International Color Consortium®

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ICC Recommendations for Color Measurement

Introduction

In order to achieve the highest quality results in color management systems including (and not limited to) those using profiles constructed according to the ICC standard, it is essential to measure color accurately and consistently.

CIE, the International Commission on Illumination, has published various recommendations for color measurement, as well as calculation procedures that can be used for this task. The calculation procedures have been extended in various ISO and ASTM standards. So, users of colorimetry are often confronted with various measurement recommendations which may seem appropriate for their task, each of which could give rise to a different colorimetric result.

It is important, then, that measurement procedures be more uniquely and unambiguously identified, to ensure consistency between users and instrument configuration. This White Paper summarizes the issues users should consider when making color measurements for the purpose of constructing ICC profiles, and describes the recommended practices.

Reflecting media

The International Organization for Standardization (ISO) standard ISO 13655 specifies how color measurements and calculations for use in Graphic Technology are to be conducted. This specification is the basis of the measurement procedures specified by the ICC. ISO 13655 requires that the instrument geometry be either 0:45 or 45:0 and that all calculations of tristimulus values be achieved using the CIE 1931 Standard Colorimetric Observer, which assumes a 2 degree field of view. ISO 13655:2017 also calls for using CIE illuminant D50 for the computation of colorimetric values and defines spectral weighting functions derived from this observer and illuminant. These weighting functions should be used when measurements are made with a spectrophotometer or spectroradiometer in which the spectral sampling interval is coarser than that specified by CIE. (The CIE specifies a sampling interval of less than or equal to 5 nm).

However, strict adherence to the ISO 13655 requirements and recommendations is not always appropriate when making measurements intended for use in developing the characterization data required for the construction of ICC profiles.

ICC color management will produce the most visually accurate results when , colorimetry is measured using the geometry, illumination and backing that will be used in practice, i.e. when the reproductions are viewed by an observer. However there are other considerations. The measurement condition may need to be different from the actual viewing condition to address measurement device shortcomings and/or interoperability considerations. For example, in order to construct ICC profiles that are most suitable for general use, the measurement condition should correspond to the most favorable practical viewing condition for a particular medium. This is why the 0:45 or 45:0 measurement geometries are specified for reflection media, even though light booths typically result in higher levels of veiling glare.

Ideally, the measurement and viewing conditions would both correspond to the most favorable practical conditions, as specified in ISO 13655 and ISO 3664. In cases where such measurements will not produce the desired results, the measurement condition should correspond as closely as possible to the actual viewing condition. When a profile is constructed based on non-standard measurement conditions, the measurement conditions (observer, backing, geometry, flare and illuminant) should be indicated in the measurementTag. For example, the difference between the veiling glare measured in the actual condition and in the standard condition should be encoded in the measurementTag as the measurement flare.

ISO 13655: 2017 defines multiple illumination conditions for different applications. These conditions are referred to as M0, M1, M2 and M3. It also permits the use of a white sample backing, which is consistent with best practice in making ICC profiles.

This White Paper seeks to clarify how the measurement conditions defined in ISO 13655:2017 should be applied for profile making purposes, as well as providing recommendations regarding other aspects of measurement.

Fluorescence

Most printing substrates in common use contain optical brighteners which cause them to fluoresce when illuminated by a source containing ultra-violet (UV) radiation.

Older instruments used in the graphic arts workplace relied on tungsten or tungsten-halogen light sources. Although these lamps emit substantially less UV than is specified in CIE Illuminant D50, they will still cause excitation of fluorescing materials. Modern instruments have shifted to LED or tungsten with enhanced LED illumination, or to filtered tungsten, in order to more closely achieve the spectral power of D50.

In practice, most indoor viewing environments in which colour reproductions are viewed outside of viewing booth have little UV present in the illumination.

ISO 3664 recommends that viewing booths for assessing proofs and prints have an illumination source corresponding closely to D50, which is defined by the CIE over the range 300-780nm.

ISO 13655 defines measurement conditions M0-M3. M0 is ideally CIE Illuminant A, but is not precisely defined and the relative amount of UV is unspecified. Measurement condition M1 requires a match to the CIE Illuminant D50 over the full range from 300nm, either by matching the relative spectral power distribution throughout the range or by a controlled adjustment such that the relative amount of power over the range 300-400nm corresponds to that of D50. Measurement condition M2 is defined as any illumination source that excludes the UV component, while condition M3 corresponds to a polarized source that suppresses gloss.

It should be noted that UV filters absorb light below a certain wavelength, typically around 400nm. However, the filters used for this purpose do not have a perfectly square cut-off and hence permit a proportion of UV below 400nm to reach the sample. Moreover, fluorescing materials are excited to some degree by light energy above 400nm. Consequently, exclusion of the UV may not completely eliminate fluorescence effects.

UV-excluded measurements of fluorescent materials will not correspond well with visual observations when using a viewing booth which simulates the D50 spectral power distribution in the UV region.

For this reason, and following the principle that the measurement condition should be as close as possible to the intended viewing condition, measurement condition M1 is recommended when proofs and prints are to be assessed in a viewing cabinet conforming to ISO 3664:2009. Otherwise, if the intended end use viewing condition does not have significant UV, or is unknown, measurement condition M2 is recommended.

Since measurements made according to M1 and M2 conditions will normally differ when measuring fluorescent samples, characterization data should always specify which condition was used. Profiles made from M1-measured data should ideally be evaluated through measurements made using an M1-conforming instrument, and similarly profiles made with M2-measured data should be evaluated through measurements made with a UV-excluding instrument.

M1 measurements may not be appropriate for profiling purposes where there are significant differences in fluorescence between the substrates used for proofing and printing. If relative colorimetry is used, which normalizes the data to the substrate, the normalization procedure can introduce unacceptable differences between the ink colors. The normalization is avoided by using the ICC-absolute colorimetric rendering intent, but this choice can lead to unacceptable highlight clipping. In this situation the best choice may be to reduce the difference in the measurements of the substrates by excluding the UV through the use of measurement condition M2.

Measurement condition M0, which does not define the spectral power of the instrument

source, is applicable to measurements made with instruments which do not conform to conditions M1-3.

Backing

ISO 13655:2017 allows both white and black backings when making color measurements for Graphic Arts. The effect of a black backing on a substrate that is not completely opaque is to reduce the color gamut (including the dynamic range). Although it can be argued that a black backing is a better match to the way that a print is intended to be viewed, the experience of many ICC members is that it is better to use a white backing for measurements. Hence, ICC recommends the use of white backing for the general case when measuring samples for making profiles.

The full description of the recommended white backing material is given in ISO 13655:2017, which tightened the requirements from 13655:2009 by providing a spectral reflectance range. Essentially the requirements are it should be opaque, diffusely reflecting, and with a C* chroma value not exceeding 2.4.

Polarization Filters

Some measuring instruments allow the user to polarize the incident beam to reduce the effect on the measurement of gloss changes following printing, as specified in ISO 13655:2017 measurement condition M3. In such instruments, a second polarizer is placed in the reflected beam in an orthogonal or “crossed” orientation and can largely remove the specular veiling glare reflections that change their characteristics as inks dry. While including these reflections may provide a better indication of the perceived final result, it can present problems in process control where measurements may be compared between prints where the ink is dry and those where it is still wet to some degree. The use of polarization filters largely eliminates the measurement differences that can arise between such samples, which can be beneficial in process control. However, since the properties of such polarization filters are undefined and vary between instrument models, the use of such filters tends to result in a reduction in inter-instrument agreement. More importantly, the use of polarizing filters removes the veiling glare present in the 0:45 and 45:0 measurements, decreasing the correspondence with visually observed results.

The ICC recommends that polarization filters should be removed, and instruments with polarization that cannot be removed should not be used. Time should be allocated to ensure that the print is properly dry before making measurements. In some cases, the drying time required to stabilize color measurements is longer than might be expected from just observing the surface gloss or tackiness. A 24 hour dry time, with unrestricted air flow, should be considered the minimum for inkjet prints. It is the experience of some ICC professionals that the use of M3 may be valuable on highly textured materials that also have gloss – the polarization can then help eliminate the veiling glare of the surface in this very specialized use case.

Number of measurements

Two significant issues must be addressed when making measurements for the construction of profiles:

- Printer consistency and uniformity, and
- Errors during measurement.

Averaging multiple measurements can minimize the impact of both factors.

A profile is appropriate for the condition obtained by the calibration of the printer at the time the profiling target was printed. But for many printers, however carefully they are calibrated, some variation will occur over time. The ideal profile should reflect the ‘mean’ of this variation, minimizing its effect by averaging measurements from a number of prints made during a reasonable time period.

Some printers, particularly offset printing presses, can suffer from a lack of uniformity over the sheet. In part, this is caused by the ink coverage in other parts of the sheet. In an attempt to minimize the effect of this variation, some profiling targets are ‘randomized’ to avoid relatively large areas of each ink being localized on the print. If available, ICC recommends the use of randomized targets. When they are not available or when the potential printed area is much larger than the target, measurements should be made of multiple targets taken from different positions on the sheet, with various orientations of the target. These should be averaged to obtain the data to be used for constructing profiles.

Errors may arise during measurement, due to operator error or poor instrument repeatability. To minimize the effect of these errors, ICC recommends the average of a number of measurements of each patch of the target be used when making profiles.

These are recommendations for the “ideal” situation. How many measurements need to be averaged depends on the consistency and/or uniformity of the printer, the instrument repeatability and/or competence of the operator. Prior knowledge of the significance of these factors may permit single measurements to suffice – however, without that knowledge multiple measurements should be averaged as described here.

An advantage of basing profiles on well-prepared measurement data, which result from averaging multiple printed samples and multiple measurements, is that the forward and inverse transforms tend to be significantly more accurate.

Measurement and calculation procedures for transmitting media

The recommendations of ISO 13655 should be followed when measuring transmitting media, with the exception of the illumination source UV content, which is generally less critical as transmitting substrates with fluorescence are uncommon.

ISO 13655 specifies that the measurement geometry for transmitting media should be either 0:diffuse or diffuse:0. If an opal glass diffuser is used, it should conform to that defined in ISO 5-2. The procedure for the calculation of tristimulus values should be the same as for reflecting media.

The recommendations as to averaging a number of measurements should be consistent with those recommended for reflection media, except where the image being measured is a commercial target for profiling input devices such as scanners, in which case the values provided by the target manufacturer should generally be used.

Measurement and calculation procedures for color displays

ISO 13655:2017 addresses the measurement of self-luminous sources, such as color displays. Many other standards or recommendations also do so, including CIE Publication 122, IEC 61966 (parts 3 to 5), and the ASTM standards E1336 and E1455. These specifications recommend measurement procedures as well as measurement instrument characteristics. Among them they cover measurements obtained with both spectroradiometers and tristimulus colorimeters. Measurements of displays should be consistent with the recommendations made in the standards appropriate to the type of display and/or measurement device used. If the measurement instrument is in conformance with these standards, then the user need address only a relatively small number of issues.

Care should be taken when making measurements to ensure that the sampling frequency, or integration time, of the instrument used is synchronized with the frequency of scanning of the display. If not, at least 10 measurements should be taken and averaged.

Although the use of telespectroradiometers or telecolorimeters for measurement from the viewer position is often advantageous, they are not in common use among those building profiles. ICC recommends that they be used whenever possible for display measurements, as they will include any veiling glare present, and therefore provide an accurate representation of the color as perceived by the viewer. Where such instruments are not available, and measurements are made in contact with the face of the display, some attempt should be made to measure the veiling glare [defined in ISO 22028-1 as ‘light, reflected from an imaging medium, that has not been modulated by the means used to produce the image’] from the viewer position, so the result can be used to correct the contact measurement data obtained. If a telespectroradiometer or telecolorimeter is not available, a spot light meter can be used to get the approximate ratio of the luminance of the display faceplate, as observed from the viewer position, with the ambient illumination on and off. This ratio can be used to estimate the veiling glare from the display black contact measurement. The contact measurements are corrected by adding the veiling glare to them, typically assuming the veiling glare has the same chromaticity as the display white point for simplicity. If it is not possible to obtain any estimate of the veiling glare, the contact measurements should be corrected by assuming a veiling glare of 1cd/m². However, users should be aware that this level of glare may not be correct for their specific viewing conditions, which is why the two

previously described methods are preferred.

Where display-profiling software allows users to specify the veiling glare as part of the input for profile construction, the software should perform the data correction. When this is not the case, the user will have to correct the data prior to building the profile.

It should be noted that in this context, veiling glare refers to the ambient light reflected from the display faceplate in the direction of the viewer. It does not refer to flare internal to the display, which should be included in contact measurements if measurement patches are displayed with an appropriate surround. It also does not refer to any flare that may result from ambient illumination ─ not from the display ─ entering the measuring instrument or eye, as this type of flare is not supposed to be included in profiles and, if present, should be removed from measurement data before it is used for profile construction.

It should also be noted that most instruments in practical use for the measurement of displays for characterization and profile building do not measure very accurately at low luminance levels. For this reason the black point (and commonly the 8-bit digital counts below 32) are often estimated rather than measured, as this ensures smooth transitions in dark shadows and a more consistent black point value. Where instruments that can measure luminances of 1.0 cd/m² with sufficient accuracy are available, it is preferable to use the measured viewer-observed black point in place of an estimate. A value of 1.0 cd/m² is recommended as a default estimate of black point luminance with flare, but if the viewing conditions are well defined a more accurate estimate can be used instead.

Since these recommendations result in the inclusion of some veiling glare in the measurement data, it is essential that the display measurement conditions, including the ambient illumination, are appropriate. When constructing profiles for general use, the display viewing conditions should meet the requirements and recommendations of ISO 3664, corresponding to the most favorable practical conditions (comparable to the 0:45 and 45:0 geometry for reflection media). In cases where such measurements will not produce the desired results, the measurement condition should correspond to the actual viewing condition. When a profile is constructed based on non-standard viewing condition measurements, the measurement conditions (observer, geometry and flare) should be indicated in the measurementTag, the display white point luminance should be indicated in the luminanceTag, and the display white point and surround tristimulus values (absolute, not normalized) should be indicated in the viewingConditionsTag.

Measurements of the display should be made to ensure acceptable levels of constant channel chromaticity, spatial uniformity, internal flare and channel independence. Those displays exhibiting poor uniformity or high levels of internal flare should be avoided, or care taken to average measurements made with varying image surround and/or position. For displays with inconsistent channel chromaticities, or poor channel independence, profiles should be based on n-component LUT rather than three-component matrix.

When spectral data is obtained during measurement, the CIE 1931 Standard

Colorimetric Observer (2 degree) should be used for the calculation of tristimulus values. Spectral data should be obtained at wavelength sampling intervals of no more than 10nm. In some cases finer sampling intervals will be required to obtain sufficient colorimetric accuracy, as some display primaries exhibit spiky spectra.

When using a telespectroradiometer, measurements should be taken from a display area of at least 4mm in diameter with an angle of collection of 10^{o} or less.

Averaging measurements to minimize the effects from poor synchronization of the scanning frequencies and measured sampling intervals, and poor uniformity or internal flare has already been described. Averaging to avoid measurement errors should also be undertaken, including where multiple measurements are not required because of good synchronization between display scanning frequency and measurement sampling interval.

Summary of the recommendations

The recommended measurement conditions and procedures described above are summarized below:

- Reflectance and transmittance measurements of non-fluorescent media should conform to ISO 13655 measurement conditions M1 or M2. The exception is when the actual illumination will be significantly different from D50. In this case, the profile construction should use the colorimetry corresponding to the actual illumination.
- Where the substrates used fluoresce and the end use viewing condition includes a significant amount of UV, the ISO 13655 M1 condition, in which the measurement source effectively matches CIE illuminant D50, should be used.
- Where the substrates used fluoresce and the end use viewing condition does not include a significant amount of UV, the ISO 13655 M2 condition, in which UV is excluded, should be used.
- The use of M1 or M2 measurement conditions should be reported when exchanging measurement data or profiles made using such data.
- For reflectance measurements a white sample backing is recommended.
- For reflectance instruments the use of polarizing optics should be avoided.
- For displays, measurements should conform to section 4.4 of ISO 13655:2017 and be performed in a viewing environment meeting the requirements and recommendations of ISO 3664:2009. Additionally, display measurement instruments should be consistent with the recommendation of CIE Publication 122, IEC 61966 (parts 3 to 5), or the ASTM standards E1336 and E1455. Measurement should be made with a telescopic instrument at the viewer position, but where this is not possible, and the measurement is made using an instrument in contact with the face of the display, the veiling glare at the viewer position should be measured. If this cannot be done a veiling glare of $1 cd/m^2$ should be assumed.
- When contact measurements are made of displays, the veiling glare should be used

to correct the data prior to profile construction, unless profile building software allows this as a separate input. Multiple measurements should be made to minimize the effect of poor synchronization between the display scanning frequency and measurement integration time.

- For all media, multiple measurements of each patch should be averaged. The extent of this should be consistent with the uniformity and/or temporal consistency of the device, and temporal consistency of the measurement instrument and/or operator.
- For all media, measurements should only be made in non-standard conditions when doing so is necessary to match the actual or anticipated viewing environment. When non-standard measurements are used for the construction of ICC profiles, the measurement conditions should be indicated in the measurementTag, the luminanceTag, and the viewingConditionsTag, as appropriate. Furthermore, profiles constructed based on non-standard measurements should be easily identifiable as such by the profile description.