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COMMISSION INTERNATIONALE DE L'ECLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

TECHNICAL REPORT

METHODS FOR RE-DEFINING CIE D ILLUMINANTS

CIE 204:2013

UDC: 535.625.45

Descriptor: Artificial Daylight

THE INTERNATIONAL COMMISSION ON ILLUMINATION

The International Commission on Illumination (CIE) is an organization devoted to international co-operation and exchange of information among its member countries on all matters relating to the art and science of lighting. Its membership consists of the National Committees in about 40 countries.

The objectives of the CIE are:

1. To provide an international forum for the discussion of all matters relating to the science, technology and art in the fields of light and lighting and for the interchange of information in these fields between countries.
2. To develop basic standards and procedures of metrology in the fields of light and lighting.
3. To provide guidance in the application of principles and procedures in the development of international and national standards in the fields of light and lighting.
4. To prepare and publish standards, reports and other publications concerned with all matters relating to the science, technology and art in the fields of light and lighting.
5. To maintain liaison and technical interaction with other international organizations concerned with matters related to the science, technology, standardisation and art in the fields of light and lighting.

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Les objectifs de la CIE sont :

1. De constituer un centre d'étude international pour toute matière relevant de la science, de la technologie et de l'art de la lumière et de l'éclairage et pour l'échange entre pays d'informations dans ces domaines.
2. D'élaborer des normes et des méthodes de base pour la métrologie dans les domaines de la lumière et de l'éclairage.
3. De donner des directives pour l'application des principes et des méthodes d'élaboration de normes internationales et nationales dans les domaines de la lumière et de l'éclairage.
4. De préparer et publier des normes, rapports et autres textes, concernant toutes matières relatives à la science, la technologie et l'art dans les domaines de la lumière et de l'éclairage.
5. De maintenir une liaison et une collaboration technique avec les autres organisations internationales concernées par des sujets relatifs à la science, la technologie, la normalisation et l'art dans les domaines de la lumière et de l'éclairage.

Les travaux de la CIE sont effectués par 7 Divisions, ayant chacune environ 20 Comités Techniques. Les sujets d'études s'étendent des questions fondamentales, à tous les types d'applications de l'éclairage. Les normes et les rapports techniques élaborés par ces Divisions Internationales de la CIE sont reconnus dans le monde entier.

Tous les quatre ans, une Session plénière passe en revue le travail des Divisions et des Comités Techniques, en fait rapport et établit les projets de travaux pour l'avenir. La CIE est reconnue comme la plus haute autorité en ce qui concerne tous les aspects de la lumière et de l'éclairage. Elle occupe comme telle une position importante parmi les organisations internationales.

DIE INTERNATIONALE BELEUCHTUNGSKOMMISSION

Die Internationale Beleuchtungskommission (CIE) ist eine Organisation, die sich der internationalen Zusammenarbeit und dem Austausch von Informationen zwischen ihren Mitgliedsländern bezüglich der Kunst und Wissenschaft der Lichttechnik widmet. Die Mitgliedschaft besteht aus den Nationalen Komitees in rund 40 Ländern.

Die Ziele der CIE sind :

1. Ein internationaler Mittelpunkt für Diskussionen aller Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik und für den Informationsaustausch auf diesen Gebieten zwischen den einzelnen Ländern zu sein.
2. Grundnormen und Verfahren der Messtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
4. Normen, Berichte und andere Publikationen zu erstellen und zu veröffentlichen, die alle Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik betreffen.
5. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

Die Arbeit der CIE wird in 7 Divisionen, jede mit etwa 20 Technischen Komitees, geleistet. Diese Arbeit betrifft Gebiete mit grundlegendem Inhalt bis zu allen Arten der Lichtanwendung. Die Normen und Technischen Berichte, die von diesen international zusammengesetzten Divisionen ausgearbeitet werden, sind auf der ganzen Welt anerkannt.

Alle vier Jahre findet eine Session statt, in der die Arbeiten der Divisionen überprüft, berichtet und neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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This Technical Report has been prepared by CIE Technical Committee 1-74 of Division 1 "Vision and Colour" and has been approved by the Board of Administration as well as by Division 1 of the Commission Internationale de l'Eclairage. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory.

Ce rapport technique a été élaboré par le Comité Technique CIE 1-74 de la Division 1 "Vision et Couleur" et a été approuvé par le Bureau et Division 1 de la Commission Internationale de l'Eclairage. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tous les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire.

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METHODS FOR RE-DEFINING CIE D ILLUMINANTS

Summary

This Technical Report gives an overview of the construction of the tables describing CIE D illuminants, and proposes two methods to smooth the daylight illuminant spectral power distributions. The first method keeps the values originally determined at the integer 10 nm intervals unchanged and interpolates between these fixed points to get smooth (twice differentiable) curves (minimal smoothing method). A second alternative method smooths more strongly, cutting fine structure maxima and minima of the spectrum (highly smoothing method).

Examples show the consequences of both methods, pointing out that smoothing has little influence on colorimetric accuracy.

The Technical Committee recommends testing the provided tables based on the two smoothing algorithms in practice and to urge users to test data of Table 4 which are based on the highly smoothing method, and ask instrument constructors to test the method for building D illuminant simulators with the eventual outcome of defining a CIE D50 and D65 standard source.

MÉTHODE DE REDEFINITION DES ILLUMINANTS D DE LA CIE

Résumé

Ce rapport technique fait le point sur l'établissement des tables définissant les illuminants D de la CIE et propose deux méthodes pour lisser la répartition spectrale d'énergie de l'illuminant lumière du jour. La première méthode préserve les valeurs fixées originellement tous les 10 nm et fait une interpolation entre ces points afin d'obtenir une courbe lisse et doublement dérivable (méthode de lissage minimal). Une méthode alternative lisse plus sévère, en rabotant les maxima et minima aigus de la courbe (méthode de lissage supérieur).

Des exemples montrent les résultats donnés par chaque méthode, soulignant que le lissage n'a que peu d'effet sur la précision colorimétrique.

Le comité technique recommande de tester dans la pratique les tables fournies par les deux algorithmes et d'inciter les utilisateurs à tester les valeurs du Tableau 4 qui sont basées sur la méthode de lissage supérieur, de demander aux fabricants d'instruments d'exploiter la méthode pour construire des simulateurs d'illuminant D avec la perspective de définir des sources de référence CIE D50 et D65.

METHODEN ZUR NEUDEFINITION DER CIE TAGESLICHT-LICHTARTEN

Zusammenfassung

Dieser Technische Bericht gibt einen Überblick über den Aufbau der die D-Lichtarten der CIE beschreibenden Tabellen. Es werden zwei Methoden zur Glättung der spektralen Strahlungsverteilung der Tageslichtarten vorgeschlagen. Die erste Methode lässt die Originalwerte im Abstand von 10 nm unverändert und interpoliert nur zwischen diesen Fixpunkten, um eine geglättete (zweimal differenzierbare) Kurve zu erhalten (Minimale Glättungsmethode). Eine zweite alternative Methode glättet strenger, indem die Strukturen feiner Maxima und Minima abgeschnitten werden (Höhere Glättungsmethode).

Beispiele zeigen die Auswirkungen beider Methoden, insbesondere dass die Glättung nur geringen Einfluss auf die farbmétrische Genauigkeit hat.

Das Technische Komitee empfiehlt, die für die beiden Glättungsmethoden erstellten Tabellen in der Praxis zu testen und Benutzer zu veranlassen, die auf der höheren Glättungsmethode basierenden Daten der Tabelle 4 zu prüfen, sowie die Gerätehersteller zu bitten, die Methode

zum Bau von Simulatoren der D-Lichtarten zu prüfen, mit dem möglichen Ergebnis, CIE-Normlichtquellen D50 und D65 zu definieren.

1 Introduction

Natural daylight was and still is the most common source of light in our environment. Our visual system likely evolved primarily for seeing under daylight conditions. It was thus natural that colorimetry should also use daylight as one of its primary illuminants. As documented in Clause 2, the present standard daylight illuminant has a long history, from the early artificial daylight source consisting of an incandescent lamp plus liquid filters to the modern daylight illuminants that exist only as spectral power distribution (SPD) tables. These tables originally contained the SPD at discrete 10 nm intervals, but the most recent official tables now contain SPD data that have been linearly interpolated for other wavelengths that fall between the original 10 nm locations. This has led to SPDs that change abruptly at the original locations and are straight lines between them. For many applications, where the energy in the source must be numerically integrated over the visible range of wavelengths, this interpolation has proved unsatisfactory, so CIE Division 1, at its meeting in 2008, decided to investigate this problem and requested the establishment of the following Technical Committee: CIE TC 1-74, *Methods for Re-defining CIE D Illuminants*. The Terms of Reference for the new committee were approved by the CIE Board of Administration in February 2009:

“To investigate the issue of smoothing the values of the D illuminants such as described in CIE 15:2004 Appendix C and to propose the calculation methods for new definitions of the D illuminants.”

This Technical Report summarizes the findings of the Technical Committee.

2 History of Daylight Illuminants

Through the ages natural daylight has been the principal light source available to humans, so it is only natural that it continues to be the most important reference illuminant, even though today there is a wide variety of available artificial light sources. It can be assumed that the “true” colour of the objects that are around us is the one seen under daylight.

2.1 Choice of Daylight

The spectral characteristics of natural daylight are ever changing, depending on the time of the day, the season, the location and whether the sky is blue or covered (fully or partially) by clouds. For colour matching professionals, and also for artists, the preferred illumination has for centuries been (in the northern hemisphere) north-sky daylight, and its use was well-established in American science and industry long before CIE adopted its daylight illuminants (McCamy, 1990). North-sky daylight, however, is not constant; it also may change in colour temperature from below 5 000 K up to at least 25 000 K and, according to McLaren (1962), “where natural daylight is used for colour matching, it would be better to use total daylight rather than north-sky daylight ...”. Although total daylight varies from a mixture of bright sunshine plus deep-blue sky to light from a totally overcast sky, its colour temperature is much more constant than that of north-sky daylight, the values reported in the literature ranging from 5 620 K to 8 000 K; Taylor and Kerr (1941) state that “the normal range is from 6 000 K to 7 000 K.”

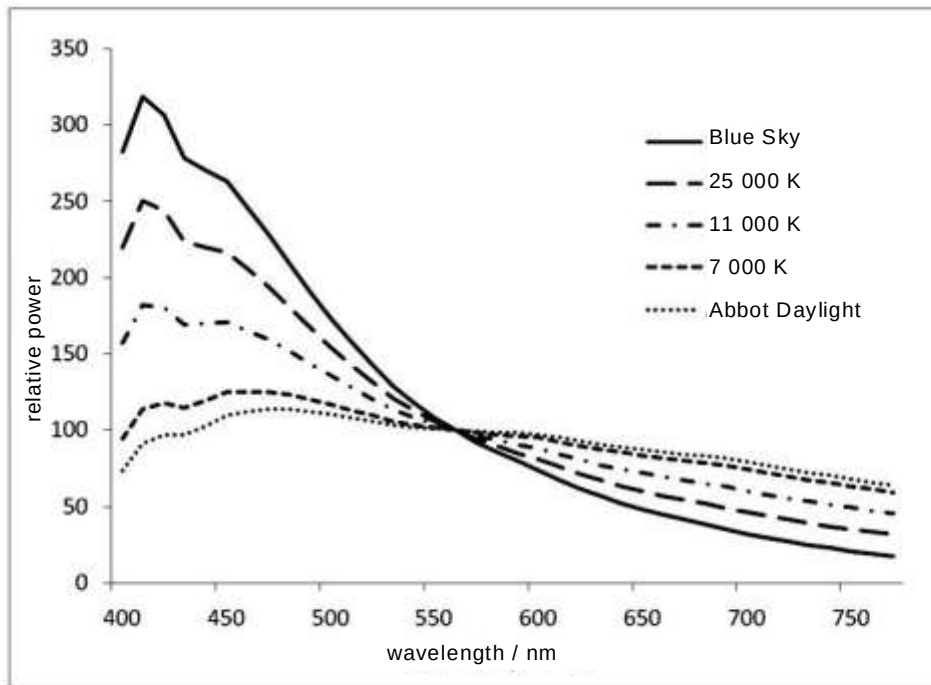


Figure 1 – Theoretical daylight curves derived by Gibson from different proportions of Abbot sun-outside-atmosphere and skylight calculated by use of the Rayleigh scattering equation (after Nickerson, 1958)

2.2 CIE Sources and Illuminants¹ B and C

In the late 1920s, at the time when the newly-formed Colorimetry Committee of the CIE decided that one of their aims should be the establishment of a standard white light for colorimetry, incandescent lamps in combination with liquid filters were in common use. In the United Kingdom, the National Physical Laboratory, NPL, used a 2 900 K lamp with filters to produce a source at 4 800 K and in the USA different thicknesses of Davis and Gibson liquid filters were used with 2 300 K lamps to provide sources of 3 500 K to 10 000 K (Halstead, 1981).

Recommendation 2 of the 8th Session of the CIE (1931) specified three standard sources (A, B and C), representing typical light from a tungsten lamp (2 848 K), noon sunlight (4 870 K)², respectively. Sources B and C were defined in terms of incandescent lamp, source A, and liquid filter combinations, with the spectral power distributions given in 5 nm intervals.

The International Practical Temperature Scale (IPTS) was changed in 1948, but at the 12th Session of the CIE (1951) it was decided to keep the spectral power distribution of source A unchanged. This necessitated changing its definition to a gas-filled coiled tungsten-filament lamp operating at a colour temperature of approximately 2 854 K, and a further change in the IPTS in 1968 led to the now accepted value of 2 856 K for standard source A together with corresponding changes to all other illuminants and sources.

Illuminant B has not been widely used. As a result it was considered obsolete and included only in the Appendix in the second (1986) and third (2004) edition of the CIE Technical Report on Colorimetry (CIE, 1986; CIE, 2004).

¹ The distinction between 'illuminant' and 'source' was first made only in 1986 in Publication 15.2 (CIE, 1986). In publications prior to that date 'illuminant' often refers to a source specified in terms of a lamp or a lamp/filter combination.

² The colour temperature of Illuminant C has very often been reported as 6 500 K (even in Judd et al., 1964) but the correct value is somewhat higher, 6 740 K according to Davis et al. (1953) or approximately 6 800 K (CIE, 2004).

The current accepted definition of illuminant C states that it is “intended to represent average daylight with a correlated colour temperature of approximately 6 800 K” (CIE, 2004). Illuminant C is no longer a recommended illuminant, but its relative spectral power distribution, tristimulus values and chromaticity co-ordinates are reproduced in the Appendix of the third edition of the CIE Technical Report on Colorimetry (CIE, 2004), as many practical measurement instruments and calculations still use this illuminant. It is however, not recommended for new applications.

2.3 The Equi-Energy Spectrum

In addition to illuminants B and C the CIE proposed the study of a further standard source to represent daylight (CIE, 1939), S_E , having equal energy at all wavelengths, chromaticity co-ordinates $x = 0,333$, $y = 0,333$ and a correlated colour temperature of 5 466 K (Halstead mentioned 5 700 K in Halstead, 1981). Although theoretically illuminant E should have a flat curve all across the spectrum, it was implemented as a source by a liquid filter designed by Davis and Gibson with the spectral power distribution published in Le Grand (1968) and illustrated in Figure 2.

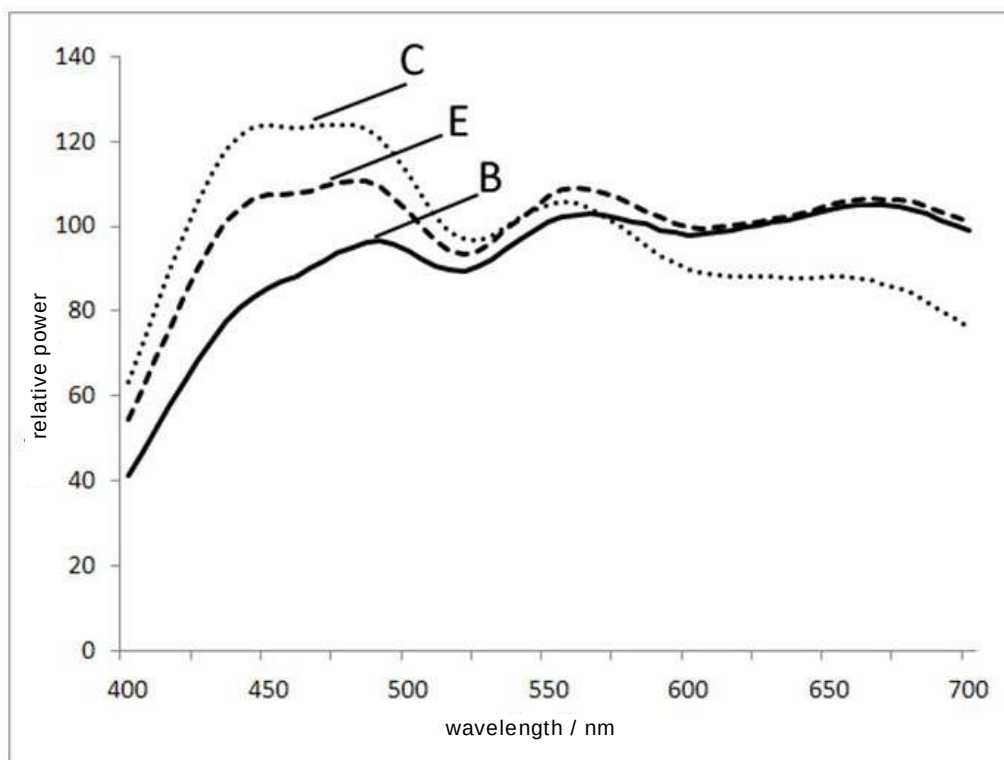


Figure 2 – Spectral power distribution of the former standard illuminants B and C and of source E (after Le Grand (1968))

2.4 The D Illuminants

Although for many years, illuminant C was accepted and widely used in colorimetry, the practical implementation of source C was limited to special laboratory use.

In 1963 the Colorimetry Committee of the CIE decided that sufficient evidence was available to supplement the existing CIE illuminants by new illuminants more adequately representing phases of natural daylight (CIE, 1963). Judd, MacAdam and Wyszecki (Judd et al., 1964) suggested a new approach based on the Simonds (Simonds, 1963) method of reducing experimental data to characteristic vectors (eigenvectors) and calculating the relative spectral power distribution of daylight of any desired correlated colour temperature by the following equation:

$$S(\lambda) = S_0(\lambda) + M_1 S_1(\lambda) + M_2 S_2(\lambda) \quad (1)$$

where

$S_0(\lambda)$ is the mean spectral power distribution of daylight;
 $S_1(\lambda)$ and $S_2(\lambda)$ are the two most important eigenvectors of the set of all daylight distributions;
 and
 M_1 and M_2 are scalar multipliers that are functions of the chromaticity co-ordinates of the D illuminants.

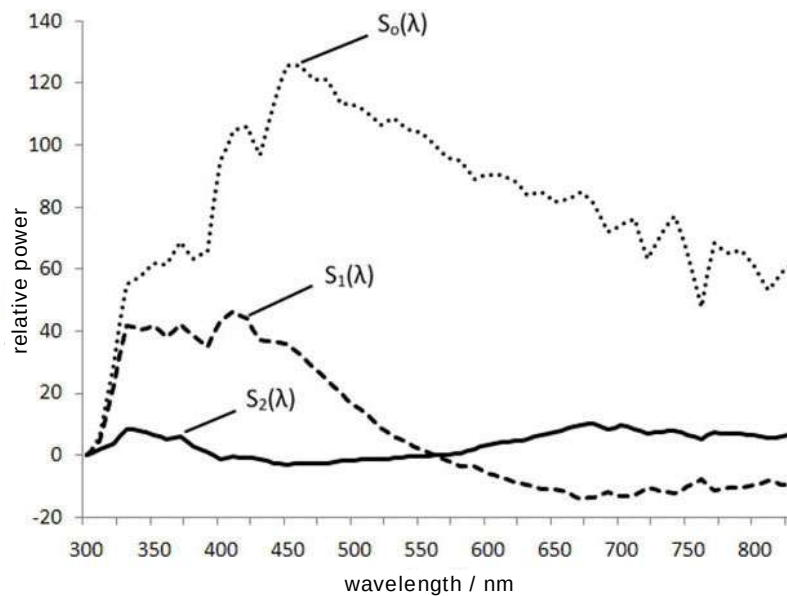


Figure 3 – Mean spectral power distribution $S_0(\lambda)$ of all phases of daylight and the first two eigenvector functions $S_1(\lambda)$ and $S_2(\lambda)$ used in the current CIE method of calculating daylight illuminants

$S_0(\lambda)$, $S_1(\lambda)$ and $S_2(\lambda)$ were originally determined at every 10 nm between 300 nm and 830 nm, and expert opinion at that time was that the variability of daylight was so large that for all practical applications it was sufficient to linearly interpolate between these 10 nm data points if values at other wavelengths were needed.

The current CIE Technical Report on Colorimetry (CIE, 2004) lists the values for the standard D65 and the recommended D illuminants (D50, D55 and D75) at 5 nm intervals (linearly interpolated from the 10 nm data). These values are consistent with values from 300 nm to 830 nm at 1 nm intervals and with six significant figures given in the CIE Standard (CIE, 2006), also interpolated linearly.

The choice of which colour temperature daylight illuminant to be used is application dependent. "It is recommended that, in the interest of standardization, D65 be used whenever possible. When D65 cannot be used, it is recommended that one of the daylight illuminants D50, D55, or D75 be used. When none of these daylight illuminants can be used, a daylight illuminant at a nominal correlated colour temperature (CCT, symbol T_{cp}) can be calculated using the equations [shown above]" (CIE, 2004). It is interesting to note here that for a long time for textile colour matching the recommended CCT was that of 7 500 K (Nickerson, 1948), for the appraisal of pictures and comparison of reproductions with originals 5 000 K, while for the comparison of press sheets with press proofs 7 500 K (McCamy, 1994). D65 seems to have emerged as the first choice of CIE (the one having the status of a *standard illuminant*) because it is a reasonable compromise between the extremes of D50 and D75 and also

because it provides some kind of continuity to the CCT (near 6 800 K) of the previous recommended daylight, illuminant C.

2.5 The ID Illuminants

There are some applications (for example paper viewed in an office situation) where the typical evaluation condition is not outdoors but indoors, and where the D illuminants (representing natural daylight) contain too much UV radiation compared to typical application viewing conditions. Following the method proposed by Clarke (1980), the CIE adopted the definition of two indoor daylight illuminants (ID50 and ID65) based on the D50 and D65 (outdoor) illuminants respectively and the transmittance of average window glass (CIE, 2009).

3 Experiments on Advantages of Smoothing

The problem with the current D65 illuminant is that it produces inconsistent results in tristimulus integrations for colour calculations, depending on the interval of integration, due to the effect of linear interpolation between the original 10 nm intervals. While the differences in computed colour are small compared to the repeatability and uncertainty of the measurements, and are insignificant for visual applications, the discrepancies are often found disturbing. Figure 4 shows the ΔE_{ab}^* differences between colours calculated using 5 nm intervals and those using 1 nm intervals (the reference condition) with the current standard illuminants D65 and A, for the 18 Macbeth ColorChecker® chart samples. Note that the differences with illuminant A are much smaller because it is a very smooth function and the tristimulus integration is very predictable.

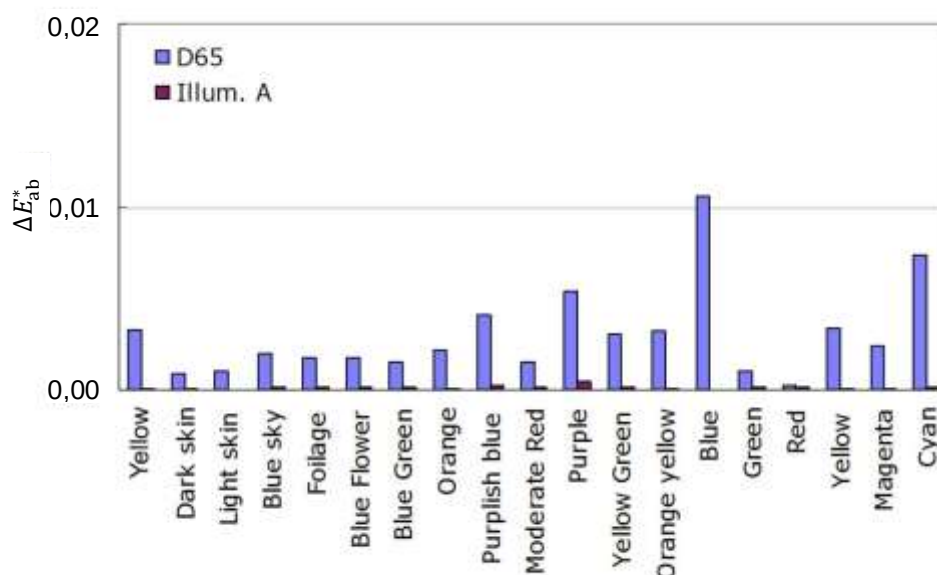


Figure 4 – The ΔE_{ab}^* differences between colours calculated at 5 nm intervals and at 1 nm intervals using the current illuminants D65 and A, for the 18 Macbeth ColorChecker® chart samples

Figure 5 shows the same analysis for integration using 4 nm intervals. These calculations show much larger differences than observed with the 5 nm intervals even though the interval is smaller. The differences in this case are close to the level of repeatability of a standard commercial spectrophotometer, and thus the operator will not be able to determine the reason for the differences – the loss of precision in the readings or the loss of precision in the calculations. It is believed that the differences increase for integration with 4 nm intervals because the relationship between the sampled points at 4 nm intervals and the original 10 nm interval points varies from one part of the visible spectral region to the next, which results in larger variations in the calculated colour co-ordinates.

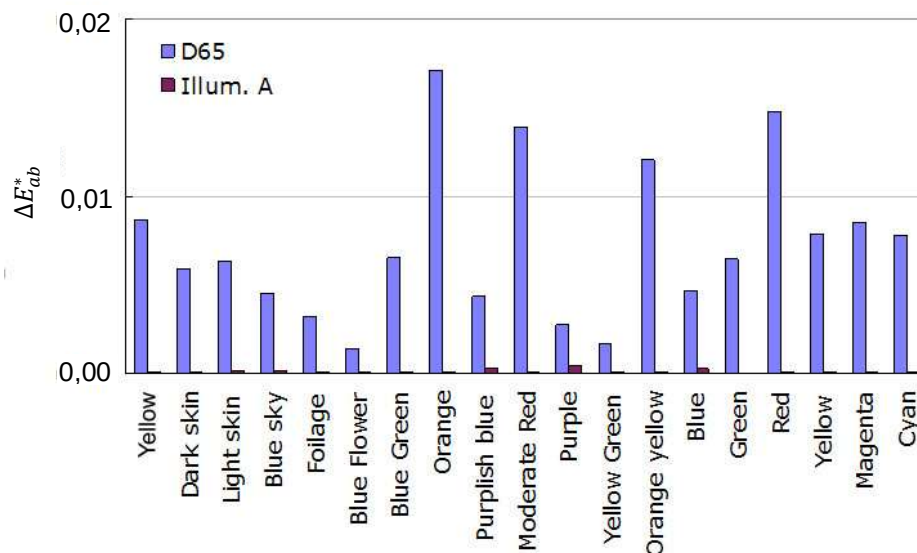


Figure 5 – The ΔE_{ab}^* differences between colours calculated at 4 nm intervals and at 1 nm intervals using the current illuminants D65 and A, for the 18 Macbeth ColorChecker® chart samples

As an experiment to solve this problem, a smoothed D65 function was created by interpolating the S_0 , S_1 , S_2 functions to 1 nm intervals from the original 10 nm interval points, as proposed in Appendix C of CIE 15:2004 (CIE, 2004). A cubic spline interpolation was used in this example. The smoothed D65 spectrum was calculated from the smoothed S_0 , S_1 , S_2 functions as specified in 3.1 of CIE 15:2004. As shown in Figure 6, the smoothed function passes through the original points at 10 nm intervals.

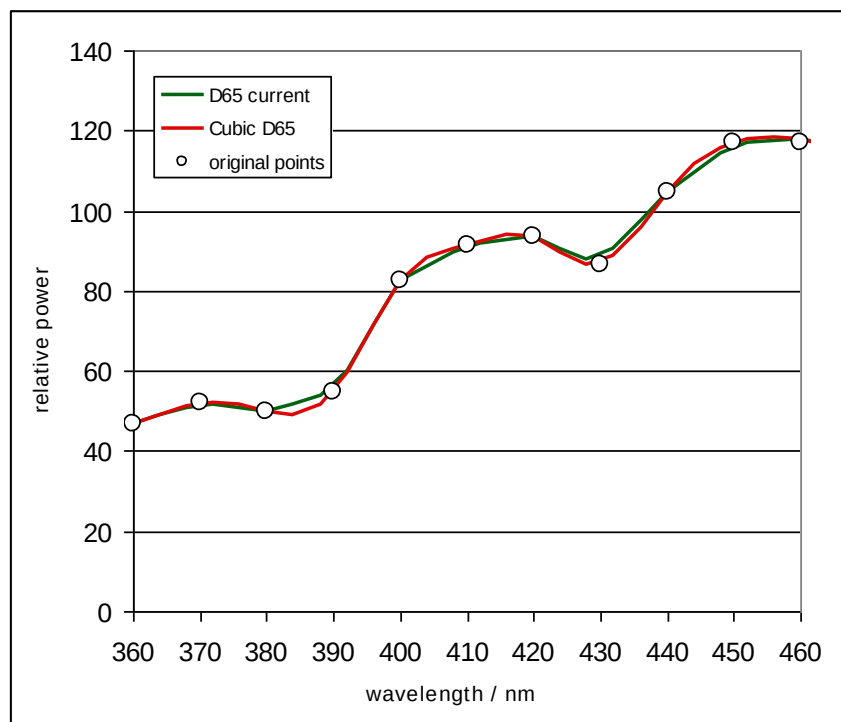


Figure 6 – Detail of smoothed D65 function (interpolated per cubic spline) compared to the current D65 function

Figures 7 and 8 show the results of the same analyses as shown in Figures 4 and 5, using the smoothed D65 function. The colour differences with the smoothed D65 function are reduced to the level of illuminant A, and by more than an order of magnitude lower in both cases.

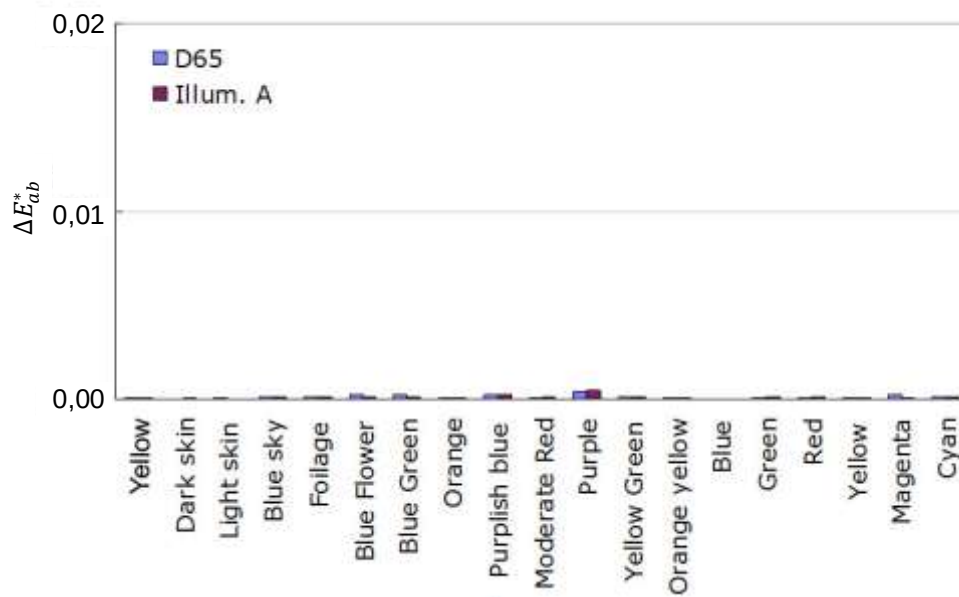


Figure 7 – The ΔE^*_{ab} differences between colours calculated at 5 nm intervals and at 1 nm intervals using the smoothed illuminant D65 and illuminant A, for the 18 Macbeth ColorChecker® chart samples (the same scale is used as in Fig. 4)

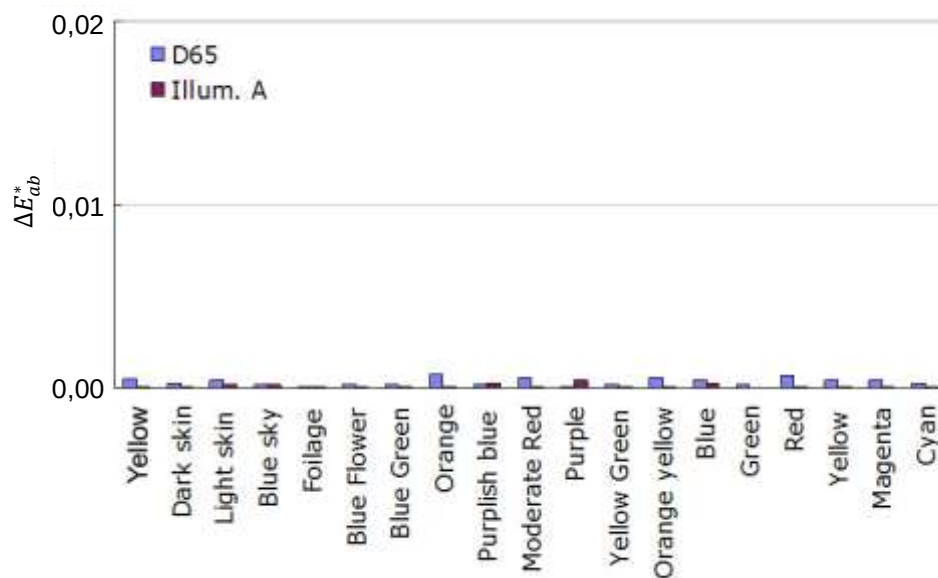


Figure 8 – The ΔE^*_{ab} differences between colours calculated at 4 nm intervals and at 1 nm intervals using the smoothed illuminant D65 and illuminant A, for the 18 Macbeth ColorChecker® chart samples (the same scale is used as in Fig. 5)

Figure 9 shows the results of such analyses of differences in colour calculation at varied wavelength intervals, using illuminants D65, smoothed D65, and A. It is shown that the results with the smoothed D65 are reduced to the level of Illuminant A at any intervals below 8 nm. Beyond 8 nm, the effect of smoothing D65 is small because the inherent abridgment error increases and dominates the error. At 5 nm and smaller intervals, the abridgment errors are reduced by more than an order of magnitude. This demonstrates that the smoothed D65

function solves the problem of inconsistent calculation results depending on data intervals, and brings more coherent results when abridged calculation is used.

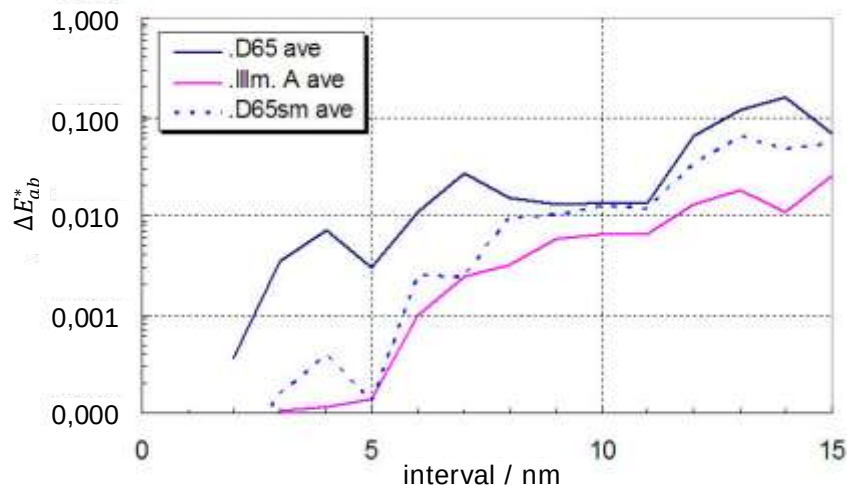


Figure 9 – The average ΔE_{ab}^* differences between colours calculated at variable intervals and at 1 nm intervals using the illuminants: current D65, smoothed D65, and A, for the 18 Macbeth ColorChecker® chart samples

There will be small differences in colour calculation results using the smoothed D65 and the current D65 due to the small changes in the curve. Figure 10 shows the ΔE_{ab}^* differences between colours calculated using the smoothed D65 and those calculated using the current D65, for the 18 Macbeth ColorChecker® chart samples, at 1 nm intervals and 5 nm intervals. This excludes the effects of abridgement, and shows only the differences caused by changing from the current D65 to the smoothed D65 at each data interval. As shown in the figure, the changes are 0,01 in ΔE_{ab}^* on the average and less than 0,05 in ΔE_{ab}^* for any colours. These differences are negligible, being one or two orders of magnitude smaller than the typical measurement uncertainties of instruments. A change of the definition of D65 to such a smoothed function will not affect practical measurements of object colours using existing instruments.

Calculations were also performed using more than one thousand Pantone colours. The maximal colour difference for these colours was below 0,07 ΔE_{ab}^* units, and average values were 0,008 ΔE_{ab}^* units.

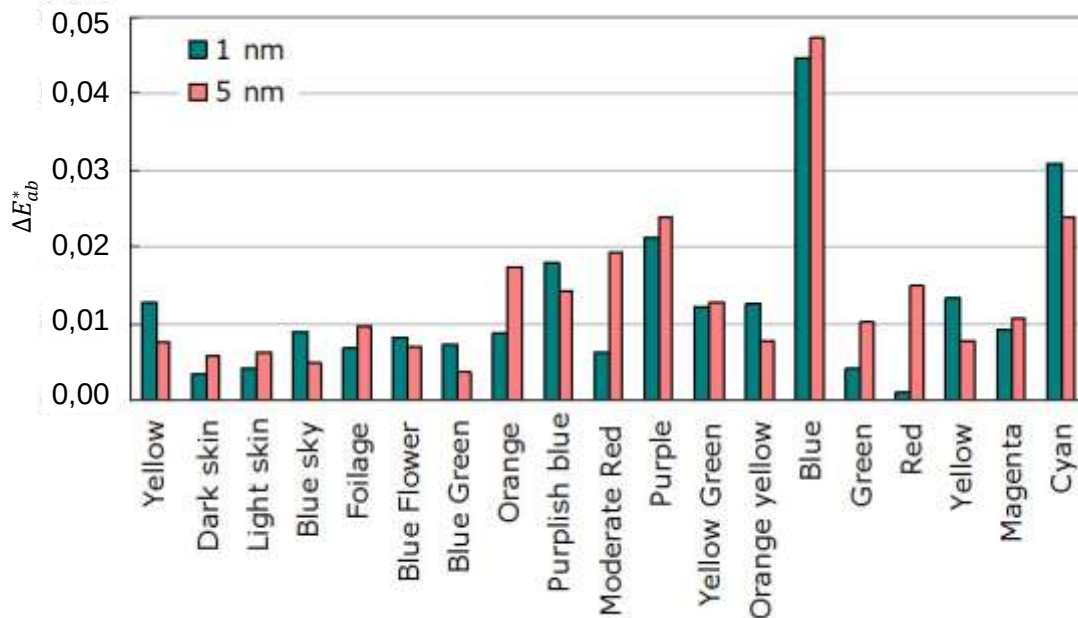


Figure 10 – The average ΔE_{ab}^* differences between colours calculated using the smoothed D65 and those calculated using the current D65, for the 18 Macbeth ColorChecker® chart samples, at 1 nm intervals and 5 nm intervals

4 Possible Smooth Daylight Spectral Power Distribution Models

Several concepts exist to construct Daylight Spectral Power Distribution (D-SPD) models.

4.1 Using Sprague Formula between the 10 nm Fixed Points (Minimal Smoothing)

The most obvious model is to retain the fixed values as described in the original recommendation (i.e. at the 10 nm intervals) and use an accepted interpolation formula, according to the recommendations of CIE 167:2005 (CIE, 2005) (most noticeably the Sprague formula), to define the required intermediate values. Tests were run also using Lagrange and spline interpolations.

The SPDs of D-illuminants can be constructed from characteristic vector data (eigenvectors), and the relative spectral power distribution of daylight of any desired correlated colour temperature can be calculated using Equation 1 (see 2.4).

The Sprague interpolated $S_0(\lambda)$, $S_1(\lambda)$ and $S_2(\lambda)$ values are reproduced in Table 1.

Factors M_1 and M_2 in Equation 1 are not to be considered as constants, as these values depend on chromaticity co-ordinates x_D , y_D that belong to the chosen correlated colour temperature, T_{cp} (Judd et al., 1964), and their values for the 10 nm sampling interval are:

$$M_1 = \frac{-1,3515 - 1,770\,3\,x_D + 5,9114\,y_D}{0,024\,1 + 0,256\,2\,x_D - 0,734\,1\,y_D} \quad (2)$$

and

$$M_2 = \frac{0,030\,0 - 31,442\,4\,x_D + 30,0717\,y_D}{0,024\,1 + 0,256\,2\,x_D - 0,734\,1\,y_D}, \quad (3)$$

where in the case of $4\,000\,K \leq T_{cp} < 7\,000\,K$

$$x_D = -4,607\,0 \frac{10^9}{(T_{cp}/K)^3} + 2,967\,8 \frac{10^6}{(T_{cp}/K)^2} + 0,099\,11 \frac{10^3}{T_{cp}/K} + 0,244\,063 ; \quad (4)$$

and in the case of $7\,000\,K \leq T_{cp} \leq 25\,000\,K$

$$x_D = -2,006\,4 \frac{10^9}{(T_{cp}/K)^3} + 1,901\,8 \frac{10^6}{(T_{cp}/K)^2} + 0,247\,48 \frac{10^3}{T_{cp}/K} + 0,237\,040 . \quad (5)$$

In both colour temperature ranges

$$y_D = -3,000\,x_D^2 + 2,870\,x_D - 0,275 . \quad (6)$$

The form of Equations 4, 5 and 6 and the parameters in them arise from curve fitting. The purpose of the curve fitting was to approximate the functional relation between the values of correlated colour temperature and the chromaticity co-ordinates of the spectral power distributions of the measurement data set.

The numbers in Equations 2 and 3 have been determined for 10 nm sampling; they depend on the sampling of the S functions (Kránicz and Schanda, 2000). A detailed description of the calculation steps is reproduced in Annex A.

Figure 11 shows as an example the results for CIE standard illuminant D65, and Figure 12 is a smaller section of this graph to give an illustration of the different interpolation methods.

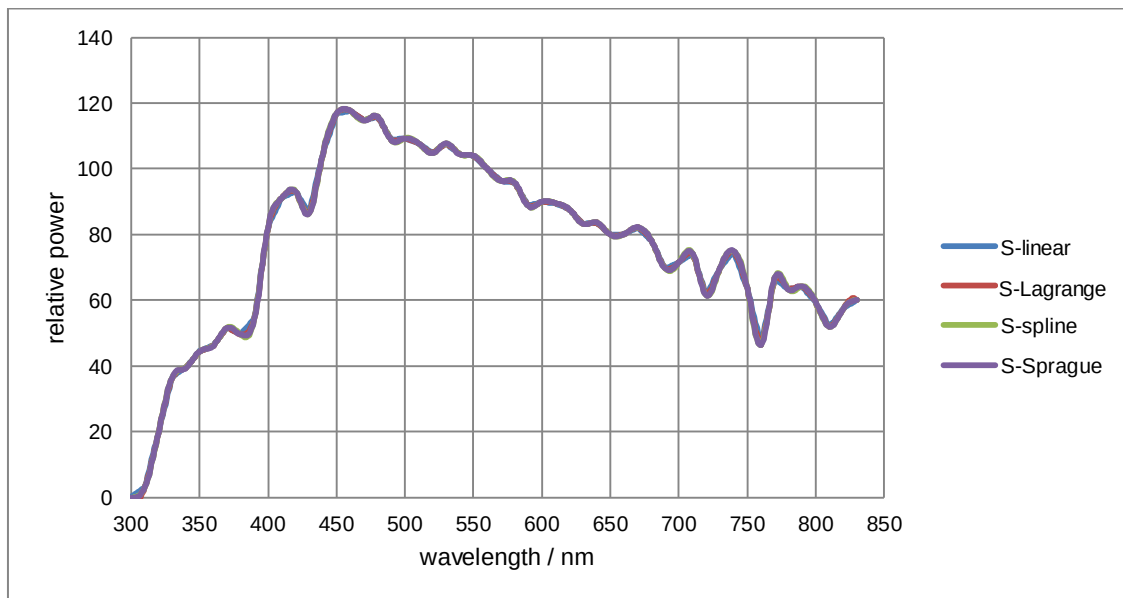


Figure 11 – Example of smoothing between fixed 10 nm points, standard D65 and smoothed with different interpolation functions

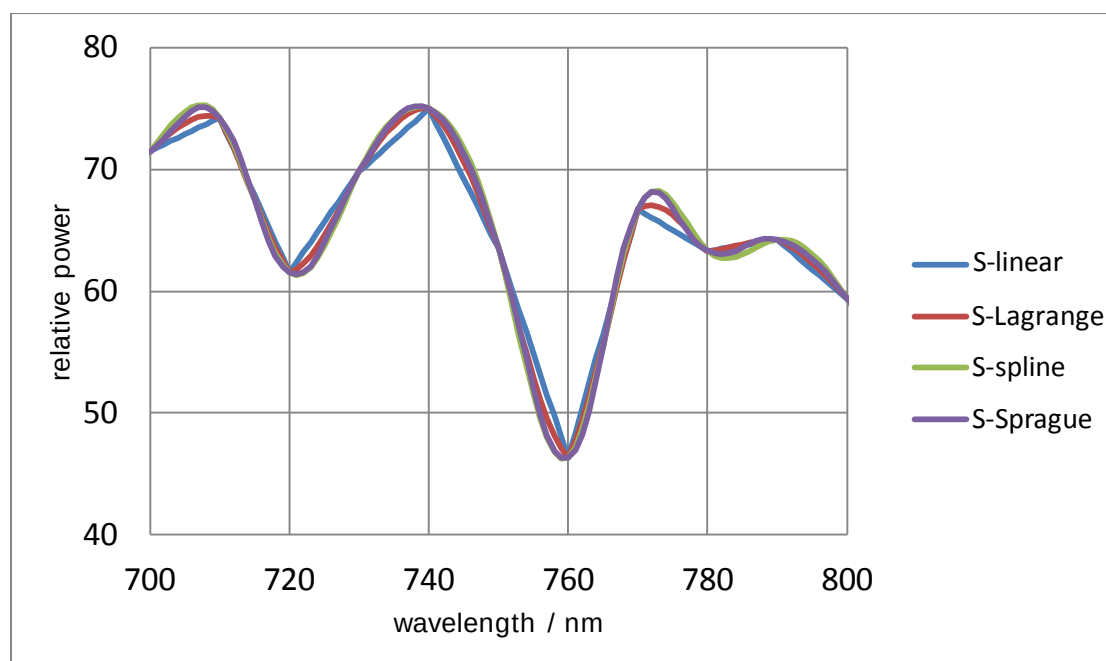


Figure 12 – Part of Figure 11, showing the results of the different interpolation functions more clearly

4.2 Smoothing some Absorption Bands (Highly Smoothing)

The CIE illuminants are used to calculate the tristimulus values of object colours that are usually smooth functions, and thus it seems to be obvious to determine whether or not smoothing of the very wavy daylight illuminants would distort the colorimetric results.

An interpolation and approximation method has been developed, whereby one can select the wavelength distance of the fixed points. Thus, for example, to get better smoothing as described in the previous section one can select $\Delta\lambda = 20$ nm for the LOWESS (Locally Weighted Scatter Plot Smooth) filter. This filter uses a moving averaging technique, in which one can select the size of the window from which data are taken, and also the weight of these data: the value in the middle of the window gets the largest weight, and towards the ends of the window the weight diminishes. Data outside of the window have no influence on the smoothing. Experimental calculations have shown that a window width of 20 nm provided a smooth function, and using two databases of more than 100 000 samples (real and artificially developed ones¹) provided colour differences between the samples illuminated with CIE standard illuminant D65 and the smoothed function gave as average and maximum colour difference the values of: $\Delta E_{ab}^*(ave) = 0,10$, and $\Delta E_{ab}^*(max) = 0,30$. Further interpolation algorithms were tested as well, and a detailed description can be found in (Kosztyán & Schanda, 2012).

In the following the results for an optimum filtering, using a window size of 10 nm and a parameter r (the percentage of the number of points taken into consideration divided by the total span of measured points; for further details see Kosztyán & Schanda, 2012) of 15 were selected. Figure 13 shows as an example the smoothed D65 function together with the standard function. Table 3 provides the $S_0(\lambda)$, $S_1(\lambda)$ and $S_2(\lambda)$ functions computed using the LOWESS algorithm. Using these functions LOWESS-smoothed daylight spectra can be calculated in the same form as in the standard method (Kosztyán & Schanda, 2012). Spectra for D50, D60, D65, D70, D75, as well as for indoor D50 (iD50) and indoor D65 (iD65) are reproduced in Table 4. To distinguish between the traditional and LOWESS-smoothed spectra, for the smoothed spectra an “s” is placed before the daylight spectral distribution symbol.

¹ A database of real samples was provided by Professor Ronnier Luo, University of Leeds; the artificially developed samples were provided by Professor Lorne A. Whitehead, University of British Columbia.

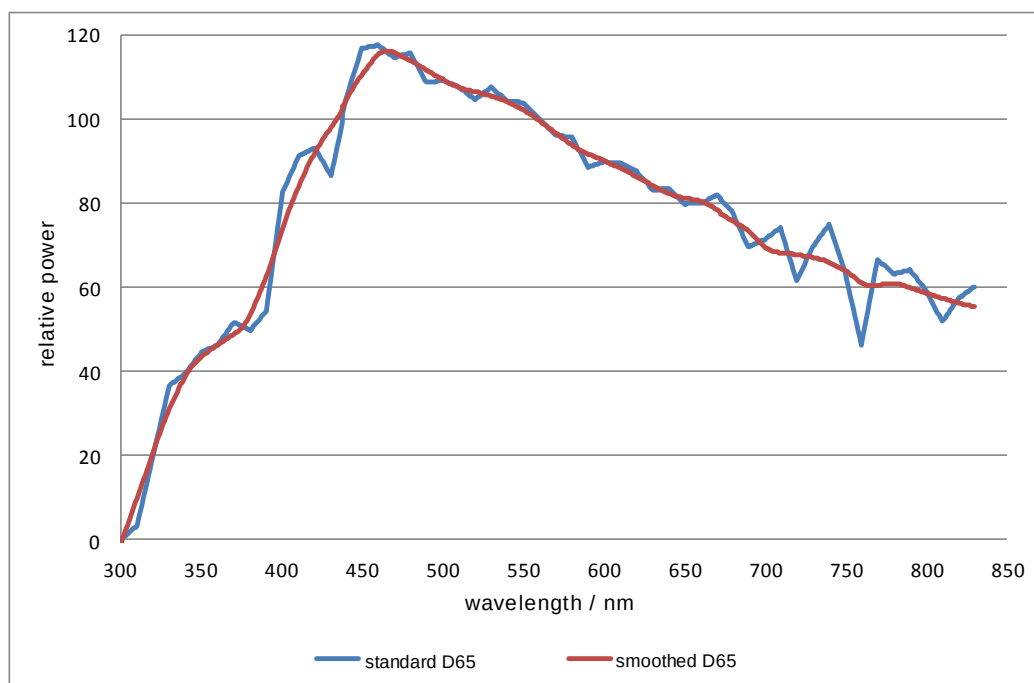


Figure 13 – LOWESS-smoothed D65 SPD compared to the standard D65 curve

5 Conclusions and Recommendation

Based on the discussion in Clause 3, the CIE recommends for trial two sets of daylight spectra: a simple one in which the original 10 nm spaced values are retained, but the interpolation between the fixed values uses the Sprague interpolation formula (minimal smoothing) rather than linear interpolation. As shown in Clause 3, this change will not influence results of practical colorimetry, but will enable the avoidance of inconvenient calculation differences in some more fundamental calculations. Table 1 provides the $S_0(\lambda)$, $S_1(\lambda)$ and $S_2(\lambda)$ values at 1 nm intervals, where the Sprague interpolation was used from the fixed 10 nm data. It is important to mention, however, that the factors M_1 and M_2 do not depend solely on the chromaticity co-ordinates of the phase of daylight (and CIE 15:2004 contains these only for the original 10 nm steps). For other wavelength intervals the numbers in Equations 2 and 3 of the present report have to be exchanged with other values, as described in detail in Annex A.

Table 2 provides spectral power distribution data for illuminants D50, D55, D60, D65, D70 and D75 interpolated using the method described in the present report. For other correlated colour temperatures, the spectral power distribution can be computed using the data of $S_0(\lambda)$, $S_1(\lambda)$ and $S_2(\lambda)$ of Table 1 and the calculation method as described in Annex A. An Excel® file can be downloaded at <http://www.cie.co.at/index.php/DOWNLOADS/TC1-74> that will provide the SPD of the daylight illuminant for the different interpolation methods described in this report after input of a required CCT.

The method described in 4.2 (highly smoothed) provides smoother spectra; it is intended for daylight simulator manufacturers to test how well they can replicate the smoothed spectra, so that at a later stage daylight sources could eventually be introduced. The symbol $S_{x,s}(\lambda)$ is recommended for the smoothed eigenvectors (x representing 0, 1, 2), the symbol sDYY for the smoothed daylight spectra and the symbol siDYY for the smoothed indoor daylight spectra (YY representing the two digits indicating the CCT of the D Illuminant).

6 Tables¹Table 1 – Sprague interpolated values of the $S_0(\lambda)$, $S_1(\lambda)$ and $S_2(\lambda)$ eigenvectors

Wavelength / nm	$S_0(\lambda)$	$S_1(\lambda)$	$S_2(\lambda)$
300	0,04000000	0,02000000	0,00000000
301	0,21942086	0,15400158	0,21706377
302	0,41023081	0,29403330	0,42663809
303	0,64619930	0,47008968	0,64056730
304	0,96035185	0,70842856	0,86123330
305	1,38400643	1,03178529	1,08446097
306	1,94580991	1,45958706	1,30242373
307	2,67077446	2,00816713	1,50654900
308	3,57931391	2,69097906	1,69042373
309	4,68628026	3,51881102	1,85269990
310	6,00000000	4,50000000	2,00000000
311	7,52946398	5,64511214	2,14374315
312	9,29975349	6,97333359	2,28257531
313	11,31607829	8,48874998	2,41732889
314	13,56021068	10,17872429	2,55465722
315	15,99748916	12,01877953	2,70489683
316	18,58382193	13,97748149	2,87992957
317	21,27269049	16,02132141	3,09104487
318	24,02215319	18,11959870	3,34680191
319	26,80184877	20,24930361	3,65089185
320	29,60000000	22,40000000	4,00000000
321	32,43596313	24,58590750	4,39014063
322	35,34947200	26,84361600	4,83584000
323	38,33466088	29,16925200	5,33892688
324	41,34105600	31,51788800	5,88432000
325	44,28914063	33,81781250	6,44570313
326	47,08592000	35,98480000	6,99120000
327	49,64048638	37,93638100	7,48904938
328	51,87958400	39,60611200	7,91328000
329	53,76317413	40,95784550	8,24938563
330	55,30000000	42,00000000	8,50000000
331	56,52090938	42,76156188	8,67857625
332	57,36960000	43,19264000	8,77488000
333	57,83162813	43,28041813	8,78482125
334	57,95760000	43,07024000	8,71760000
335	57,84179688	42,64648438	8,59140625

¹ Copies of the tables can be downloaded at <http://www.cie.co.at/index.php/DOWNLOADS/TC1-74>.

Wavelength / nm	$S_0(\lambda)$	$S_1(\lambda)$	$S_2(\lambda)$
336	57,60080000	42,11344000	8,42912000
337	57,35211563	41,57618063	8,25401125
338	57,19280000	41,12144000	8,08544000
339	57,17808438	40,79848688	7,93455625
340	57,30000000	40,60000000	7,80000000
341	57,50836125	40,48142750	7,67124438
342	57,83632000	40,47424000	7,55248000
343	58,30226625	40,59520250	7,44731563
344	58,88400000	40,82304000	7,35392000
345	59,53203125	41,11093750	7,26679688
346	60,18288000	41,39904000	7,17856000
347	60,77237625	41,62695250	7,08170813
348	61,24896000	41,74624000	6,97040000
349	61,58698125	41,73292750	6,84222938
350	61,80000000	41,60000000	6,70000000
351	61,92302625	41,38089313	6,54837875
352	61,92704000	41,04944000	6,38096000
353	61,80379125	40,59864938	6,19651625
354	61,58368000	40,05744000	6,00176000
355	61,32265625	39,47851563	5,80859375
356	61,08912000	38,92624000	5,63136000
357	60,95082125	38,46451188	5,48409125
358	60,96176000	38,14464000	5,37776000
359	61,14908625	37,99321813	5,31752875
360	61,50000000	38,00000000	5,30000000
361	61,98457938	38,13558438	5,31909813
362	62,64832000	38,43168000	5,38720000
363	63,50166063	38,89625063	5,50643938
364	64,50032000	39,49664000	5,66416000
365	65,56367188	40,17304688	5,83789063
366	66,59312000	40,85200000	6,00032000
367	67,49047313	41,45983313	6,12427188
368	68,17632000	41,93616000	6,18768000
369	68,60840438	42,24734938	6,17856313
370	68,80000000	42,40000000	6,10000000
371	68,80266063	42,43047625	5,96380313
372	68,59952000	42,33008000	5,75904000
373	68,18564188	42,09293375	5,48215188
374	67,58992000	41,73120000	5,14352000
375	66,86445313	41,26953125	4,76289063
376	66,07392000	40,73952000	4,36480000

Wavelength / nm	$S_0(\lambda)$	$S_1(\lambda)$	$S_2(\lambda)$
377	65,28495438	40,17414875	3,97399938
378	64,55552000	39,60224000	3,61088000
379	63,92428563	39,04290625	3,28689813
380	63,40000000	38,50000000	3,00000000
381	62,95019313	37,95646813	2,73931125
382	62,52960000	37,38960000	2,51232000
383	62,14115688	36,80159438	2,32287875
384	61,83152000	36,21712000	2,16560000
385	61,67539063	35,67539063	2,02890625
386	61,75984000	35,22224000	1,89808000
387	62,16863438	34,90219688	1,75831375
388	62,96656000	34,75056000	1,59776000
389	64,18374813	34,78547313	1,41058125
390	65,80000000	35,00000000	1,20000000
391	67,77993938	35,37643063	0,97415688
392	70,19600000	35,94304000	0,72640000
393	73,05664813	36,70474938	0,45508063
394	76,27984000	37,63104000	0,16768000
395	79,72304688	38,66757813	-0,12226563
396	83,21328000	39,74784000	-0,39824000
397	86,57711563	40,80473688	-0,64382188
398	89,67072000	41,78224000	-0,84576000
399	92,40987438	42,64700563	-0,99704813
400	94,80000000	43,40000000	-1,10000000
401	96,90854313	44,06802063	-1,16234188
402	98,69152000	44,64000000	-1,17776000
403	100,12192188	45,10554188	-1,14450313
404	101,22528000	45,46784000	-1,06944000
405	102,06289063	45,73945313	-0,96523438
406	102,71504000	45,93808000	-0,84752000
407	103,26422938	46,08233438	-0,73207563
408	103,77840000	46,18752000	-0,63200000
409	104,29415813	46,26140563	-0,55488688
410	104,80000000	46,30000000	-0,50000000
411	105,25457063	46,29137875	-0,46062438
412	105,68800000	46,24000000	-0,44000000
413	106,11586688	46,14893375	-0,44048813
414	106,51824000	46,01488000	-0,46032000
415	106,85195313	45,83046875	-0,49492188
416	107,06288000	45,58656000	-0,53824000
417	107,09820938	45,27454375	-0,58406563

Wavelength / nm	$S_0(\lambda)$	$S_1(\lambda)$	$S_2(\lambda)$
418	106,91872000	44,88864000	-0,62736000
419	106,51105563	44,42819875	-0,66557938
420	105,90000000	43,90000000	-0,70000000
421	105,11810938	43,31068813	-0,73431938
422	104,10496000	42,64496000	-0,76672000
423	102,85601063	41,90293188	-0,79644563
424	101,44448000	41,10496000	-0,82544000
425	99,99492188	40,28476563	-0,85742188
426	98,65680000	39,48256000	-0,89696000
427	97,57806313	38,73816938	-0,94854813
428	96,87872000	38,08416000	-1,01568000
429	96,62441438	37,53896313	-1,09992438
430	96,80000000	37,10000000	-1,20000000
431	97,34216750	36,75169563	-1,31341438
432	98,30512000	36,50784000	-1,44304000
433	99,70552250	36,37364688	-1,58917813
434	101,48800000	36,33696000	-1,74816000
435	103,54843750	36,37382813	-1,91367188
436	105,75728000	36,45408000	-2,07808000
437	107,98283250	36,54689938	-2,23375563
438	110,11456000	36,62640000	-2,37440000
439	112,08638750	36,67720063	-2,49636938
440	113,90000000	36,70000000	-2,60000000
441	115,61339938	36,70912063	-2,68835563
442	117,22192000	36,70448000	-2,75952000
443	118,70742813	36,68193938	-2,81243438
444	120,06208000	36,63888000	-2,84848000
445	121,28554688	36,57382813	-2,87070313
446	122,38224000	36,48608000	-2,88304000
447	123,35853563	36,37532688	-2,88954188
448	124,22000000	36,24128000	-2,89360000
449	124,96861438	36,08329563	-2,89717063
450	125,60000000	35,90000000	-2,90000000
451	126,10116813	35,68899125	-2,90001250
452	126,45904000	35,44800000	-2,89728000
453	126,67283688	35,17653375	-2,89234750
454	126,75264000	34,87568000	-2,88544000
455	126,71601563	34,54765625	-2,87656250
456	126,58464000	34,19536000	-2,86560000
457	126,38092438	33,82191875	-2,85241750
458	126,12464000	33,43024000	-2,83696000