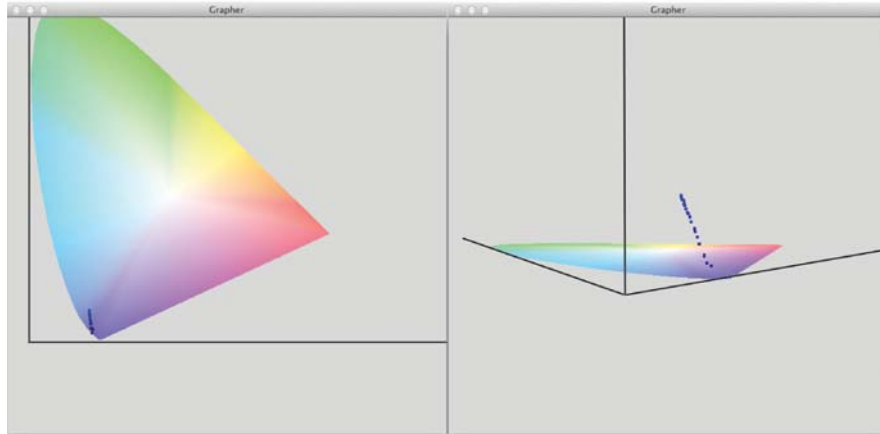


Figure 4 – OBA effect chromaticity - magenta samples (2-D and 3-D)

This suggests that the ink is filtering the emitted light and changing its chromaticity. Since the ink lays on top of the media, the OBA effect light passes through it in a transmissive mode. This idea led to the following diagram, which illustrates the path of light through the ink and media. We are aware this is an over-simplification, but it serves to explain the two-step attenuation of the inks.

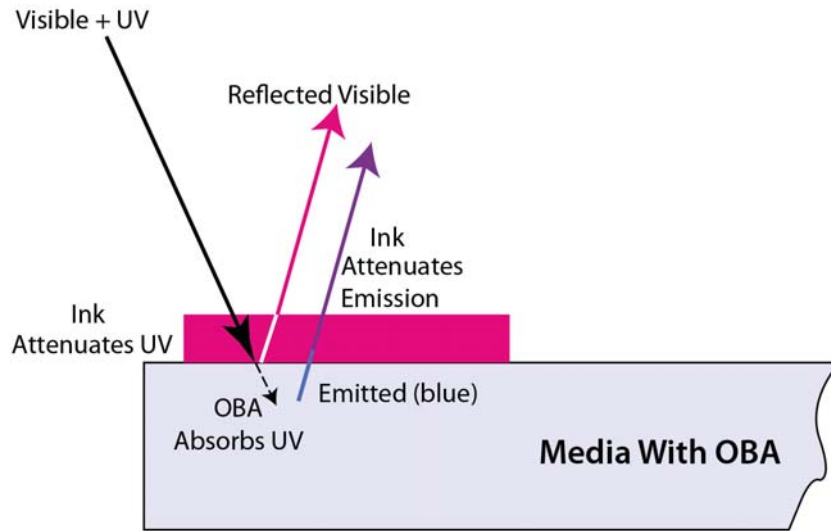


Figure 5 - Light path diagram

We know the spectral reflectance of the samples. The transmittance of the ink is approximately the square root of the reflectance, relative to the unprinted media. We adjusted the OBA effect using this approximated transmittance.

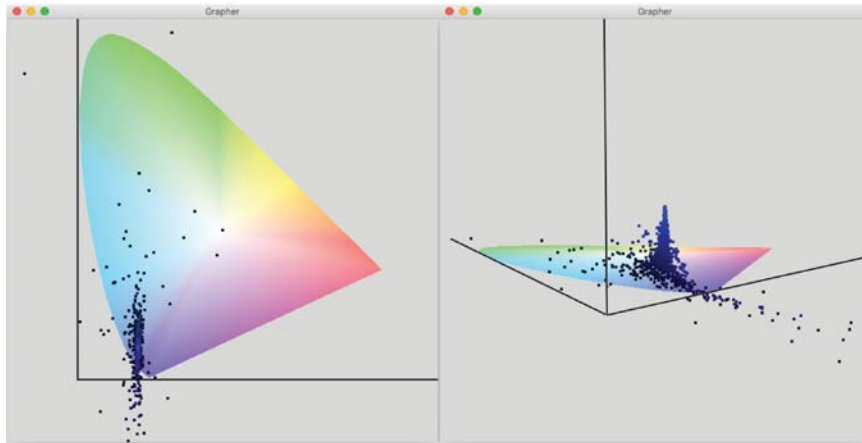


Figure 6 - OBA effect chromaticity – adjusted for inks (2-D and 3-D)

This tightened the distribution of samples quite a bit, which supports the assumptions made. The outlying samples are very small values. After adjusting for the visible attenuation of the inks, we have samples with fairly uniform chromaticity that vary in intensity. We theorize the intensity variation is due to the UV attenuation of the inks. We have no means to measure that directly. But we can build a simple numerical model of this one-dimensional ‘OBA activation function’. We fitted a third degree polynomial model with four inputs to this data. Then, we reconstructed the OBA effect. Figure 7 shows the reconstructed version (compare to the measured OBA effect on the bottom of page 5).

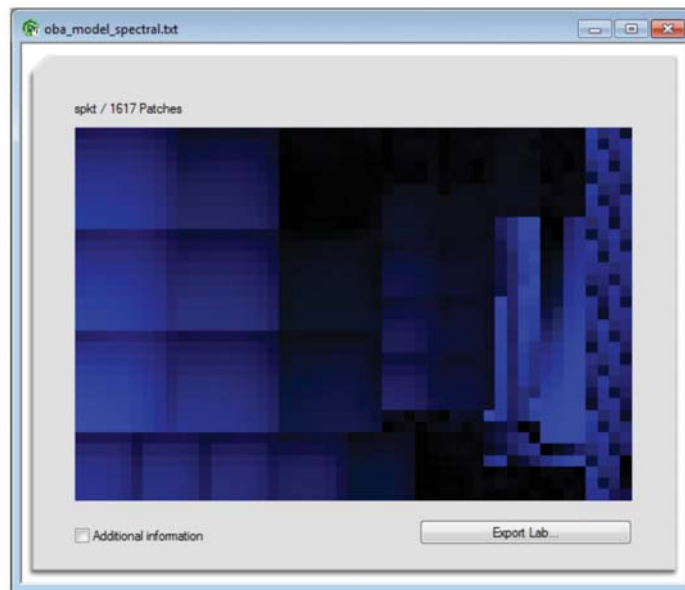


Figure 7 - OBA effect reconstructed from model

We feel this modeling work provides a good understanding of the OBA effect, and confirms, to some extent, the OBA properties we cited. We recognize we are computing the OBA effect from values that are probably modeled themselves, and are not exactly as portrayed in the ISO standard (see Appendix C). That could account for the good results we've obtained. To test that possibility, we took measurements with two other types of instruments. There were some differences, but overall the results were very similar. There are many additional materials from this modeling work, which are available from the authors on request.

Measuring the UV Content of Illumination

In theory, a standard viewing booth with updated fluorescent tubes has UV levels equivalent to D50. In practice, we often encounter non-standard viewing conditions (to say it nicely). Our calculations use a UV attenuation factor to allow for that (see appendix A). We needed a way to measure the UV content of the viewing illumination.

We could measure the visible spectrum (380 to 730 nm) with our i1Pro 2, but not the UV spectrum. So we looked for a measuring instrument that could measure both. The Minolta FD-7 spectro can measure irradiance from 360 - 730 nm (Konica Minolta, 2016), however typical OBA sensitivity peaks at about 360 nm, and extends all the way to 300 nm. We found other instruments that measure shorter UV wavelengths (GL Optic, 2016). However, we could not justify the purchase of this equipment for our research.

Instead, we constructed our own UV measuring device using an inexpensive sensor designed for smart watches and health bands (Vishay VEML6070, 2015). This sensor responds to UVA radiation, similar to the UV sensitivity of typical OBAs, as shown in the following figure.

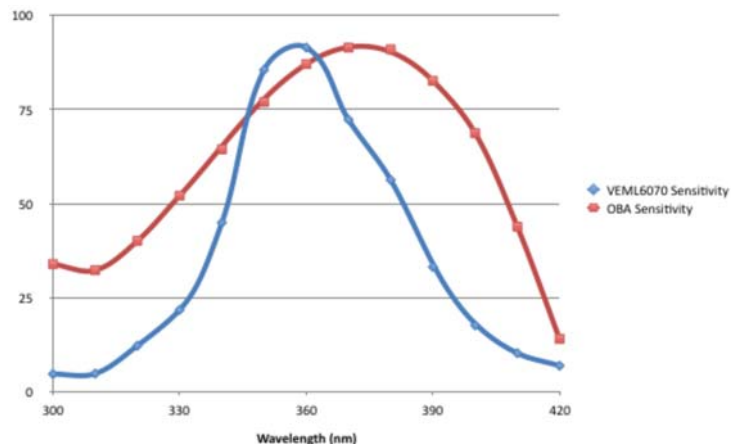


Figure 8 – VEML6070 and typical OBA spectral sensitivity

The UV content must be measured relative to luminance, so we added a second sensor to measure that (Vishay VEML6040, 2015). Vishay, the company that makes these sensors, provided free evaluation test boards and software. We placed the sensors side-by-side, connected to a laptop via USB cable.



Figure 9 - UV measuring tool connected to laptop

With this simple tool we were able to measure the UV and luminance simultaneously. But we needed to calibrate against D50 illumination. We used sunlight for this purpose. On a clear winter day, we waited for the color of direct sunlight to be approximately 5000K, and took readings with our tool. At the same time we measured the sunlight with our i1Pro 2. The color temperature was actually 4826K, so we computed the D-series SPD for that color temperature, and adjusted our measurements. Then we measured our viewing locations to see how they compared to D50.

The Green value is the green channel output of the VEML6040 device, which has a spectral sensitivity close to $V(\lambda)$. The UV value is the output of the VEML 6070 device.

1. Direct sunlight at 8:50 AM, clear blue sky,

Green = 42300, UV = 2360

Green = 42500, UV = 2388

Green = 42700, UV = 2416

Green = 43500, UV = 2485

CCT = 4826K, LUX = 81997 (measured with i1Pro 2)

adjusted calibration (UV/Green) for D50 (5003K) = 0.05897

2. GTI PDV with new ISO 3664:2009 compliant tubes,

Green = 824, UV = 39, UV/Green = 0.04733 (80.3% of D50)

3. GTI PDV with old style tubes,

Green = 797, UV = 31, UV/Green = 0.03889 (65.9% of D50)

4. Macbeth booth with really old tubes,

Green = 706, UV = 27, UV/Green = 0.03824 (64.8% of D50)

5. Philips TL950 in Macbeth luminaires (glass diffusers)

Green = 1375, UV = 48, UV/Green = 0.03491 (59.2% of D50)

This confirmed our suspicion that our viewing equipment was deficient in UV, compared to D50.

These measurements suggest we should increase the UV levels in our viewing equipment, but even brand-new ISO 3664:2009 tubes, without diffusers, did not produce D50 UV levels. It would probably require supplementary UV lamps to reach those levels. A more practical solution is to measure the UV excitation and adjust our media measurements accordingly. We will show how to do this in the next section.

Practical Color Management with OBAs

If you have M1 and M2 measurements, and you know the UV content of your viewing illumination, color management with OBAs is straightforward (see appendix A). In practice, you might not have all of this information. Furthermore, some of the problems attributed to OBAs are actually due to misalignment of white points. The following discussion illustrates these issues.

Suppose we're asked to color-manage an ink-jet proof to the GRACoL2013UNC data set. The white point of this data set is L*a*b* 95, 1, -4, using D50 colorimetry. We are told to use a specific ink-jet media for this proof. We print a profiling chart and measure it. The M1 and M2 white points are as follows:

M1 media white point (L*a*b*):	95.6	2.7	-10.4
M2 media white point (L*a*b*):	95.1	-0.2	1.3

This media has a high OBA index, 18.3%. If we build a media profile from the M1 measurements, and use absolute colorimetric rendering intent, our prints will have a considerable yellow tint in the whites. If we use the M2 measurements, we'll get the opposite effect, a blue tint in the whites. Under the right viewing conditions, either print is theoretically correct.



Figure 10 - Proofs using M1 profile (left) and M2 profile (right)

We believe our viewing booth has D50 illumination, so we use the M1 measurements. Our client does not like the yellow background tint. We insist this is a technically correct result, but our client won't budge. The background tint has to go!

The quick solution is to use relative colorimetric rendering intent instead of absolute. This aligns the white point of the media with the white point of the reference, and the background tint disappears. The math behind this trick actually takes place during the creation of the ICC profiles. The XYZ measurements of the profiling test chart are scaled so the unprinted media has XYZ values of D50. This is known as media relative colorimetry, and has been used in ICC color management from the beginning (ICC, 2010).

So, we can align the white points using relative colorimetric rendering intent. But we have two media profiles, one made from M1 measurements, and the other from M2 measurements. Which profile should we use? The M1 measuring condition is D50 illumination, including UV. To view with this light, you would need to go outdoors. The M2 measuring condition specifies a filter to remove the light that excites OBAs (wavelengths shorter than 420 nm). Our actual viewing conditions probably fall somewhere between these extremes.

If we measure the OBA excitation of our viewing light, relative to D50, we can determine which measuring condition is most appropriate. For instance, if the OBA excitation is only 10% of D50, we should use the M2 measurements. If the OBA excitation is 80% of D50, we should use the M1 measurements.

Better yet, we can mix the M1 and M2 measurement according to the OBA excitation level. Mixing is done with the XYZ measurements, which are linear. For example, if the OBA excitation is 60% of D50, using the example media above,

M2 media white point (XYZ):	84.5	87.8	70.9
M1 media white point (XYZ):	87.4	89.1	86.0
0.4 * M2 + 0.6 M1 (XYZ):	86.2	88.6	80.0
0.4 * M2 + 0.6 M1 (L*a*b*):	95.4	1.6	-5.9

This is a technically correct result, because the OBA effect (fluorescence) is linear and additive. If the illuminant is D50, the M1 and M2 colorimetry may be blended using weights based on the relative OBA excitation. If the illuminant is not D50, the problem is slightly more complex, because the OBA effect is emitted light “rolled into” the M1/M2 reflectance values.

Once the M1/M2 XYZ values are blended, they can be used to build a media profile. The colorimetry of our prints should now be correct. If the background tint is still a problem, it can be eliminated by the using relative colorimetric rendering intent, as explained above.

So, we can build a profile with M1 values, M2 values, or a blend of these values, then align the white point to our reference using relative colorimetric rendering intent. This raises the obvious question of how these results might differ, since the effective media white point is identical. The answer is that the contrast at the white point will be different.

Contrast is normally thought of in one-dimensional terms, that is, one input and one output. But in this case, we have four inputs, C, M, Y, K, and three outputs, X, Y, Z. If you make a small change in the cyan value, you will see a change in each of the three outputs, X, Y, Z. The same is true for magenta, yellow and black inks. So, there are actually twelve different contrasts, depending on which input and output you choose (see appendix B).

Using the M1/M2 data cited above, here are tables of these 12 contrast values. The M1/M2 data was adjusted by XYZ scaling to have a white point of L*a*b* 95, 1, -4. These contrast values were computed by fitting a numerical model to each data set,

M1 contrasts:

	Cyan	Magenta	Yellow	Black
X	-73.29121	-65.17922	-33.79773	-161.95926
Y	-65.22125	-93.00559	-24.20947	-166.12249
Z	-22.74197	-62.29178	-110.67356	-149.65408

M2 contrasts:

	Cyan	Magenta	Yellow	Black
X	-74.37382	-65.03075	-30.35694	-161.34605
Y	-65.51886	-93.01676	-23.06862	-165.83333
Z	-19.73916	-62.17842	-107.89761	-146.79507

There are numerical differences, but it's not obvious how appearance is affected. So, we can go one step further, and compute the color change of a CMY isometric vector, [1, 1, 1, 0],

M1 vector:

X	-172.26815
Y	-182.43631
Z	-195.70731

M2 vector:

X	-169.76151
Y	-181.60423
Z	-189.81519

Notice that the Y-values are nearly the same, but the X and Z values of the M1 vector are greater in magnitude. Figure 11 shows two versions of the same photo, tagged with M1 and M2 profiles and converted to sRGB using relative colorimetric rendering. The M1 photo has a greenish-yellow cast compared to the M2 photo, as predicted by the M1 and M2 vectors. The difference is subtle.



Figure 11 - Photos using M1 profile (left) and M2 profile (right)

So far, our discussion has focused on matching a printing process to a given reference. Now, let's consider the reference. Most likely, the samples were measured with M0 or M1 condition, and converted to XYZ using D50 colorimetry. Without M2 measurements, we cannot adapt the reference side to our viewing conditions, using the methods described.

In the future, standard data sets might contain both M1 and M2 data. If so, we could process that data according to our viewing conditions. With M1/M2 data we can select paper and media with OBA content similar to the reference, or modify the reference data to match the OBA content of the paper we've chosen. So, there are some good arguments for including M2 data in reference data sets.

If we are color matching a proof to a reference data set, the simplest way to proceed is to use the measuring condition of the data set to measure the proofing media, then build and install the media profiles. This will produce a technically correct proof that passes verification. If this result is satisfactory to all stakeholders, there is nothing more to do.

But if this literal proof has OBA problems, there is an easy solution. First, pick a proofing media with a color and OBA index similar to the printing paper. Then, align the white point of the proofing media to that of the data set, by blending the M1/M2 data for minimum color difference (delta E).

This technique will always yield a pleasing result. Although we're actually modifying the media measurements by increasing or decreasing the OBA effect, that is nearly the same as decreasing or increasing the OBA effect of the reference data set. Since we don't have M2 reference data, this is a reasonable approximation. Here is sample output from this technique,

data set wp values:	95.0	1.0	-4.0
media M1 wp values:	95.6	2.7	-10.4
media M2 wp values:	95.1	-0.2	1.3

media OBA index: 18.3%
optimizing M1/M2 coefficients for minimum deltaE
L-M optimization completed at 56 iterations

M1 coefficient: 0.436
M2 coefficient: 0.564

blending mode 1

adj media wp values:	95.3	1.1	-4.0
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The optimal blending for this data set and media is 43.6% M1 + 56.4% M2. This produces a media white point of $L^*a^*b^*$ 95.3, 1.1, -4.0, which has minimum deltaE to the data set white point of $L^*a^*b^*$ 95, 1, -4. Keep in mind that the blending is done with XYZ data, not $L^*a^*b^*$ data. You may or may not accept the premise of this technique, but you will definitely like the result.



Figure 12 - Proofs using M1 profile (left) and blended profile (right)

To summarize, M1/M2 blending adjusts the data for the UV content of the illumination. M1/M2 blending should be based on measurements of the relative UV content of the viewing environment. It may also be appropriate in a proofing application, to align the reference data set with the printing/proofing media.

Conclusions and Recommendations

Color management with OBAs is still a problem, despite the revised standards of 2009. These revisions, however, spurred the development of instruments that can measure both M1 and M2 conditions in a single session. With these measurements, and knowing the relative UV content of the illumination, it is now possible to compute accurate colorimetry for any illuminant.

Color appearance (Fairchild, 2013) is more complex than color matching. Even with accurate colorimetry, we may still have unsatisfactory results. A common problem is the unstable white point adaptation caused by tinted backgrounds surrounded by unprinted media. Practitioners may find it necessary to align white points. This can be done with more finesse using M1 and M2 data.

In order to scale the OBA effect, we need a practical way to measure the UV excitation of the viewing illumination. We have demonstrated a solution using inexpensive, off-the-shelf light sensors (Vishay VEML6070, 2015). Hopefully, some enterprising startup will build an affordable tool for this purpose.

Many printers now use standard data sets as a reference to color manage their proofs. The latest data sets from Idealliance and FOGRA are said to contain M1 measurements. We are left to guess the OBA content of the papers, and the effect of inks on OBA emissions. It would be far better if these standard data sets were supplied as both M1 and M2 measurements.

The print standards ISO 13655:2009 and ISO 3664:2009 specify D50 as the ideal illuminant. Unfortunately, there is no recommended artificial source for D50 (CIE, 2004). So, we are left to approximate D50 with dubious guidelines (ISO, 2009). For measuring devices, the difficulty of simulating D50, and the vagueness of ISO 13655 in this area is responsible for inconsistency among the new breed of graphic arts instruments (Wyble and Seymour, 2015).

Furthermore, some of our most popular instruments use illumination that doesn't conform to this ISO standard at all. Their M1 and M2 measurements are computed using proprietary algorithms, to simulate the M1/M2 conditions (Ehbets, 2008), (Wegmuller, 2010).

In our opinion, the next version of ISO 13655 should include two new measuring conditions. The first would be illuminant A with quartz bulb, as defined by the CIE (CIE, 2004). The second would be illuminant UV365, implemented as an LED with peak output at 365 nm and a specified bandwidth (Nichia, 2016). Both of these measuring conditions are easy to implement, and there is no ambiguity. We would expect very good agreement among instruments from different manufacturers.

The illuminant A measurements would be normal reflective values, while the UV365 measurements would be emissive values. Software could utilize these dual measurements to compute regular and OBA colorimetry. This would be a great improvement over the current situation, where manufacturers use various illumination sources, and proprietary models for deriving the M1/M2 data.

The reason for specifying UV excitation at 365 nm is that it coincides with the mercury vapor I-line, which is the primary UV excitation from fluorescent tubes. The D50 viewing illuminant is often simulated with fluorescent tubes, which contain a controlled amount of I-line radiation. Furthermore, OBAs have peak excitation sensitivity near 365 nm. Variation due to wavelength is minimum at this peak.

In the future, LEDs may be used to simulate D50 light (Yuji, 2016), (Westcott, 2016). The LEDs used for illumination generally lack UV content, so it will be necessary to add supplemental UV LEDs to provide OBA excitation. The current ISO 3664 standard sets D50 as the target, and measures UV conformance with a metamerism index. The UV region of the D50 SPD is continuous and linear, which makes it difficult to simulate with LEDs. We suggest it would be better to define the UV region in a way that can be directly realized and verified, as with our recommendation for ISO 13655.

In the future, fluorescent tubes may be replaced entirely by LEDs, which would eliminate UV light from our indoor environments. Without UV light, OBAs are ineffective. This could cause changes in the manufacture of paper. Maybe we should start preliminary work on standards appropriate for LED lighting.

Creating industry standards is a difficult job, where politics may take precedence over technical considerations. Ideally, the standards process considers all proposals, and chooses the ones that are ultimately good for the industry. A strong standard chooses the single best solution, whereas a weak standard blesses all solutions.

References

ASTM E2153-01, Standard Practice for Obtaining Bispectral Photometric Data for Evaluation of Fluorescent Color, ASTM International, West Conshohocken, PA, 2011, <http://www.astm.org>

Blum, Thierry, Linhart, Friedrich, Frenzel, Stephan, Method for production of coated paper with extreme whiteness, US Patent 7,641,765, Jan. 5, 2010

CIE International Commission on Illumination, CIE 015:2004 Colorimetry, 3rd Edition, section 3.2, CIE Central Bureau, Vienna, 2004

Donaldson, R. (1954). Spectrophotometry of fluorescent pigments, British Journal of Applied Physics. 5, 210-214.

Ehbets, Peter, Beat Frick, Mark Wegmuller, and Adrian von Orelli, Process for the colour measurement of printed samples including brighteners, US Patent 7,466,417, Dec. 16, 2008

Fairchild, Mark, (2013). Color Appearance Models – Third Edition, Chichester, West Sussex, United Kingdom: John Wiley & Sons, Ltd

GL Optic – GL Spectis 1.0 (2016, March 7). Retrieved from <http://gloptic.com/products/gl-spectis-1-0/>

GL Optic – GL Spectis 5.0 Touch (2016, March 7). Retrieved from <http://gloptic.com/products/gl-spectis-5-0-touch/>

Gonzalez, Sergio and Fairchild, Mark D., (2007) Evaluation of Bispectral Spectrophotometry for Accurate Colorimetry of Printing Materials, Society for Imaging Science & Technology, 8th Color and Imaging Conference Final Program and Proceedings, pp. 39-43(5)

ICC, Image technology colour management — Architecture, profile format, and data structure, Annex D.6.1, Relative and absolute intents, Specification ICC.1:2010, Available at http://color.org/specification/ICC1v43_2010-12.pdf

ISO. Graphic technology — Spectral measurement and colorimetric computation for graphic arts images, ISO 13655:2009, ISO, Geneva, 2009, Available at: <http://www.iso.org>.

ISO. Graphic technology and photography — Viewing conditions, ISO 3664:2009, ISO, Geneva, 2009, Available at: <http://www.iso.org>.

ISO. Graphic technology — Input data for characterization of 4-colour process printing — Part 2: Expanded data set, ISO 12642-2:2006, Geneva, 2006, Available at: <http://www.iso.org>.

Kasha M. (1950). Characterization of electronic transitions in complex molecules. *Discussions of the Faraday Society* 9, 14–19.

Konica Minolta, FD-7 Spectrodensitometer, (2016, March 7). Retrieved from <http://sensing.konicaminolta.us/products/fd-7/>

Lakowicz, J. (2006). *Principles of Fluorescence Spectroscopy – Third Edition*, New York NY: Springer Science+Business Media, LLC

Nichia - UV LED Products, (2016, March 7) Retrieved from <http://www.nichia.co.jp/en/product/uvled.html>

Shi, H., Liu, H., Ni, Y., Yuan, Z., Zou, X., and Zhou, Y., (2012). Review: Use Of Optical Brightening Agents (OBAs) In The Production Of Paper Containing High-Yield Pulps, *BioResources* 7(2), 2582-2591.

Tominaga, S., Hirai, K., and Horiuchi, T., (2015). Estimation of bispectral Donaldson matrices of fluorescent objects by using two illuminant projections, Division of Information Sciences, Graduate School of Advanced Integration Science, Chiba University, Chiba 263-8522, Japan

Vishay VEML6070 – UV A Light Sensor with I2C Interface. (2015, July 31). Retrieved from <http://www.vishay.com/docs/84277/veml6070.pdf>

Vishay VEML6040 – Designing the VEML6040 RGBW Color Sensor into Applications. (2015, August 11). Retrieved from <http://www.vishay.com/docs/84331/designingveml6040.pdf>

Wegmuller, M., Ehbets, P., Frick, B. Method of measuring the colour of printed samples containing brighteners. US Patent 7,847,264, December 7, 2010

Westcott, F.J. Co., Flex LED lighting, (2016, March 5). Retrieved from <http://www.fjwestcott.com/lighting/flex>

Wyble, D., and Seymour, J., (2015). Investigation of the Implementation Aspects of the M1 Condition, Technical Association of the Graphic Arts – TAGA Proceedings

X-Rite, Inc., i1Pro 2 Spectrophotometer, (2016, March 18). Retrieved from <http://www.xrite.com/i1basic-pro-2/Specifications>

Yuji International, High CRI Lighting, (2016, March 17). Retrieved from <http://www.yujiintl.com/high-cri-led-lighting>

Appendix A – Color Management with OBAs

OBAs convert UV light to visible light, which is added to the normally reflected light, as measured by instruments. The UV content of viewing and measuring illumination will interact with OBAs in the paper. Until recently, this UV content was not standardized, which led to variable results with OBAs.

The ISO 3664:2009 standard defines the viewing illuminant as D50, including the UV region. The ISO 13655:2009 standard defines the M1 measuring condition in a similar way. If we upgrade to new equipment conforming to these standards, we can simply use M1 measurements, and normal color management works correctly.

When the visible illumination is close to D50, but the UV content is not, M1 measurements will be incorrect. If we know the UV content is some percentage (UV_r) of D50, we can compute corrected reflectance measurements through simple blending of the M1 and M2 spectral reflectance data,

$$R(\lambda) = UV_r * R_{M1}(\lambda) + (1 - UV_r) * R_{M2}(\lambda)$$

As a check,

$$\text{if } UV_r = 1, R(\lambda) = 1 * R_{M1}(\lambda) + 0 * R_{M2}(\lambda) = R_{M1}(\lambda)$$

$$\text{if } UV_r = 0, R(\lambda) = 0 * R_{M1}(\lambda) + 1 * R_{M2}(\lambda) = R_{M2}(\lambda)$$

Note this blending formula may be used with XYZ data, but not L*a*b* data.

When the visible illumination is not D50, the problem is more complex. The light emitted by the OBAs is “rolled into” the M1 reflectance data, and must be handled separately with non-D50 illumination. In this case, we calculate the combined spectral product, which is a sum of the normally reflected light plus the OBA emitted light,

$$P(\lambda) = R_{M2}(\lambda) * SPD(\lambda) + (R_{M1}(\lambda) - R_{M2}(\lambda)) * D50(\lambda) * UV_r$$

Where P(λ) is the combined spectral product, and SPD(λ) is the normalized spectral power distribution of the non-D50 illuminant.

When we extract the OBA emitted light from the M1/M2 measurements, the difference (R_{M1}(λ) - R_{M2}(λ)) is a reflectance value, which must be multiplied by the D50 SPD, not the illuminant SPD.

As a check,

$$\text{if } SPD(\lambda) = D50(\lambda),$$

$$P(\lambda) = R_M2(\lambda) * D50(\lambda) + (R_M1(\lambda) - R_M2(\lambda)) * D50(\lambda) * UVr$$

$$P(\lambda) = UVr * R_M1(\lambda) * D50(\lambda) + (1 - UVr) * R_M2(\lambda) * D50(\lambda)$$

$$P(\lambda) = R(\lambda) * D50(\lambda)$$

Appendix B – Multicolor Contrast

The contrast values are actually partial derivatives, defined as the ratio of the change of an output divided by the change of an input, as that change becomes infinitesimally small. For each partial derivative, all other inputs are fixed. The notation for partial derivatives is $\partial y/\partial x$, where y is the output and x is the input.

The table of contrasts is actually known as the Jacobian matrix. This matrix is widely used in linear algebra problems, especially for optimization. We are using it here to describe the contrast of a process with multiple inputs and outputs. The Jacobian matrix is a function of the ink values (CMYK).

The reason contrasts in our example are negative is that an increase in ink value (CMYK) causes a decrease in the colorimetric values (XYZ). The reason the contrasts are larger numbers is that the CMYK values range from 0 to 1, while the XYZ values range from 0 to 100.

Appendix C – Concerns About the Veracity of Measurements

The instrument we used to measure charts is an X-Rite i1Pro 2 with an i1iO table. We operated this device in the so-called ‘dual-scan’ mode, using i1Profiler software. The measurements were returned in CxF3 format – a single file containing M0, M1 and M2 spectral data.

The i1Pro 2 instrument has two sources of illumination, an incandescent lamp, and a UV LED. Each row of measurements is scanned twice, in one direction with the incandescent lamp, and the other direction with the UV LED. We were able to measure the visible SPD of these light sources with an i1Pro instrument.

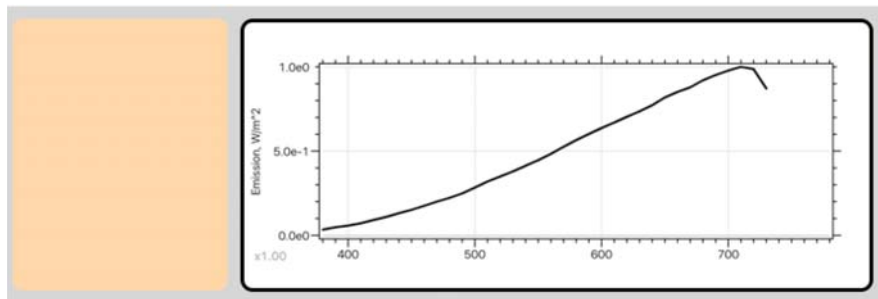


Figure 13 - i1Pro 2 incandescent spectrum

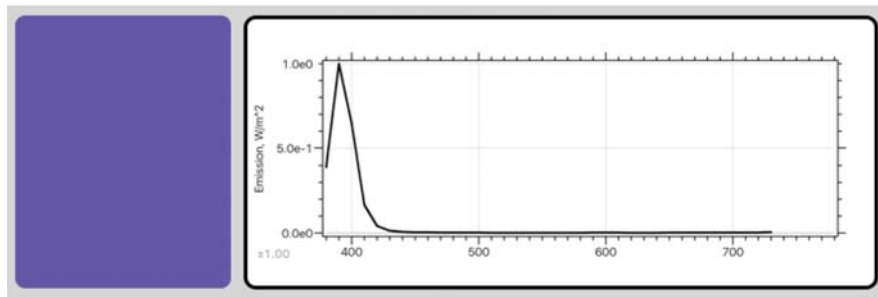


Figure 14 - i1Pro 2 UV LED spectrum

We don't know the UV content of these sources, but we're sure that the incandescent lamp does not have a UV-cut filter of the type specified in ISO 13655. It appears the instrument is making an M0 measurement, and then a measurement with UV excitation only. Apparently, firmware or software is processing these actual measurements into the M1 and M2 values returned.

Considering the time it took to make the i1Pro 2 fully functional in the dual-scan mode (about 4 years), we imagine X-Rite did a thorough job engineering these devices to provide a good approximation of the ISO 13655 standard. But that is a matter of faith, not fact (Wyble and Seymour, 2015).

Another concern we have is with the M2 data. According to the ISO standard, the illumination is passed through a UV-cut filter that eliminates most of the light with wavelengths less than 420 nm. Without illumination, the instrument cannot take an actual reading. So, if the instrument returns values in these 'cut' wavelengths, they must be estimated or extrapolated. Earlier UV-cut instruments performed that way.

But to our surprise, the 'cut' M2 measurements from the i1Pro 2 appear to be real. This seems like a deviation from the ISO standard, but a good one, if these values are correct. Ideally, M2 values would be the diagonal (illumination and measurement wavelengths are equal) of the Donaldson matrix.

Despite these concerns about the veracity of the i1Pro 2, we believe our results are sound and useful.