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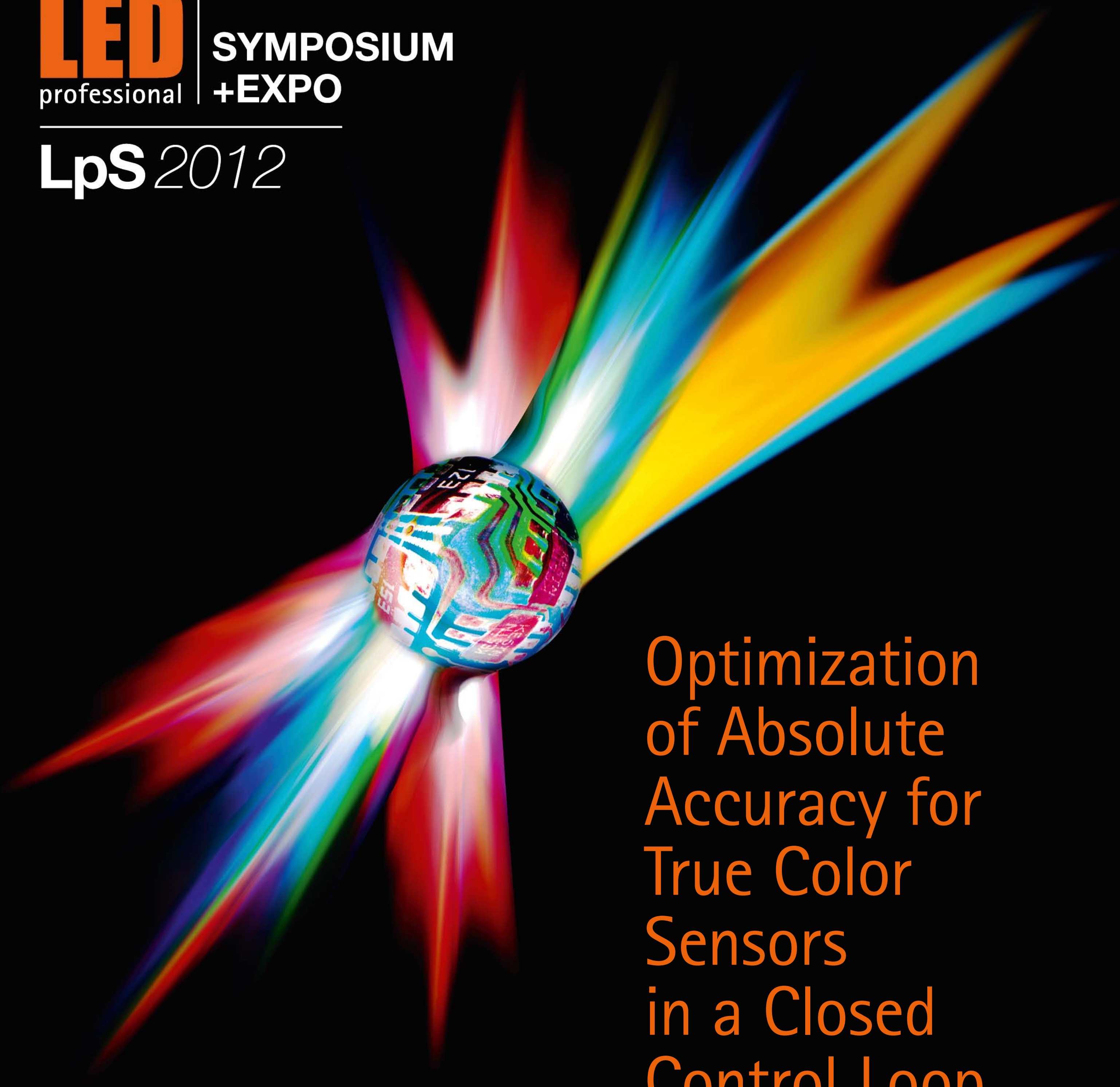

Optimization of Absolute Accuracy for True Color Sensors in a Closed Control Loop

LED Lighting Technologi

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Optimization of Absolute Accuracy for True Color Sensors in a Closed Control Loop

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Abstract

It is well known, that LEDs have a drift of peak wavelength and intensity. This leads to shifts of chromaticity coordinate and intensity, which could be measured and controlled by true color sensors. The aim is a stable luminous color over the whole life time of a LED lamp. This paper illustrates an optimized calibration method, with which those lamps are measured with accuracy even better than human eye does. It is stable over a temperature range of 60K. The presented method can be easily implemented in microcontrollers.

The results are verified with a measurement setup consisting of 8 selectable LEDs warm-White wW, cool-White cW, neutral-White nW, Red R, Green G, Blue B, Red-Orange O und Amber A.
Three combinations are examined with 4, 6 and 8 different LED colors. The combinations are RGBcW, RGBwWcWA and RGBwWOcWnWA.

Four applications are observed. At first all color temperatures around the Planckian locus. The second, third and fourth applications are specified on color temperatures 2700 K, 4500 K and 6500 K.

Introduction

IThe aim is an optimization of known calibration methods for color sensors. An increased duration of the calibration process should be avoided in order to reach short production times. The algorithm of the new method to correct sensor data needs to be kept simple for a short computing time on microcontrollers of a few milliseconds. This supports a feedback control, which is not noticeable for the human eye.

Existing lamps, which use true color sensors, are calibrated with the primary colors and if necessary with mixed colors. The presented method only uses primary colors with an additional weighting factor. Those factors are adjusted with specifically adapted optimization methods. Without any additional effort the result can be applied on further lamps of the same type. Another optimization is not necessary.

Calibration Method

The used calibration method is a polynomial regression of 1st degree (1). The reference values θh are measured with a reference spectrometer and the values σh are raw sensor data measured with a true color sensor, where h is the number of calibration targets (primary colors).

$$K = (\theta_h \cdot \sigma_h^T) \cdot (\sigma_h \cdot \sigma_h^T)^{-1} \tag{1}$$

$$\theta_h = \begin{pmatrix} X_1 & \dots & X_h \\ Y_1 & \dots & Y_h \\ Z_1 & \dots & Z_h \end{pmatrix} \tag{2}$$

$$\sigma_h = \begin{pmatrix} \tilde{X}_1 & \tilde{\dots} & X_h \\ \tilde{Y}_1 & \tilde{\dots} & Y_h \\ \tilde{Z}_1 & \tilde{\dots} & Z_h \end{pmatrix} \tag{3}$$

... using the combination
RGBcW h = 4,
RGBwWcWA h = 6 and
RGBwWOcWnWA h = 8.
The primary colors are measured with a PWM of 100% duty cycle. During the calibration it is important that the sensor is placed in exactly the same position as later in operation. So no other optical disturbances can influence the spectrum, like additional lenses, light guides or even different angels of incidence. For further information please refer to [1].

Optimization of the calibration method

This chapter examines a method for optimizing the calibration method. It refers to [2]. The objective function of the optimization (4) is a minimization of the mean differences between gj and *fj(βh)*, where n is the number of targets (mixed LED colors),
gj is the reference value in the desired color space L*u'v' and *fj(βh)* is the corresponding value measured with the true color sensor and corrected

with the calibration matrix K. The Euclidean distance d is the color difference Δu'v' between gj and *fj(βh)*. *βh* is considered as an additional weighting factor for each calibration target *θh* and *σh*. The aim is to minimize the objective function by optimizing *βh* with the constraint (5).

$$\min\left(\frac{1}{n}\sum_{j=1}^{n} d(g_j,f_j(\beta_h))^2\right) + \rho\cdot\varepsilon \qquad (4)$$

$$\varepsilon = \max\left(d(g_j,f_j(\beta_h))^2\right),\ j=1,\ldots,n$$

If βj = 0, the corresponding calibration target is not factored into the calculation of K. If βj > 0, the calibration target is weighted in the calculation.

$$0 \le \beta j \le 1\ ,\ j = 1,\ \ldots,\ h \qquad (5)$$

The quasi-Newton method is used to minimize nonlinear functions. The function is available in the MATLAB Optimization Toolbox from MathWorks. One significant criterion for the success of the optimization is the selection of the initial value for *βh*. Because it is only possible to find one of many local minima when using numerical methods for nonlinear optimization problems, the initial value must be determined experimentally. Finding a global minimum is impossible. [3]

$$\min\max\left(d(g_j,f_j(\beta_h))^2\right)$$
$$j = 1,\ \ldots,\ n \qquad (6)$$

Particle swarm optimization PSO is used to solve the problem of the initial value. PSO was originally developed to simulate the social behavior of flocks of birds. Enhanced for today's multi-dimensional spaces and the latest technological developments, it is used to optimize continuous, non-linear functions. Similar to genetic algorithms, it is used to generate various different solutions optimizing analytically unsolvable problems. Here the position *βh* of a particle describes a solution to the problem (6), which minimizes the maximum difference. First, a number of particles are initialized with random positions in space. In the following steps, the new position of a particle is governed by its own local minimum, the global minimum of all particles and the speed. To avoid synchronization of the particles, random numbers are also included to calculate the speed. [4] [5]

Measurement Setup

In order to verify the described method a measurement setup is realized, which automatically measures a lamp with up to 8 different LEDs. The measurements are performed simultaneous with a MAZeT True Color Sensor MTCS and a JETI Specbos 1211 as reference spectrometer. The used Luxeon Rebel LEDs have the color warm-White wW, cool-White cW, neutral-White nW, Red R, Green G, Blue B, Red-Orange O und Amber A. They are separately controlled with 8 bit PWM and 350 mA constant current. The heat sink of the LEDs is combined with a Peltier element and a temperature sensor to realize a closed control loop and control temperatures between 20°C and 80°C.

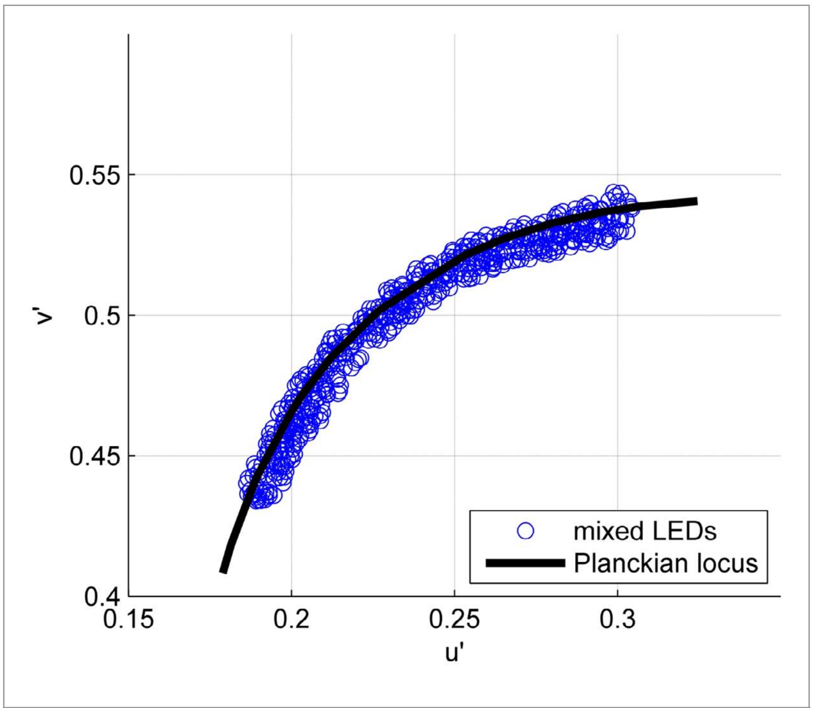

Figure 1: 516 mixed colors of RGBwWOcWnWA LEDs around the Planckian locus at 20°C

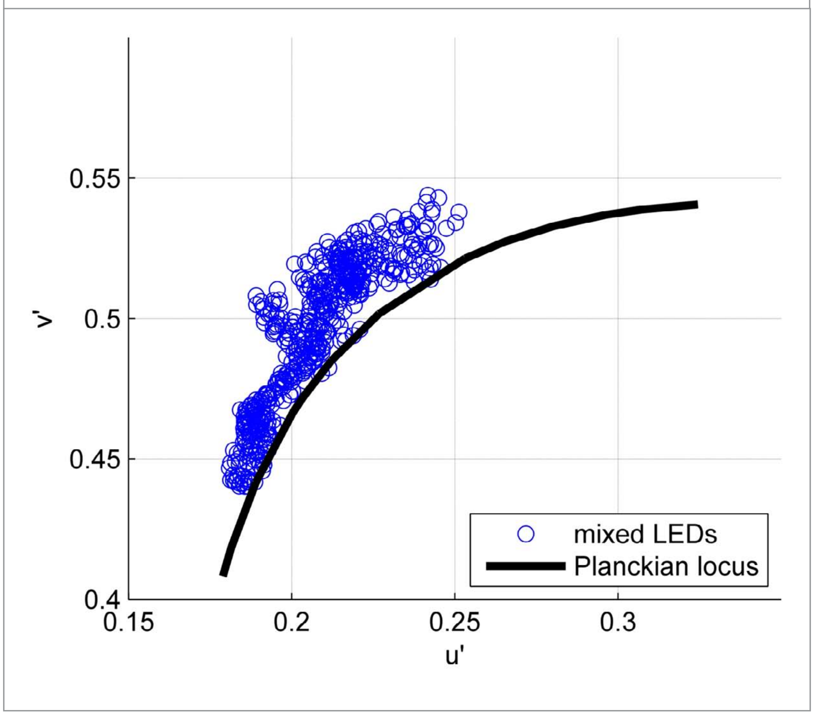

Figure 2: 516 mixed colors of RGBwWOcWnWA LEDs around the Planckian locus at 80°C

The aim of the first application is to measure mixed LED colors around the Planckian locus with an accuracy of Δu'v' < 0.003, which is not noticeable for the human eye. A following closed control loop could compensate the temperature-dependent color drift, which is shown in figure 1 for the combination RGBwWOcWnWA and temperatures of 20°C (Figure 1) and 80°C (Figure 2). The figure shows the Planckian locus (1800 K – 40.000 K), the single LEDs RGBwWOcWnWA and 516 mixed LED colors.

In this way 516 mixed colors are generated for each LED combination RGBcW, RGBwWcWA and RGBwWOcWnWA and measured with the MTCS sensor and the reference spectrometer at temperatures of 20°C up to 80°C with a step size of 10 K (Figures 1 and 2 on page 3).

A similar way is used to measure about 110 mixed colors for the other applications 2700 K, 4500 K and 6500 K.

Optimization

For a practical solution it is not desired to measure such a high amount of mixed colors at different temperatures in order to perform an optimization of the accuracy of the sensor. Because of that, the following, general approach is made for lamps with 4 or more LEDs. Decisions for the present applications are put in parentheses:

1. Selection of LED types (3 combinations: RGBcW, RGBwWcWA and RGBwWOcWnWA).
2. Localization of the desired color space (4 applications: Planckian locus, 2700 K, 4500 K and 6500 K).
3. Selection of several, uniformly distributed mixed colors in the localized color space (26 for Planckian locus, 20 for 2700K, 4500 K and 6500 K). Example: Figure 3 and 2700 K.
4. Measuring of each single LED for calibration use and of the mixed colors for optimization with the MTCS sensor and a reference spectrometer at a medium operation temperature (50°C medium operation temperature in a range of 20°C up to 80°C).
5. Searching the initial value and subsequent optimization to minimize the maximum / mean deviation of the mixed colors.

The Particle Swarm Optimization PSO minimizes the maximum deviation of the objective function during the search for the initial value (6). Afterwards the quasi-Newton method QNM optimizes the mean deviation Δu'v'. The additional penalty term in equation (4) is set to $\rho = 1$ to optimize the maximum deviation as well.

Table 1 shows the result for the four applications "Planckian locus", 2700 K, 4500 K and 6500 K of the three combinations RGBcW, RGBwWcWA and RGBwWOcWnWA at 20°C and 80°C. All combinations have a Δu'v' > 0.003 except for RGBwWcWA and RGBwWOcWnWA at 6500 K with the standard calibration method. The optimization improves the maximum Δu'v' from 0.0246 down to 0.0104. All maximum values are improved in average with -0.0028. The best results are reached for the combinations RGBwWOcWnWA and RGBwWcWA at 4500 K and 6500 K with a maximum Δu'v' smaller than 0.0023. These two applications can be measured with a high accuracy. The warm white 2700 K and the application using the Planckian locus have maximum Δu'v' between 0.005 and 0.0107 instead of 0.0069 and 0.0246 with the standard calibration.

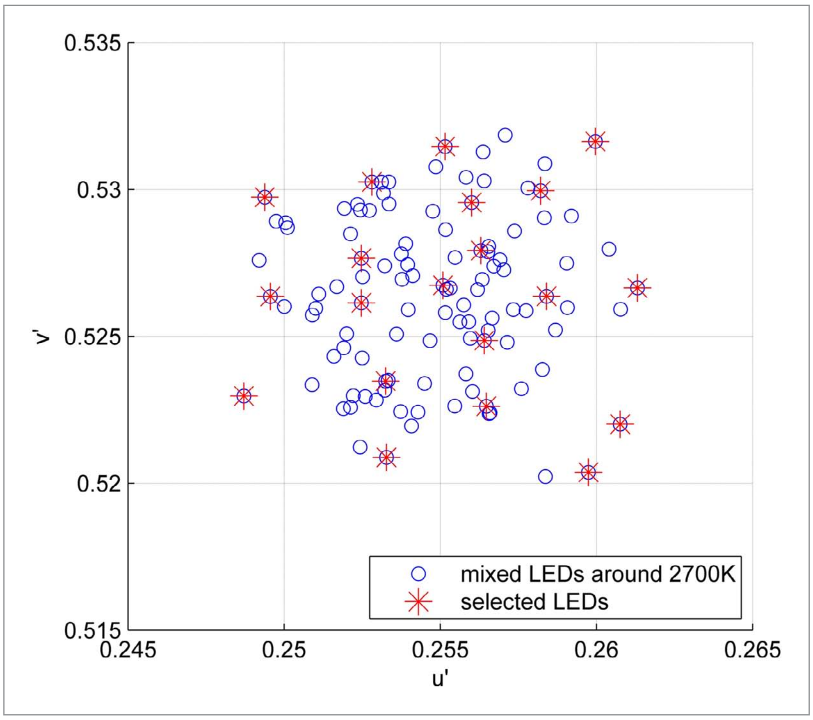

Figure 3: **110 mixed LEDs around 2700 K with 20 selected LEDs for the optimization**

Conclusion

It is demonstrated that the known intensity and wavelength drift of LEDs over temperature can be measured with true color sensors and the presented optimized calibration method. Here the application is focused on lamps with 4 or more combined LEDs. The aim of Δu'v' < 0.003 is reached for neutral white (4500 K) and cool white (6500 K) color temperatures. Further improvements needs to be done for warm white (2700 K) colors and applications, which need to use the complete Planckian locus.

The aim of a stable luminous color over the whole life time of a LED lamp can be reached with the optimized calibration method as feedback values for a closed control loop. Further investigations will be done regarding differentiated illumination levels and interpolations between selected applications. ■

Table 1:
Result of the optimization versus standard calibration

max Δu'v' (mean)					
application	combination	°C	standard	optimized	improvement
Planckian locus	RGBcW	20°C	0.0098 (0.0027)	0.0058 (0.0018)	-0.004 (-0.0009)
		80°C	0.0078 (0.0025)	0.007 (0.0022)	-0.0008 (-0.0003)
	RGBwWcWA	20°C	0.01 (0.0032)	0.0055 (0.0028)	-0.0045 (-0.0004)
		80°C	0.0074 (0.0023)	0.005 (0.0024)	-0.0024 (0.0001)
	RGBwWOcWnWA	20°C	0.0243 (0.0073)	0.0069 (0.0029)	-0.0174 (-0.0044)
		80°C	0.0246 (0.0055)	0.0104 (0.003)	-0.0142 (-0.0025)
2700K	RGBcW	20°C	0.0069 (0.0038)	0.0061 (0.003)	-0.0008 (-0.0008)
		80°C	0.0073 (0.0041)	0.0077 (0.0045)	0.0004 (0.0004)
	RGBwWcWA	20°C	0.0083 (0.005)	0.0055 (0.0027)	-0.0028 (-0.0023)
		80°C	0.007 (0.0037)	0.0053 (0.0032)	-0.0017 (-0.0005)
	RGBwWOcWnWA	20°C	0.0144 (0.0098)	0.0107 (0.0062)	-0.0037 (-0.0036)
		80°C	0.0096 (0.0064)	0.0073 (0.0048)	-0.0023 (-0.0016)
4500K	RGBcW	20°C	0.0056 (0.0017)	0.0044 (0.0031)	-0.0012 (0.0014)
		80°C	0.0078 (0.0015)	0.006 (0.0016)	-0.0018 (0.0001)
	RGBwWcWA	20°C	0.0029 (0.002)	0.0016 (0.001)	-0.0013 (-0.001)
		80°C	0.0035 (0.002)	0.0019 (0.0006)	-0.0016 (-0.0014)
	RGBwWOcWnWA	20°C	0.0033 (0.0025)	0.0018 (0.0008)	-0.0015 (-0.0017)
		80°C	0.0025 (0.0018)	0.0016 (0.0005)	-0.0009 (-0.0013)
6500K	RGBcW	20°C	0.0059 (0.0013)	0.0044 (0.0017)	-0.0015 (0.0004)
		80°C	0.0077 (0.0015)	0.0066 (0.0011)	-0.0011 (-0.0004)
	RGBwWcWA	20°C	0.002 (0.0011)	0.0016 (0.0008)	-0.0004 (-0.0003)
		80°C	0.002 (0.0007)	0.0022 (0.0004)	0.0002 (-0.0003)
	RGBwWOcWnWA	20°C	0.0026 (0.0016)	0.0023 (0.0009)	-0.0003 (-0.0007)
		80°C	0.0021 (0.0014)	0.0015 (0.0006)	-0.0006 (-0.0008)