ICC Technical Note

Recommendations on calculation of tristimulus values

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Introduction

CIE tristimulus values are defined as the result of integrating the colorimetric observer, illuminant and spectral stimulus function. In practice CIE XYZ values are calculated by summation of the product of observer, illuminant and stimulus function at finite wavelength intervals. [1]

CIE 15 [1] defines the procedures for calculating XYZ values. However, CIE 15 provides some flexibility with the result that there can be different XYZ values calculated from a given spectral stimulus function, depending on the implementation. The goal of this white paper is to make recommendations that incorporate current best practice and reduce the possible differences between valid calculation methods.

ICC.1 [2] is based on a unitary profile connection space, with a well-defined observer and illuminant. This unitary PCS enforces a precise definition of colorimetry on all PCS data, removing any possibility of ambiguity when connecting source and destination. Other illuminants and observers are supported; for the former, a simple and well-defined chromatic adaptation transform to the PCS is defined [3][4], while for the latter a Waypoint estimate [5] is recommended.

ICC.2 [6] introduced the concept of alternate connection spaces, making it possible to connect between different 'flavours' of stimulus (including colorimetry, spectra an, bi-spectra and material) either directly or via a suitable transform. This gives the user the potential freedom to select the properties of the connection space, and thus optimise for a particular application. To minimise the risk of ambiguity in the resulting colorimetry, ICC makes a number of observations and recommendations regarding the data and transform procedures.

1. Illuminant

The ICC.1 PCS is based on the CIE D50 illuminant, and colorimetry which employs a different illuminant can be converted to D50 using the Linear Bradford CAT, as described in ICC.1 Annex E [2]. If the measured spectra are available, a better procedure is to simply use D50 as the illuminant in calculation of colorimetric values. Where measured spectra are not available, it should also be noted that good results can obtained by spectral estimation from colorimetry calculated using a different illuminant [7].

In colorimetry, the illuminant represents an intended reference viewing condition. ICC.2 permits the use of alternate illuminants in PCS colorimetry, which may be appropriate in industries using a different reference illuminant or where it is desired to match the spectral power distribution of the actual viewing condition.

Certain materials, including most white papers and textiles, contain optical brighteners which cause incident energy to be re-emitted at longer wavelengths. For this reason, illuminants are usually defined from 300nm, even though there is no visual response below approximately 380nm, and the range over which colour matching functions are defined typically begins at 360 or 380nm.

ICC recommends that the illuminant used in colorimetric computation is defined over the same range as the spectral tristimulus function or weighting function used; if the reference illuminant is defined over a wider range it can be clipped, while if defined over a narrower range a third-order interpolation should be applied to compute values for the missing intervals, at both short and long-wavelength ends of the function. When a 'no-UV' illuminant is used, the illuminant spectral power should be set to zero for the wavelengths defined to be in the UV-suppressed region of the reference illuminant.

2. Observer

CIE 15 provides spectral tristimulus functions for 1931 and 1964 observers [1]. While the 1931 observer is standardised in graphic arts and in ICC colour management, in other industries (including the paper and display industries) the 1964 observer is more widely used. More recently, a spectral tristimulus function based on a modification to the spectral sensitivities of the 1964 observer [8] has been adopted by CIE, since it has been shown to be more physiologically accurate and to correct for an error in the photopic luminous efficiency function which particularly affects the relative S-cone response and hence the CIE Z value [9][10]. CIE TC1-36 is currently working to derive new XYZ colour matching functions that are a linear transform of the modified spectral sensitivities.

Differences between original and new CMFs, using 1269 Munsell reflectances and D65 illuminant, have been found to be a maximum of 0.02 CIELAB ΔE^*_{ab} units [11].

Where compatibility with ICC.1 is required, it is recommended that users either use the 1931 observer or apply a suitable transform in the profileConnectionConditions so that the PCS data is identical to that in ICC.1

In other situations the user has a choice of observer, which could include the 1964 or 2015 observer, or a custom observer based on either a directly-measured or categorical colour matching function. Where accurate prediction of response is the main criterion, and individual variation colour matching functions are not taken into account, it is expected that the 2015 observer would give the best results.

3. Range

The long, middle and short wavelength cone fundamentals peak at 570nm, 543nm and 442nm respectively [8], and fall to zero at the edges of the range. A calculation made over the range 400-700nm may therefore not be result in significantly different tristimulus values from one made over a wider range, such as 380-780nm. However, in the interests of consistency it is useful to define a standard method to handle differences between the range of the spectral tristimulus function and that of the measurement. CIE suggests a number of possible methods [1], the simplest being to extend the last known data point in the measured data to the full range of the spectral tristimulus function.

ICC recommends that measured spectral stimulus data be extended to the range of the spectral tristimulus function or weighting function by extending the last known data point.

However, exceptions may apply when the measured spectral stimulus is known to have peaks close to one or other end of the range.

ICC.2 supports communication and exchange of data with arbitrary ranges [2]. In some cases this may involve data outside the visible range, or the range over which the spectral tristimulus function is defined: for example, a MID profile connecting to a Material Connection Space may support data in the UV or IR regions for the purpose of material identification.

4. Interval

Most surface colours have smooth spectral reflectances without sharp peaks, and the choice of interval is less critical than for displays. Widely-used spectrophotometers have a measurement interval of 10nm, which is sufficient to characterise the reflectance of the material. Such instruments typically integrate the signal over a small set of narrow bandpasses.

Self-luminous colours, on the other hand, typically have extremely narrow peaks whose magnitude, width (FWHM) and centre wavelength (CWL) depend on the technology used.

The reference calculation defined by CIE is based on wavelength intervals of 1nm, and procedures are given for a 5nm-interval calculation, including the provision of a 5nm observer function [1]. However, many instruments have a measurement interval which is neither 5 nor 1nm, and moreover have a bandpass function which may be different from the assumption behind the continuous CIE observers.

CIE does not provide precise guidance on how to use spectral measurement data with different intervals, but suggests that Sprague interpolation can be used to calculate equivalent 1nm data. This would add considerably to the computational cost of calculation, since it has to be done for each measured spectral stimulus, and can also introduce a source of uncertainty if different calculation procedures are followed in the interpolation. The alternative is to compute a weighting function for a given combination of observer and illuminant, which can then be applied to the measured spectral stimulus.

ICC recommends the use of suitable weighting functions when calculating tristimulus values with intervals that are not 1 or 5nm. If no suitable weighting function is available, ICC recommends that measured spectral stimulus values be interpolated to 1nm using Sprague interpolation as recommended in CIE 167.

ICC recommends that where it is critical that the spectral stimulus function of a self-luminous display be accurately recorded and exchanged, the measurement interval is no greater than 5nm, and preferably 1nm or less.

5. Weighting functions

Several methods of generating weighting functions have been described. Functions published in ASTM E308 [12] are widely used, and include all combinations of nine illuminants (no LED), 10 and 20nm intervals, and 1931 and 1964 observers. The 1931 observer/D50/10 and 20nm functions are incorporated into ISO 13655 [13] and form the basis of current graphic arts colorimetry. Li, Luo, Melgosa and Pointer [14] evaluated a wide range of different methods, and found that a least-square method performed best, in terms of agreement with CIE reference calculations at 1nm.

CIE TC-102 is currently evaluating methods of calculating tristimulus values, and in particular the performance of different weighting functions. Pending the outcome of this work, it can be said that the least-squares method published by Li et al represents the state of the art and the best agreement with CIE reference calculations.

Where compatibility with ICC.1 is required, it is recommended that colorimetric PCS data continues to be based on the weighting functions defined in ISO 13655. In other situations ICC recommends the use of weighting functions computed by the Li et al least-squares method, with the choice of interval, observer and illuminant that is most suitable for the application.

ICC intends to work with CIE to make such weighting functions more widely available. The colorimetry page on color.org (https://www.color.org/chardata/colorimetry/) contains pointers to CIE data tables for observers and illuminants, and also weighting functions computed using the Li et al method.

For more information on weighting functions for calculation of XYZ tristimulus values, see ICC White Paper

6. References

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