

Investigation of the Implementation Aspects of the M1 Condition

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Abstract

The need for consistent viewing conditions of prints has been established through the use of light booths conforming to ISO 3664 (ISO 2009), designed to simulate CIE illuminant D50. In particular they are designed to produce the appropriate amount of UV energy to consistently excite fluorescent compounds in the media. For instruments to predict color that will align with the visual perception of samples viewed under ISO 3664 lighting, the source in the instrument must also contain the proper amount of UV energy. ISO 13655 (ISO 2009) refers to such an instrument as having achieved measurement condition M1. Most modern instrument manufacturers have responded to this requirement by either: 1) a single flash method where the UV component is tuned such that measurements match those that would result from an actual D50 source, or 2) a multi-flash numerical method published by Imura (2007 and 2012). The multi-flash method also attempts to match colorimetry that would result from the use of an actual D50 source.

The experiments described here are based upon bispectral measurements of a series of acrylic reference standards representing a range of ISO brightness. These standards have been measured by the NRCC (National Research Council Canada) reference bispectral spectrophotometer. This measurement reports a 2D bispectral matrix that enables the prediction of total radiance factor given any arbitrary incident illuminant. From total radiance factor the color is predicted.

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Introduction

This paper will seek to answer two questions:

1. Are ISO 3664 and ISO 13655 adequate for the evaluation of instrument sources?
2. Using various hypothetical instrument sources how do measurements of the acrylic standards compare?

To answer the first question, the measurement condition “M1” will be explored, both in terms of its definition, application, and implications. To answer the second question, the definition and application of bispectral measurements will first be discussed followed by the description of the methods used here for simulating the instrument sources.

ISO 13655 specifies two different ways of achieving the M1 condition: either by providing illumination of the sample which matches D50 illumination within a specified tolerance, or by providing illumination which has the same effect on paper with FWAs. In practice, this simulation can be created with the “one-flash” method or the “two-flash”.

Method 1 – Actual D50 illumination

According to ISO 13655:2009

The spectral power distribution of the measurement source at the sample plane should match CIE illuminant D50. It shall conform to the UV range metamerism index specified for viewing condition P1 of ISO 3664. This method is to be used when both luminescent colorants and optical brighteners are of concern.

The words “should” and “shall” have precise meanings in an ISO standard. The word “should” flags a recommendation that is not mandatory for compliance to the standard. The word “shall” refers to mandatory parts of a standard. Thus, D50 is the target, but this is not easy to achieve in practice, since D50 is a theoretical illuminant, not based on any existing light sources. While D50 fluorescent tubes and cool blue white LEDs may have correlated color temperature of D50 (a near colorimetric match), neither is a close spectral match, especially in the UV.

The mandatory portions of this section of ISO 13655 is the test which is described in ISO 3664.

Method 2 – Single flash method

ISO 13655:2009 specifies an acceptable approximation to D50 illumination:

A spectral match of the spectral power distribution of the measurement source in the range from 400 nm to 700 nm at the sample plane is not required if a compensation method is used with a controlled adjustment of the radiant power in the UV spectral region below 400 nm. This can be done by active adjustment of the relative power in this range with respect to a calibrated standard for D50.

This may be met by a spectrophotometer that combines a UV deficient light source, for example, and incandescent bulb or white LED, used in conjunction with a UV rich light source such as a UV LED. The two light sources may illuminate the sample at the same time. There is an adjustment of the relative power in the two light sources in order to attain the same level of UV excitation as D50. This may be accomplished in the factory by using a certified reference material (CRM) – a physical sample with FWAs that has been measured by a national standards lab, or by a secondary lab. This method was described by Gärtner and Griesser (Gärtner and Griesser, 1975).

There is an assumption in the single-flash method that minimal error is introduced from the fact that the combined light source adequately mimics D50 on the FWAs that appear in paper. This will be the case if the light source exactly replicates D50 or if the FWA CRM exactly replicates the FWAs in paper, but neither of these will be the case in practice.

This assumption will be addressed later in the paper.

Method 3 – Two flash method

The most recent draft revision of ISO 13655, dated Dec. of 2014, contains this same language but includes references to two papers by Imura (Imura 2007 and Imura 2012). Imura describes a method whereby the sample is measured twice: once with a UV deficient illuminant (less UV than D50), and one with a UV rich illuminant (more UV than D50). The M1 spectrum is then approximated by a weighted average of the spectra from the two measurements.

In theory, these weighting factors could be determined directly from measurements of the two light sources. In practice, better calibration may be attained through the use of a CRM.

Calibration starts with measurements of a CRM with known M1 reflectance spectrum, $M1(\lambda)$. This can be expressed as a weighted average of measurements with the other two light sources as follows:

$$M1(\lambda) = k(\lambda)M_{rich}(\lambda) + (1 - k(\lambda))M_{deficient}(\lambda) \quad (1)$$

The value of the weighting constant can be derived by solving Equation 1 for k :

$$k(\lambda) = \frac{M1(\lambda) - M_{deficient}(\lambda)}{M_{rich}(\lambda) - M_{deficient}(\lambda)} \quad (2)$$

For subsequent measurements (of different samples) the calibrated weighting factor determined through Equation 2 are used in Equation 1 to report M1 spectra.

Note that in the two flash method, a separate value for k is computed for each wavelength. If a single value of k is used, this reduces to a digital implementation of the single flash method. The value for k plays the role of the analog adjustment on the illuminant. This ability to calibrate at each wavelength can presumably improve the accuracy of the M1 simulation.

Clearly, the two flash method can be no worse than the single flash method. The question still exists as to the magnitude of the error that is introduced by calibrating the weighting factors $k(\lambda)$ on a CRM with a different FWA than that of paper.

One benefit of the two flash method is that it is possible to additionally derive M0 and M2 measurements. One disadvantage is that two measurements are required. For some applications, such as inline measurement, this is not possible.

Simulation of M1

To simulate the behavior of instrument sources, it is first appropriate to examine the existing commercial instrumentation to ensure that the simulation is plausibly consistent with the actual implementations.

There are currently five M1 devices available on the market from four different vendors. The product literature provides some clues as to which actual light sources were utilized.

The Barbieri SpectroPad Series 2 uses a combination of seven LEDs to simulate D50 illumination. Their description of the illumination system is: “Thanks to 7 LED, D50 illumination is reached. This illumination is based on LED technology by Just Normlicht. It fully matches the new measurement condition M1 introduced with the ISO standard 13655-2009.)”

Just Normlicht has a patent (Gall et al., US Patent 8,592,748) which describes a combination of two white LEDs along with five additional LEDs. One of the LEDs has a peak emission between 400 nm and 405 nm, so it is suitable for excitation of the FWAs in paper. Presumably, this spectrophotometer uses method 1 in ISO 13655.

The literature for the Techkon SpectroDens is somewhat less detailed, but reads similar to the Barbieri device. “Using the latest LED technology, the new SpectroDens provides D50 illumination and therefore fulfills the M0 – M3 measuring conditions in accordance to ISO 13655.”

According to their product literature, the *Konica-Minolta FD-7* uses “Virtual Fluorescent Standard”, which is a phrase used in the papers by Imura (Imura 2007, and Imura 2012), who is employed by Konica-Minolta. From this it seems likely that the FD-7 uses the two flash method. The only additional information in the product literature is that it states that their light source is LED based.

The *X-Rite eXact* and *iPro* both refer to their lighting as “gas filled tungsten (illuminant type A) and UV LED”. The *iPro* is also sold by EFI under the name *EFI ES-2000*. The method for emulating M1 illumination is not precisely described, but insight may be gained an X-Rite patent. US Patent 7,466,417 describes a method similar to the previous description of the two-flash method, except that one measurement is made with illumination devoid of UV light, and the other measurement is made with only UV light. It is important to note that Equation 1 cannot be used to estimate the M1 spectra for this instrument, since the two spectra to be averaged in this equation are both reflectance spectra. When one of the two measurements is devoid of visible light, it is not possible to determine the reflectance spectra in the visible region from the UV illumination. The proper correction would not be a weighted average, but rather the sum of the spectrum under visible illumination and a weighted portion of the spectrum under UV illumination.

This short review of existing instruments demonstrates that different companies have implemented the M1 condition by utilizing different physical light sources. Thus, there is at least the potential for this to be one source of disagreement between different models of spectrophotometer. These devices are those instruments known to the authors and the quotes here are directly from their respective web pages or other marketing literature. We do not imply this list is exhaustive, nor to the correctness of the claims, nor to we specifically endorse any of these products.

To simulate an instrument source (single flash method only) we therefore specified the visible portion of the spectrum using some defined source, and then augmented that with a narrow band UV source with spectral shape similar to a commercial UV LED. In all cases the UV LED can be freely adjusted to match the D50 colorimetric output for a calibrated physical artifact. That is, the CIELAB of the artifact when illuminated by the test source is matched to the CIELAB of the artifact when illuminated by D50.

To enable the application of arbitrary sources and predict the reflected radiance for fluorescent when illuminated by those sources, traditional reflectance is insufficient. A better understanding of the material is required, which can be gained by bispectral (two monochromator) spectrophotometry.(Jordan et al, 2003).

For the most popular configuration of traditional spectrophotometry, the sample is illuminated by a single flash (typically white light) and the reflected light is the dispersed with a diffraction grating. An array detector measures the individual spectral bands across, for example, 400 to 700nm. This procedure cannot account for the behavior of a fluorescent sample since the instrument cannot distinguish between light *reflected* at a given wavelength and light *fluorescently emitted* at that same wavelength. To differentiate between these two sources of measured light, an instrument must sequentially illuminate the sample with narrow band light (eg: 10nm wide) and detect the full visible range.

In this way, a two-dimensional reflectance matrix is created, one column for each incident wavelength and one row for each detected wavelength. Elements of the matrix diagonal represent non-fluorescent reflectance since the incident and detected wavelengths are the same. Elements off the diagonal are fluorescently reflected, since the incident wavelength is different from the detected wavelength.

Experimental procedure

Physical samples

The samples used in this experiment are manufactured by Avian Technologies, LLC. Most measurements were of five tiles: AT-FTS-9a, AT-FTS-11a, AT-FTS-13a, AT-FTS-15a, and AT-FTS-17b. For the balance of this paper they will be referred to only as 9a, 11a, etc. In the order listed above the samples are of increasing fluorescent behavior, with the 9a being non-fluorescent and the 17b being the most fluorescent. Note that the alphabetic suffix indicates the type of fluorescent doping; to achieve its high fluorescence the 17b uses a slightly different compound. It has, however, been shown to behave very similarly to the “a” compound in terms of excitation and emission wavelengths.

Physically, The FTS tiles are all 2”x3”x0.1” acrylic with fluorescent doping added. This experiment used the glossy versions.

A similar series of tiles (save the 9a) was sent to the National Research Council Canada (NRCC) for measurements on their reference bispectral spectrophotometer. The samples used here while not the identical tiles, were selected from the same fabrication run, and determined in advance to be as close to the NRCC-measured tiles as could be determined with conventional instrumentation. The reflectance factor under D50 was computed from the bispectral measurements, as shown in Figure 1.

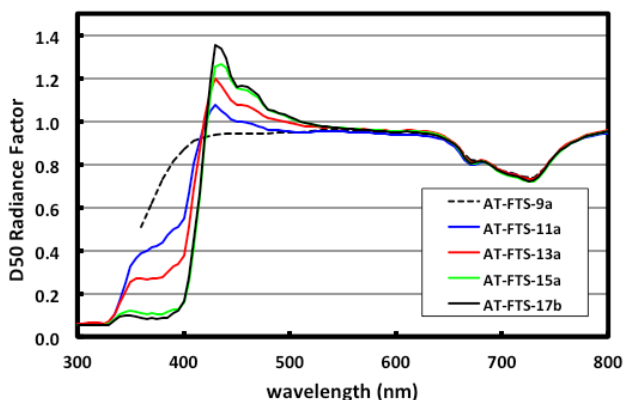


Figure 1. D50 reflected radiance factor for 5 FTS tiles.

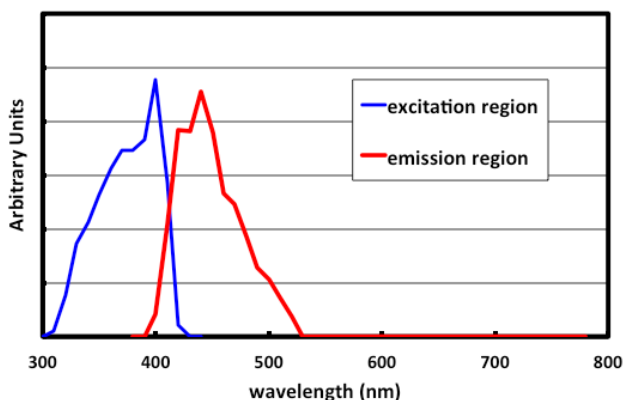


Figure 2. Spectral excitation and emission regions for FTS standards (normalized).

The bispectral data allows the reflected radiance factor to be estimated under any arbitrary light source. (Leland, 1997). This feature of the data will be used heavily in most of the following experiments. In each of these experiments, a virtual instrument source will be created and measurement of the FTS tiles will be simulated. The measured data, after conversion to CIELAB, will be compared to the traceable NRCC data via color difference equations.

From the bispectral data, the spectral regions of excitation and emission can be calculated. These are shown in Fig 2. The location of the excitation region in particular will be critical when considering the impact of instrument light sources later in this article. Sources with more content in this region will stimulate the fluorescent emission more than sources with less.

Experiment 1: Virtual Sources

The first experiment used the instrument descriptions in the introduction to determine a series of plausible choices for instrument sources. The following configurations were selected for testing:

- UV1+W: This source used a typical white LED, with a blue pump LED and a yellow phosphor, augmenting the UV output with an additional UV LED.
- UV2+W+C: This source is similar to UV1+W with the addition of a cyan LED.
- UV1+All: This source uses the same UV LED as UV1+W but completes the visible spectrum with four LEDs.
- UV1+A: This source used the same UV LED as UV1+W and completed the spectrum with tungsten (illuminant A).

Nominal plots for these hypothetical light sources are in Fig 3.

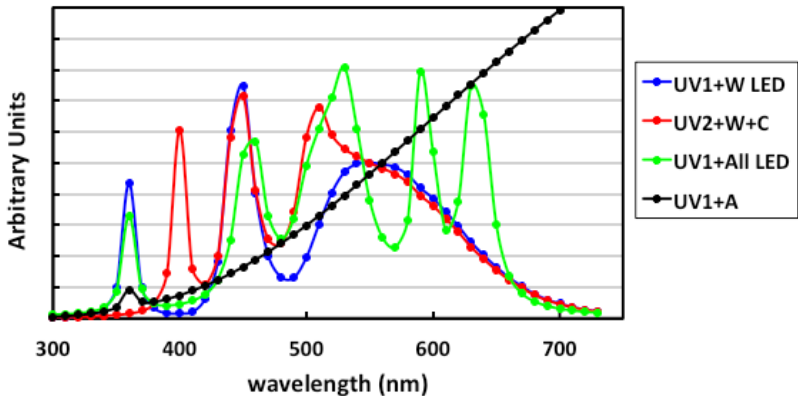


Figure 3. Relative spectral power distribution of the sources used in experiment 1. These are nominal levels, as the UV component of each is individually adjusted as a part of the calibration procedure described in the text.

For each of these four sources, there was only one adjustable component: the UV LED. This should yield enough freedom to closely match the NRCC D50 CIELAB for at least one particular sample. The samples used in this experiment were: two FTS tile (15a and 17b) three commercial papers for which bispectral data was already available: 70lb Wausau, Epson S0410341, and Becket Platinum Mohawk.

The procedure for experiment 1 was:

1. Select one hypothetical instrument source
2. Select one of 15a, 17b, or 70lb Wausau to use the calibration standard
3. Calculate the reference CIELAB for this calibration standard. This is the reflected radiance factor resulting from applying illuminant D50 to the standard's bispectral matrix.
4. Adjust the UV LED until there is an optimum CIELAB match between the reflected radiance factor of the standard and the D50 colorimetry calculated in step 3.
5. Calculate the reflected radiance factor resulting from illuminating the other samples with the source determined in step 4.
6. Calculate the color difference between the test CIELAB from step 5 and the reference CIELAB from step 2.
7. Repeat 1-6 for each of the four hypothetical sources and each of 15a, 17b, and 70lb Wausau calibration standards.

Experiment 2: M1 Compliant Sources

For experiment 2, various hypothetical sources were generated that met the M1 condition as specified in ISO 13655. Two methods were used: vary the correlated color temperature (CCT) for CIE daylight (CIE 15.2004), and vary the UV component of CIE D50. In all cases, the M1 condition was verified using a spreadsheet provided by Dr Danny Rich. Compliance is verified by the following metrics:

- The source chromaticity is within a distance of 0.0005 from the chromaticity of D50.
- The color rendering index RA (CIE 13.3) is at least 90. The minimum CRI Ri for any given tile must be at least 80.
- The Visible Metamerism Index (ISO 23603) color difference of five non-fluorescent colors is at most $1.0 \Delta E^*_{ab}$.
- The UV Metamerism Index (ISO 23603) color difference of 3 fluorescent white colors and 3 non-fluorescent white colors is at most $1.5 \Delta E^*_{ab}$.

With the set of M1-compliant sources, the spectral radiance factor of the FTS standards were calculated. From the reflected spectra, CIELAB and then ΔE^*ab were calculated, the color difference being from the reference condition of using D50 as the source.

For the first method, using CIE daylight, various CCTs were selected starting with 5000 (corresponding to D50) and tested for M1 compliance. The CCT was varied to determine the upper and lower bounds of compliant CCTs. CCTs between 4976 and 5028 (inclusive) were found to meet the M1 condition.

For the second method, the starting spectral data were again D50. For this case, the values from 300 to 400nm (inclusive) were scaled up and down to determine the boundaries of M1 compliance. That portion of the spectrum could be scaled from 60% to 140% (inclusive) and still meet the M1 condition.

Results and discussion

Experiment 1: Virtual Sources

The question being considered here is how well the FTS standards act as calibration references as compared to fluorescent commercial paper. As described above each test source was used to virtually illuminate the selected calibration artifact. CIELAB for the resulting reflected radiance factor were calculated, and the UV component particular to the test source was varied until the color difference to the calibration artifact when viewed under D50 was minimized. We have now achieved M1 compliance for this source. It is now reasonable to virtually illuminate the other test materials (commercial papers and FTS tiles) and determine the color difference of those reflected radiance factors to the D50 reference CIELAB.

Three calibration standards were selected: 15a, 17b, and Wausau 70lb. Each chart below shows results for one standard. Note that in all cases, the results for the calibration standard itself are not zero. This indicates that the optimization was not able to find a scaling for the UV LED that resulting in a perfect match to the D50 color.

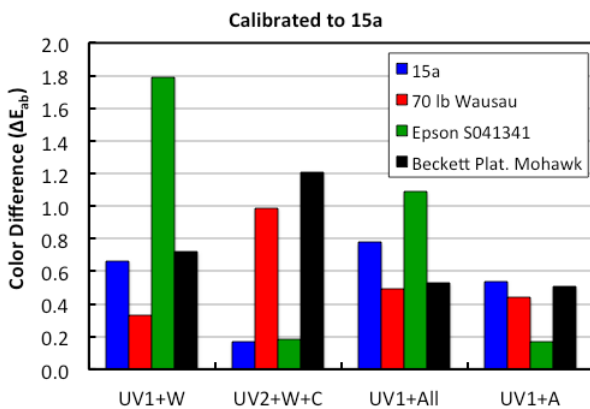


Figure 4a. Experiment 2 results when using the 15a as the calibration standard.

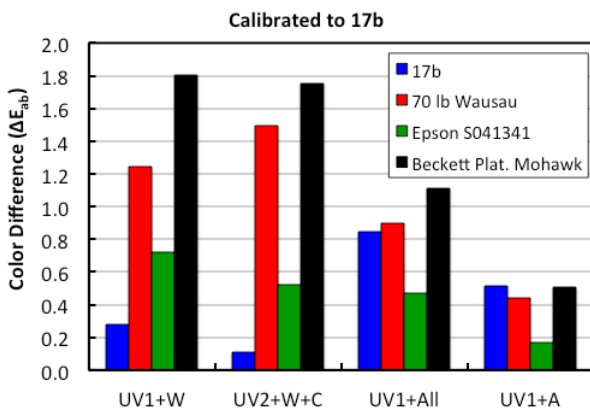


Figure 4b. Experiment 2 results when using the 17b as the calibration standard.

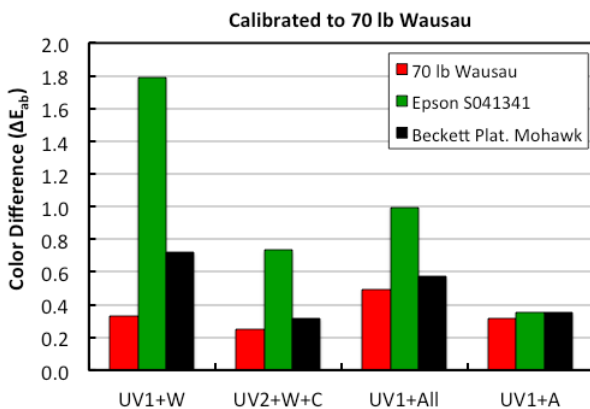


Figure 4c. Experiment 2 results when using the 70lb Wausau paper as the calibration standard.

Interpreting Fig 4a-c can help with two important aspects of a fluorescent measurement system. First, it can be inferred to what degree the test sources differ from D50. If any source precisely duplicated D50, or even precisely duplicated the way in which D50 excites the various test samples, some bars in the charts would be zero. Therefore we can conclude that none of the test sources replicate D50 in either of these fashions, since there are no entries of zero in any of the three charts.

It can also be readily seen that some of the hypothetical light sources in this collection emulate D50 better than others. For example, the UV1+W light source performs poorly on at least one sample, no matter how it was calibrated. The UV1+A light source performs consistently better than the others.

Second, we can infer how close the fluorescent behavior of the 15a and 17b FTS tiles replicates that of the commercial papers. Unfortunately the best that can be claimed towards this end is “it depends.” *Some* papers perform quite well for the 15a and/or 17b calibrations, and others perform quite poorly. There are confounding effects here, including the differences in the virtual source spectral power distribution and the different excitation ranges of the samples. The typical excitation range of commercial papers extends deeper into the UV than FTS tiles so any sources with content below 300nm can partially explain the difference between paper and FTS behavior. Likewise, the FTS emission extends to 550nm, while the emission from commercial papers is extinguished by about 520nm. To show this graphically, the excitation and emission curves of FTS (Fig 5a) and papers (Fig 5b) are shown below.

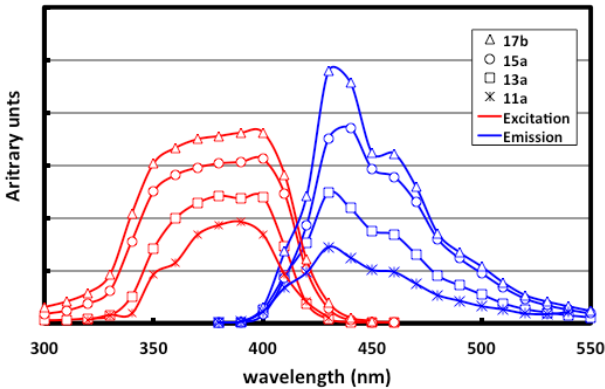


Figure 5a. Excitation (red) and emission (blue) regions for FTS tiles. Note that the FTS tiles are not significantly stimulated below 300nm.

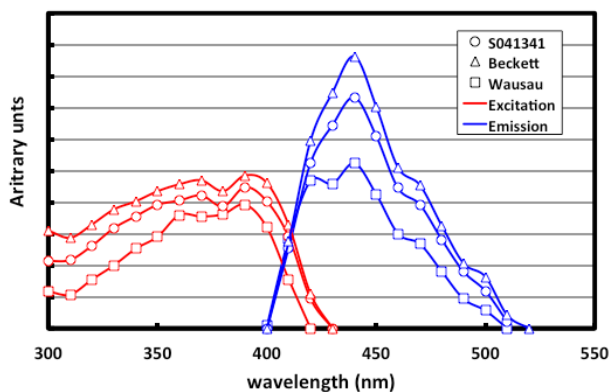


Figure 5b. Excitation (red) and emission (blue) regions for commercial papers.

Note that at 300nm the commercial papers are still being excited at greater than 50% of their peak levels.

As an addendum to experiment 1, a series of commercial instruments, all of which claim M1 compliance, were used to measure the set of FTS standards.

The results of these measurements are shown in Figure 6, along with the CIELAB values calculated from the calibrated NRCC D50 radiance factor for the tiles. NRCC reference data are X's, instrument are the other symbols. Color indicates the particular FTS tile measured, as noted in the caption of Figure 6.

It can be seen that the range of measurements for non-fluorescent 9a tiles (gray points, near the top left) are clustered in a region about 0.5 units across. This indicates that the instruments are in general agreement in absolute calibration and accuracy. The size of the clusters increases with the amount of fluorescence in the sample. Note that to differentiate among the points the a^* axis is elongated compared to the b^* axis. Still, the size of the clusters grows to several units in CIELAB coordinates.

One important feature to note is that all instruments show a larger color difference from the non-fluorescent 9a than the NRCC reference data. For each of the black, red, blue, and green clusters the NRCC data (X) are in the top left, the nearest to the non-fluorescent 9a data. The commercial instruments, therefore, all overestimate the impact of the fluorescence when compared to the reference NRCC data.

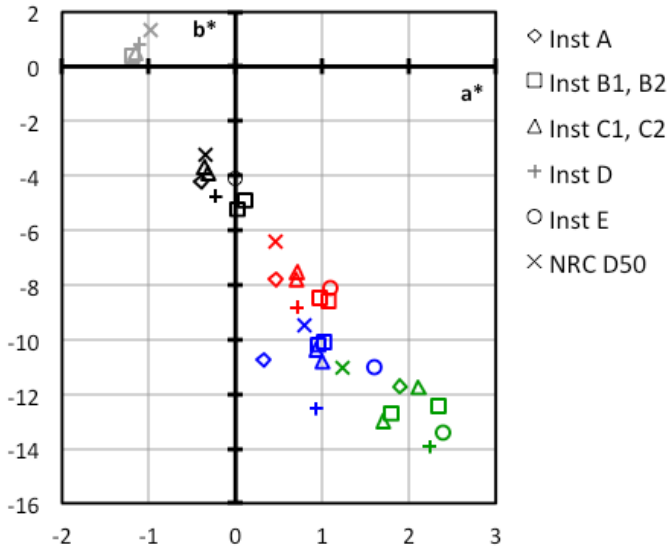


Figure 6. Measured CIELAB data from five commercial instruments and NRC theoretical D50 radiance factor. For instruments B and C there were two sets of measurements made with two different instruments. Note that to better show the spread of the data the a^* and b^* axes are on different scales. Color code: gray 9a; black 11a; red 13a; blue 15a; green 17b.

Experiment 2: M1 Compliant Sources

Experiment 1 dealt with M1 compliance in a colorimetric sense: if, for a given sample, an instrument calculates the same CIELAB values as would have been calculated if the source was D50, then it is acceptable to consider the instrument in the M1 conditions. Experiment 2 defines the M1 condition somewhat more rigorously; the source must be closer to a *spectral match* with D50. While strictly speaking most of the metrics in ISO 3664 are colorimetric, in practical terms a near spectral match is required to fulfill all of the constraints.

The sources used for the first method of experiment 2 are shown in Figure 7 below. A set of theoretical sources were generated with CCT near 5000 K. It was found that the range of compliant sources was extremely small, from 4976 to 5028 K. As seen in the inset, this amounts to a difference in emission of only 0.5% at 500 nm. In this regard it seems ISO 3664 tolerances might be unreasonably tight.

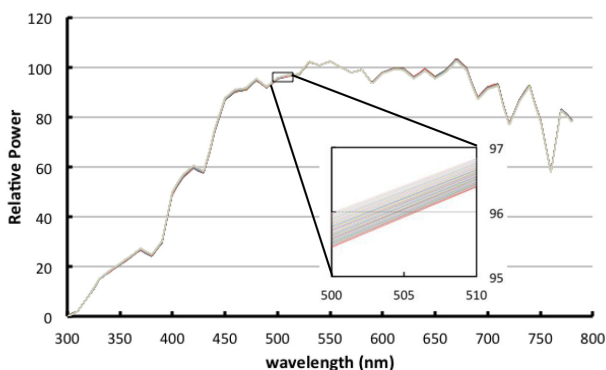


Figure 7. Relative spectral power distribution of M1 compliant CIE daylight.
The range of CCTs in this plot are 4976K to 5028K.

The results of this test are in the Figure 8. The plot shows CIELAB b^* vs a^* , and can be seen to be tightly clustered. A reasonable question is if these differences can be detected with the typical equipment. The right side of Fig 8 shows the 15a data on an expanded scale. The cross in the center indicates the length of one standard deviation of 50 replicate measurements with one modern M1 compliant instrument. The a^* range is too small, and well inside the 1σ limits, while the b^* range is likely large enough such that the instrument could differentiate between the colors.

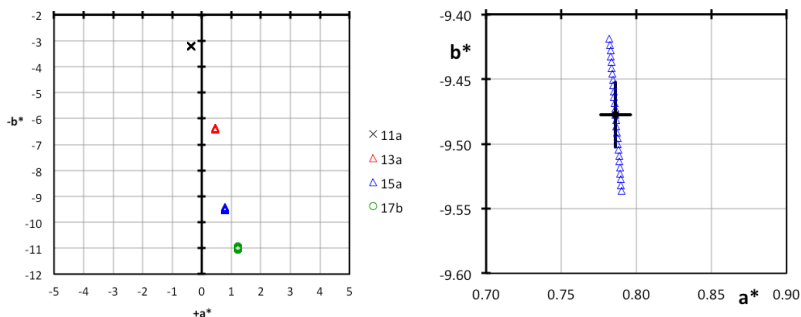


Figure 8. CIELAB b^* vs a^* for the spectra shown in Figure 7. Left are for all four FTS tiles.
Right shows the data for FTS-15a with expanded axes.

The second method of source simulation in Experiment 2 was to scale the UV component of D50 and examine the range of colors produced when these sources are used to virtually illuminate the FTS tiles. Figure 9 shows the set of M1-compliant sources generated with this method.

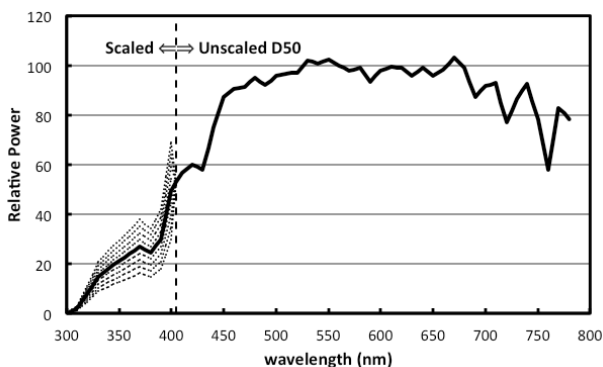


Figure 9. Spectra generated with method 2 of experiment 2. The region at and below 400nm was scaled up and down 40%; past that limit the source no longer was M1 compliant.

As with the first method, these spectra were used to virtually illuminate the FTS tiles and the resulting reflected radiance and CIELAB were calculated. The b^* vs a^* plot for these calculations is below in Figure 10.

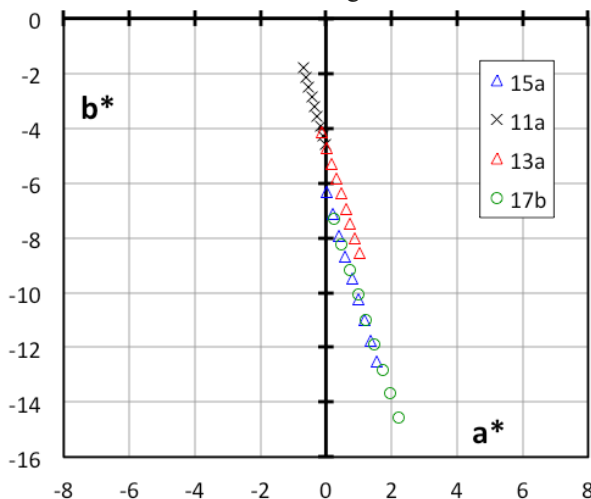


Figure 10. Colors generated with method 2 of experiment 2. The large range of compliant UV component has results in a correspondingly large range of colors, especially along the b^* axis.

The range of CIELAB values in Fig 10 will be quite obvious to any color-critical observation, and equally easy to detect with any of the instrumentation discussed in this article.

Conclusions

This paper set out to consider two questions: 1) Are ISO 3664 and ISO 13655 adequate for the evaluation of instrument sources? and 2) Using various hypothetical instrument sources how do measurements of the acrylic standards compare? The first question, addressed in experiment 2, showed that the color difference resulting by applying various M1 compliant sources to FTS acrylic standards is significant. This is especially true for sources stretching the limits of UV content permitted in ISO 3664. A more UV-sensitive definition for M1 needs to be determined. The constraints applied to the visible portion of the spectrum are likely sufficient, but the UV component is too open, resulting in these large colorimetric errors. Any new constraints will necessarily be confounded with the types of optical brighteners used, in particular the shape and location of their excitation regions, making the adjustment of this specification a very difficult one.

The second question, addressed in experiment 1, showed that the selection of different source technologies can impact the colorimetric differences when those sources are applied to commercial papers and the FTS standards. Implementing the “dual flash” correction will improve, but possibly not eliminate these differences. Also, given the range of colors measured from the five M1 compliant commercial spectrophotometers, some additional constraints are needed for the specification of that compliance for instruments. As with the conclusions for question 1, there is again a confounding of instrument source and sample fluorescent properties. Without industry convergence on optical brighteners (which the authors are not advocating) instruments with different source configuration are likely to continue to measure fluorescent materials differently.

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