



Tristimulus Calculation

Emeritus Professor Phil Green, NTNU

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Introduction

Calculation of XYZ tristimulus values is defined by CIE

$$X = k \int S(\lambda) \rho(\lambda) \bar{x}(\lambda) d\lambda$$

$$Y = k \int S(\lambda) \rho(\lambda) \bar{y}(\lambda) d\lambda$$

$$Z = k \int S(\lambda) \rho(\lambda) \bar{z}(\lambda) d\lambda$$

Summation at finite intervals is used in place of integration for practical purposes, e.g.

$$X = k \sum_{\lambda=380}^{780} S(\lambda) \rho(\lambda) \bar{x}(\lambda)$$

$$Y = k \sum_{\lambda=380}^{780} S(\lambda) \rho(\lambda) \bar{y}(\lambda)$$

$$Z = k \sum_{\lambda=380}^{780} S(\lambda) \rho(\lambda) \bar{z}(\lambda)$$

Ideally this is at the smallest possible interval to ensure best correspondence with values obtained by integration: 1nm



Observers and illuminants

CIE defines spectral tristimulus values (aka colour matching functions (CMFs), colorimetric observers, or ‘observers’), at 1 and 5nm.

- **1931**
- **1964**
- **2015**

CIE defines a range of illuminant spectral power distributions

Also at 1 and 5nm

Spectral ranges vary

All data is available under CCBY license at <https://cie.co.at/data-tables>



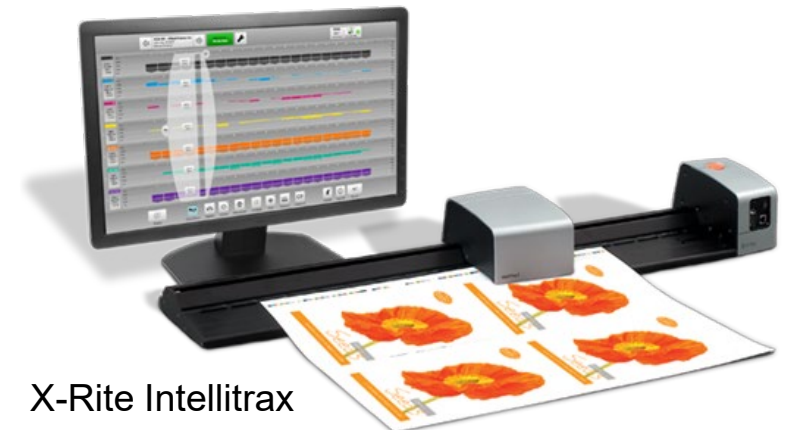
Issues

In industry, the measurement interval is usually larger (typically 10nm) and the range smaller than CIE recommendations

- **Interval:** CIE does not currently recommend a method of tristimulus calculation for intervals other than 1 and 5nm
- **Range:** Various methods are available for handling mismatched data ranges; the most common being to extrapolate the measurement data range to the range of the colour matching function
- **Calculation:** Different methods of calculation are possible, but these can give different results



Barbieri LFP qb



X-Rite Intellitrax



Example of calculation differences

Differences in the D50 illuminant XYZ

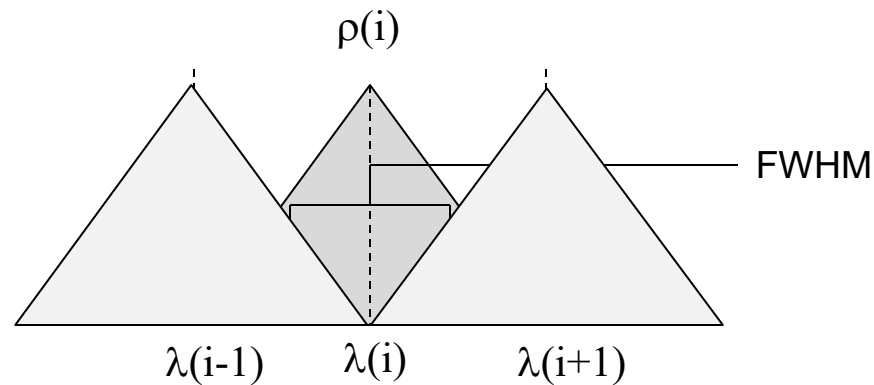
	X	Y	Z
Calculated at double precision according to CIE 15	96.419865576090	100	82.511648322104
Specified by CIE 15.2 (and ICC)	96.42	100	82.49
Specified by CIE 15: 2004	96.42	100	82.51
16-bit fractional approximation of CIE 15.2	96.420288085938	100	82.489013671875
Calculated according to ISO 13655	96.422	100	82.521

The difference between CIE 15.2 and the double precision calculation according to CIE 15 is ΔE^*_{ab} 0.018

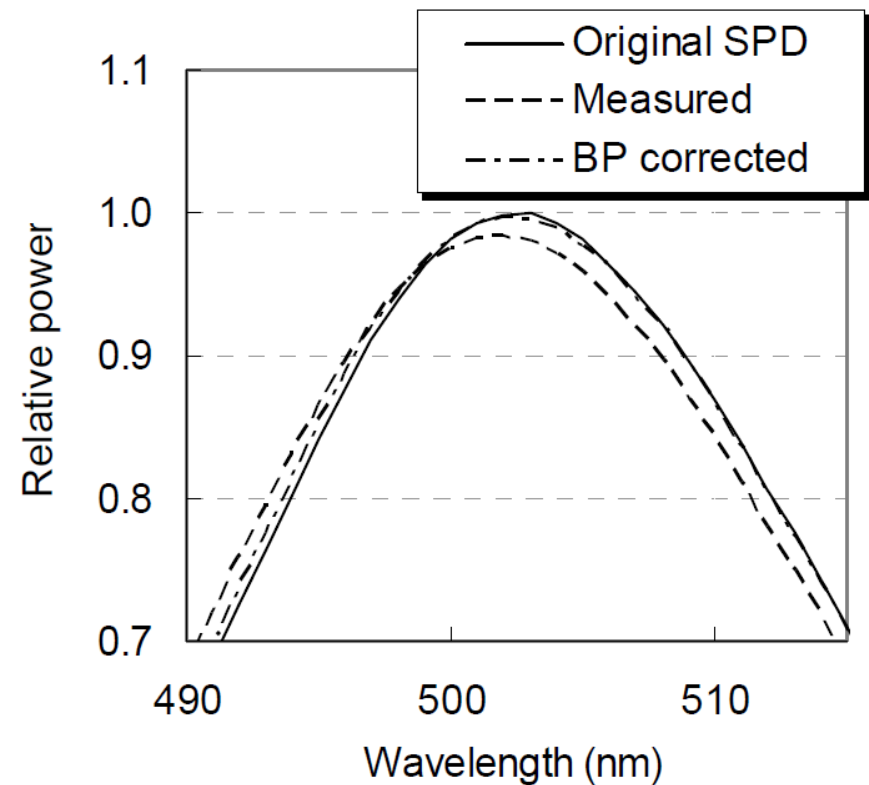


Bandwidth, sampling and bandpass correction

In many measurement instruments the sampling (or scanning) and reporting intervals are different
The instrument function is usually assumed to be symmetric triangular over a given bandwidth



When the bandpass is widened, the spectral data will not agree with 1nm data unless a bandpass correction is applied





Methods for handling intervals $\neq 1$ or 5nm

Direct selection

Select intervals from the CMF corresponding to the measurement intervals

- *Gives large errors*

Interpolation of R

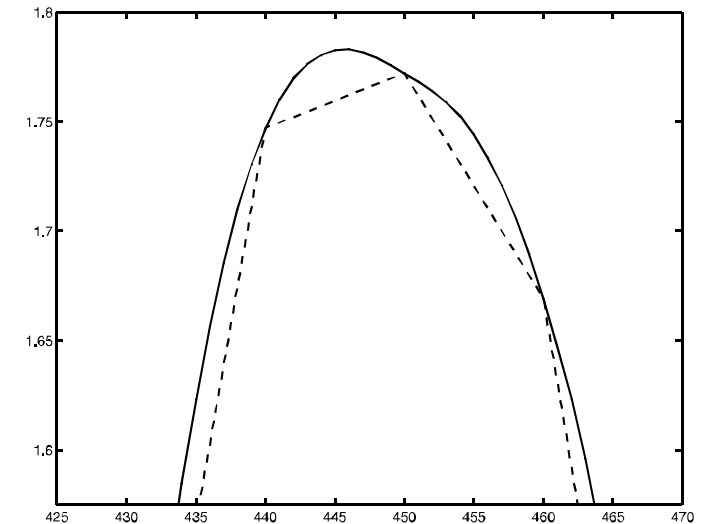
The spectral reflectance is interpolated to the desired interval using Sprague interpolation

- *Involves additional computation per measured sample and gives errors*

Weighting table

The CMF is re-computed for the new interval and a given illuminant

- *Minimises errors and simplifies the calculation*





Weighting tables

A weighting table is calculated to optimize the match between XYZ calculated at 1 and n nm, where n is any number $\neq 1$ or 5

Thus:

$$X = \sum_l^u S(\lambda) \bar{x}(\lambda) \rho(\lambda)$$

becomes:

$$X = \sum_l^u w_x(\lambda) \rho(\lambda)$$

where w_x is the vector of optimized weights for a given illuminant S and spectral tristimulus vector $\bar{x}$

A weighting table can also

- optimise the match between XYZ calculated at 1nm over the full range 380-780nm (where missing data is provided by extrapolation) and XYZ calculated at interval n nm over a different range
- incorporate bandpass correction



CIE TC1-102

CIE TCs have been considering methods of tristimulus calculation

The goal is a unified method which can be applied to reflectance or transmittance data of different intervals and ranges, eliminating differences in tristimulus values arising solely from the method of computation

TC1-102 has examined different methods of handling measurement intervals and ranges. It has made recommendations on the calculation of weighting tables and the extrapolation of data



Changjun Li, CIE TC1-102 chair



TC 1-102 status

Final report is approved by TC ballot

- Report will be published in due course by CIE
- Includes worked example and procedure for least-squares calculation of weighting tables using Cholesky decomposition
- Weighting tables will be published at <https://cie.co.at/data-tables>



ICC and spectral data

ICC profile specification:

Colorimetric Profile Connection Space based D50 illuminant, 1932 observer.

iccMAX

Colorimetry can be any illuminant and observer

Spectral connection possible:

- Spectral to spectral (with conversion between interval and range)
- Spectral to colorimetric (for any illuminant and observer)
- Colorimetric to spectral (via spectral estimation)





ICC and spectral data

Who needs spectral colour management?

Image acquisition

A number of user communities especially in cultural heritage and archiving are interested in standardizing spectral source data with embedded ICC profiles which give the conversion to colorimetry

Spectral reproduction

Finding the colorant combination (from a limited set) that gives the best reproduction of a given spectral reflectance





ICC and spectral conversion

All ICC / iccMAX profiles encapsulate transforms between colour spaces

When creating an iccMAX the user can select an arbitrary illuminant and observer (including a custom observer)

Data needed to build the transform can be specified by reference to an external file: a local file or a URL

To simplify spectral connection, ICC provides:

- Links to CIE observers and illuminants
- 10nm weighting tables for a range of observers and illuminants





ICC and weighting tables

ICC publishes a number of data registries

The Colorimetry Data Registry is at <https://registry.color.org/colorimetry-data/>

It provides pointers to the CIE illuminants and observers data sets on <https://cie.co.at/data-tables>

Following agreement by TC1-102 on the calculation method, and with agreement of CIE, ICC now also provides weighting tables (calculated by Tanzima Habib at NTNU) for the following:

Observers	Illuminants	Ranges
1931	A	380-780
1964	D50	380-730
2015	D65	
	LED B1	
	LED RGB	
	LED V1	



Colorimetry Data

CIE data

Data in this section is drawn from [CIE Datasets](#)¹ with permission of the CIE.

ICC.1 colour management assumes a fixed colorimetric PCS, with a D50 illuminant and CIE 1931 Standard Colorimetric Observer. In ICC.2 the profile creator can choose to apply different illuminants and observers when computing XYZ tristimulus values. For interoperability it is highly desirable that when profiles use such alternative data, the same values are used and that the values correspond directly to those defined by CIE.

Data is provided at 1nm or 5nm intervals, over the range 360-780 for observers and 300-780nm for illuminants (which ensures that any fluorescent excitation is included). Where the range or interval of the observer, illuminant or measurement data do not match, the procedures described in [CIE Publication 15](#)², should be followed.

The entries in the CIE Data Page column link to the information on the observer or illuminant on the CIE site, including data description, metadata and citation details. Metadata is available in machine-readable .json files.

Illuminant or observer	CIE designation	Interval (nm)	CIE data page
Illuminant	CIE standard illuminant D50	1	CIE standard illuminant D50 - 1 nm
Illuminant	CIE standard illuminant D65	1	CIE standard illuminant D65 - 1 nm
Illuminant	CIE standard illuminant A	1	CIE standard illuminant A - 1 nm
Observer	CIE 1931 colour matching functions, 2 degree observer	1	CIE 1931 observer - 1nm
Observer	CIE 1964 colour matching functions, 10 degree observer	1	CIE 1964 observer - 1nm



Weighting tables

CIE defines the calculation of colorimetric values at 1 and 5nm intervals². Many of the measurement instruments in common use in colour management output spectral data at 10nm intervals. Rather than calculate interpolated values for every measurement, it is recommended to use tabulated weighting functions which combine both observer and illuminant.

ISO 13655³ includes weighting tables for 10nm data, based on a table published in ASTM E.308⁴. This combines the D50 illuminant and the CIE 1931 standard colorimetric observer. These tables should be used for ICC.1 and for all cases where compatibility with legacy data is needed.

In ICC.2 the Profile Connection Space can be colorimetric or spectral, and profile connection conditions provide a mechanism to connect data with different observers or illuminants. In an ICC.2 workflow it is also possible to connect colorimetric and spectral data via estimated reflectances.

There are different methods of calculating weighting tables, and work by Li and others, (2016)⁵ showed that a least-squares method produced the best agreement with tristimulus values calculated with 1nm data. To support spectral connection in ICC.2, we provide a selection of weighting tables for different colorimetric observers (1931, 1964 and 2015⁷ and illuminants, at 10nm intervals, calculated using a least-squares method by Tanzima Habib, a researcher at NTNU, Norway, using the LWL method described by Li and others (2016)⁵ and revised by CIE TC1-102⁶.

TC1-102 recommends using the full range 380-780nm, linearly interpolating measurement data to this range as needed. An alternative method is to use tables calculated by the LWL method over a smaller range; results using this method will be almost identical. Tables below are given at 380-780nm, 380-730nm (commonly used in colour management) and for the 2015 observer 400-780 and 400-730nm (since the 2015 observer is only defined from 400nm).

Observer	Illuminant	Range	Weighting table	
1931	A	380-730	Wts-1931-A-380-10-730nm.csv	Wts-1931-A-380-10-730nm.csv
1931	A	380-780	Wts-1931-A-380-10-780nm.csv	Wts-1931-A-380-10-780nm.csv
1931	D50	380-730	Wts-1931-D50-380-10-730nm.csv	Wts-1931-D50-380-10-730nm.csv
1931	D50	380-780	Wts-1931-D50-380-10-780nm.csv	Wts-1931-D50-380-10-780nm.csv
1931	D65	380-730	Wts-1931-D65-380-10-730nm.csv	Wts-1931-D65-380-10-730nm.csv
1931	D65	380-780	Wts-1931-D65-380-10-780nm.csv	Wts-1931-D65-380-10-780nm.csv
1931	LED B1	380-730	Wts-1931-LED B1-380-10-730nm.csv	Wts-1931-LED B1-380-10-730nm.csv
1931	LED B1	380-780	Wts-1931-LED B1-380-10-780nm.csv	Wts-1931-LED B1-380-10-780nm.csv
1931	LED RGB1	380-730	Wts-1931-LED RGB1-380-10-730nm.csv	Wts-1931-LED RGB1-380-10-730nm.csv
1931	LED RGB1	380-780	Wts-1931-LED RGB1-380-10-780nm.csv	Wts-1931-LED RGB1-380-10-780nm.csv
1931	LED V1	380-730	Wts-1931-LED V1-380-10-730nm.csv	Wts-1931-LED V1-380-10-730nm.csv
1931	LED V1	380-780	Wts-1931-LED V1-380-10-780nm.csv	Wts-1931-LED V1-380-10-780nm.csv
1964	A	380-730	Wts-1964-A-380-10-730nm.csv	Wts-1964-A-380-10-730nm.csv



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Prof. Changjun Li, who led the CIE TCs studying this problem, and was the main author of many of the studies in this field and of the TC1-102 report

Dr. Tanzima Habib, who performed all the calculations for the ICC-published weighting tables

Other members of TC1-102

