Data-driven spectral sky models: A review

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Spectral power distribution of light plays a significant role in people's comfort, visual performance, as well as their psychological and physiological health. Yet, most daylight simulations rely only on photometric quantities. This paper presents a differentiated colorimetric approach based on direction specific spectral data. It opens with a review of existing spectral sky models and a comparison study of their accuracy based on a large dataset of spatially, spectrally and temporally resolved measurements conducted at the TU Berlin. To conclude with the next steps towards creating a novel model to describe temporal variability and spatial distribution of spectral daylight characteristics.

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Introduction

Spectral power distribution (SPD) of light can play a significant role in people's comfort, visual performance, as well as their psychological and physiological health. Yet, most daylight simulations to predict or investigate these visual and non-visual effects rely only on photometric quantities [1-3]. The colorimetric information is typically reduced to a global spectral irradiance or set to a correlated colour temperature (*CCT*) of 6500 K [4-5]. This implies a uniform distribution over the entire sky-dome, even though the spectral characteristics and the resulting *CCT*s, do not only vary over time, but also depend on the orientation of the analysed sky part. In order to include spectral characteristics in daylight studies, for example to incorporate new spectral weighting functions for non-visual responses or to assess the potential of spectrally selective fenestration materials, a differentiated colorimetric approach based on direction specific spectral data is necessary. This paper presents a review of existing spectral sky models and their accuracy based on a large dataset of spatially, spectrally and temporally resolved measurements conducted at the TU Berlin. The measurements and the comparison study of existing models are fundamental for the next steps towards creating a novel model to describe temporal variability and spatial distribution of spectral daylight characteristics.

Review of existing spectral sky models

Takagi *et al*. [6], Chain, Dumontier and Fontoynont [7], Chain [8] and Rusnák [9] suggest that the *CCT* of a specific sky patch corresponds to the sky patch's luminance (Figure 1).

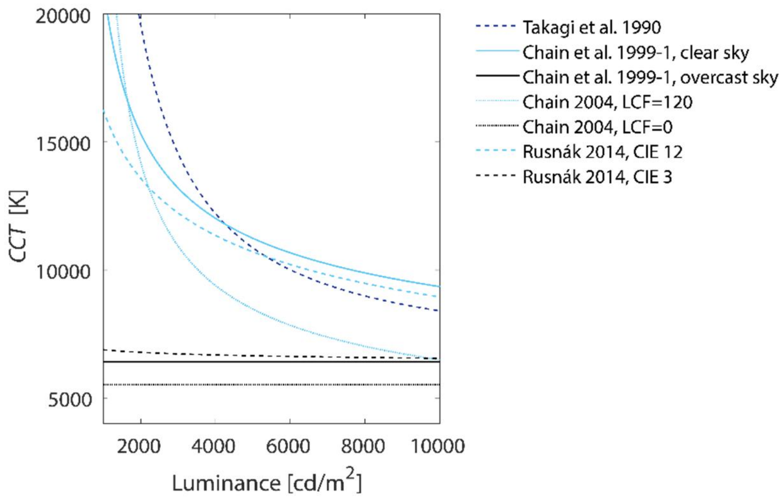

Figure 1: Current state-of-the-art, data-driven, spectral sky models based on the relationship between luminance and CCT *by: Takagi* et al. *[6] (--, dark blue), Chain, Dumontier and Fontoynont [7] (-); Chain [8] (...), and Rusnák [9] (---, light blue/black).*

Takagi *et al*. [6] first proposed an expression linking the luminance to the *CCT*.

$$CCT = \frac{1.1985 \cdot 10^8}{L^{1.2}} + 6500 \quad (1)$$

where L is the luminance at any point of the sky (cd/m²), *CCT* is the correlated colour temperature (K).

This formula is based on experimental measurement data conducted in Japan (the exact location was not stated), and according to Takagi and colleagues [13], it can be applied to any point in the sky under any weather condition.

The relation between luminance and *CCT* was confirmed by Chain, Dumontier and Fontoynont [7], who presented two novel models in which, however, this relation differs depending on weather conditions and, therefore, sky type. These models are based on spatially resolved spectral measurements conducted in Vaulx-en-Velin, France. The measurements were conducted manually with an aperture angle of 1° in 51 series of measurements in 77 directions. Chain, Dumontier and Fontoynont [7] observed three major tendencies:

i. for clear sky conditions: *CCT* values decrease as luminance values increase;
ii. for overcast sky conditions: the *CCT* can be considered uniform over the whole hemisphere and set to a fixed value of 6415 K;
iii. for intermediate sky conditions: the behaviour of blue and cloudy sky patches corresponds with the behaviour of clear and overcast skies, respectively.

For clear skies, the correlation between luminance and *CCT* was expressed with the fitting function, where the coefficients are the mean values observed for 36 series under clear sky conditions:

$$CCT = \frac{10^6}{-132.1 + 59.77 \cdot log_{10} L} \quad (2)$$

For the 6 series of overcast sky measurements, the fitting resolved to a mean constant value of:

$$CCT = (6415 \pm 133)\ K \quad (3)$$

The remaining 9 series corresponded with an intermediate sky, no general fitting function was formulated for intermediate sky conditions.

Further refinement of the method [8, 10], based on 101 single SPD measurements and a long-term validation with a total set of 56942 measurements from five chromameters combined with measurements of the Lyon IDMP station, led to the introduction of a new parameter called the Luminance Colour Factor (LCF). The LCF depends on the sky type and can be determined based on the sun height γ_S and sky clearness ε [8]. Chain [8] related the *CCT* distribution to the luminance distribution using the All-Weather model [11] and proposed one equation for all sky states:

$$CCT = \frac{10^6}{181.35233 + LCF \cdot (-4.22630 + log_{10} L)} \quad (4)$$

where the Luminance Colour Factor LCF is given by:

$$\text{LCF} = 21.56308 + (82.33165 - 0.77050 \cdot \gamma_S) \cdot (1.10439 + log_{10}(\varepsilon - 0.9)) \quad (5)$$

where γ_S is the sun height (°) and ε is the sky clearness according to Perez *et al*. [11].

Rusnák [9] measured the spectral characteristics of daylight with a mobile spectral sky scanner. The luminance to *CCT* correlation draws upon the sky type classification of CIE Standard General Skies in accordance with the ISO / CIE Standard [12]. This standard defines 15 sky types for clear, overcast, and intermediate skies with standardised luminance distributions. 89 series of measurements in 145 directions (spatial distribution according to Tregenza [13]) resulted in 12905 SPDs. One scan took approximately 5 minutes. Rusnák [9] transformed the expression used in Chain, Dumontier and Fontoynont [7] and determined the coefficients for all 15 CIE sky types:

$$CCT = \frac{10^6}{pL^q} \quad (6)$$

where the coefficients *q* and *p* are the mean values of the empirical measurements per sky type.

Consequently, these researchers proved a strong correspondence between the luminance of a sky patch and its *CCT*, which was further confirmed by measurements in Berlin and Beijing [5, 14]. For now, this luminance to *CCT* relationship is reflected in empirically fitted spectral sky models for three locations: Vaulx-en-Velin in France, Bratislava in Slovakia and Japan, for which the conditions are summarised in Table 1.

Paper	Measuring site	Length of record	Number of SPDs	Series of measurements	Sky division	Aperture angle	Scan time	Relates to luminance / radiance model
Takagi *et al*. [6]	Japan	n/a	n/a	n/a	n/a	n/a	n/a	-
Chain, Dumontier and Fontoynont [7]	Vaulx-en-Velin, France	Apr 1997-Sept 1997	3927	51	77	1°	5 mins	-
Chain, Dumontier and Fontoynont [10] Chain [8]	Vaulx-en-Velin, France	Oct 1999-Dec 2000	none, just x,y colour coordinates	11388	5	20°	n/a	All-Weather model
Rusnák [9]	Bratislava Slovakia	2011-2012	12905	89	145	11°	5 mins	CIE Standard General Sky

Table 1: Summary of existing spectral models based on the luminance to CCT *correlation.*

Problem statement

As shown in Figure 1 the review of existing data-driven, spectral sky models shows substantial discrepancies in the predictions of *CCT*s for clear sky conditions. The main research question thereby is: Which of the models performs best when validated against data from another location? (forecast accuracy analysis).

Methodology

A spatially and temporally dynamic light source such as daylight sets particular requirements for the measuring system. Spectral irradiance or radiance measurements must be carried out in short time frames. To combine luminance measurements with the spectral information, it is recommended to adopt the time frame for luminance measurements according to CIE [15], set to an upper limit of 2.5 minutes. The subdivision of the sky hemisphere, according to Tregenza [13, 15], results in 145 sky patches. The spectral irradiance must be measured within a maximum solid angle of 0.0289 steradian (11° aperture angle), for a bandwidth of 280 – 830 nm. A spectral sky scanner was built according to these specification requirements. It is one of the few measuring sites in the world gathering this kind of data. Spatially and temporally resolved spectral daylight measurements have been carried out at the TU Berlin since October 2014. Every second minute, the spectral sky scanner measures the SPD between 280 nm and 980 nm from 145 sky patches distributed over the entire sky-dome. The duration of a scan is one minute. This has resulted in over 30 million daylight spectra, and the measuring process is still ongoing. The measuring conditions for the data gathered in Berlin are listed in Table 2. The exemplary luminance and *CCT* distributions are shown in Figure 2.

Measuring site	Length of record	Number of SPDs	Series of measurements	Sky division	Aperture angle	Scan time	Relates to luminance/ radiance model
Berlin	since October 2014	> 30 Mio.	> 200 000	145	10°	1 min	CIE Standard General Sky

Table 2: Summarised measuring conditions for the data gathered in Berlin.

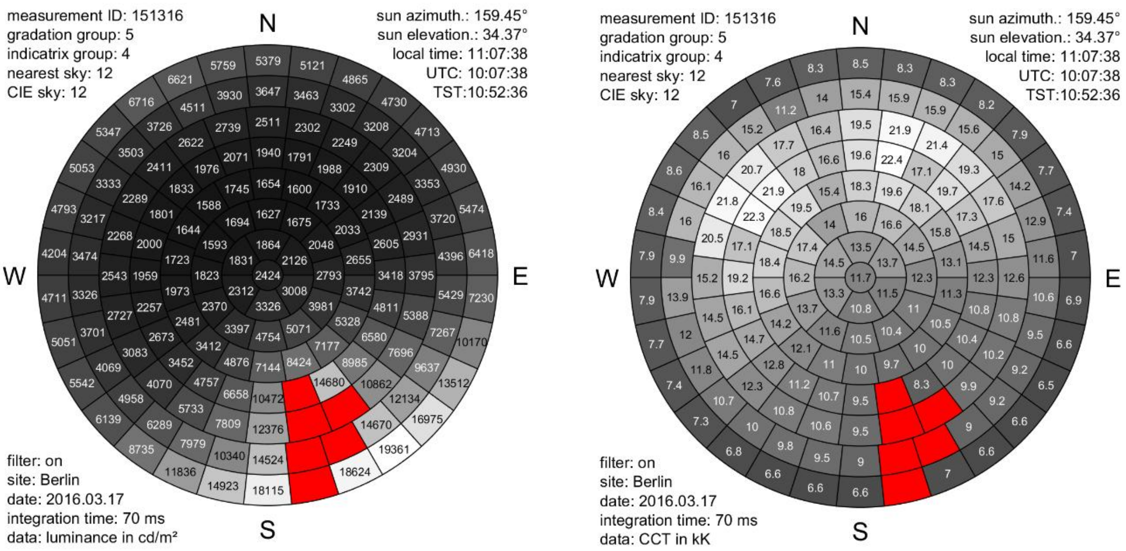

Figure 2: Exemplary luminance and CCT *distributions for a clear sky; Berlin 17 March 2016. The exemplary datasets are available for download at www.li.tu-berlin.de.*

The spatially resolved SPD measurements collected at the TU Berlin allow verification of the accuracy of the interrelation between the luminance and the *CCT* of a sky patch dependent on prevalent sky conditions of existing models. The research follows the big data approach. For this purpose, specialised data analysis and representation tools, as well as a database were developed. The luminance, chromaticity coordinates and *CCT* of each sky patch were derived from measurements. Subsequently, the relationship between luminance and *CCT* was modelled based on the SPD measurements for the 145 sky patches per scan. The research at the TU Berlin draws upon the CIE standard skies, which were derived from the luminance distribution as proposed by Kobav *et al*. [16]. The analysis sequence can be found in Figure 3.

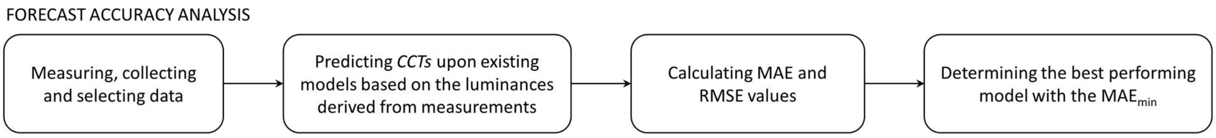

Figure 3: Schematic representation of the data analysis.

Results

The models by Takagi *et al*. [6], Chain, Dumontier and Fontoynont [7], Chain [8] and Rusnák [9] were used to predict the *CCT* based on the luminances derived from the measurements conducted in Berlin. The predicted values were subsequently compared with the measured data. For the comparison two sky types were considered, the CIE 12 (clear sky) and the CIE 3 (overcast sky) Standard General Skies.

For the analysis presented in this paper, only measurements between 1 January 2016 and 31 December 2016, for sun heights γ_S above 10° and UTC between 9:00 and 13:00 were used. This resulted in 58548 measurements for clear skies and 625288 for overcast skies. The measures mean absolute error (MAE) and root mean square error (RMSE) were used to estimate the discrepancy between predicted and measured *CCT* values. Table 3 illustrates the MAE and RMSE values between measured and predicted *CCT*s for clear (CIE 12) and overcast (CIE 3) sky conditions.

Spectral Sky Model	CIE 12		CIE 3	
	MAE (*K*)	RMSE (*K*)	MAE (*K*)	RMSE (*K*)
Takagi *et al*. [6]	2275	3734	14721	19707
Chain, Dumontier and Fontoynont [7]	1893	2532	384	564
Chain [8]	2182	2719	661	829
Rusnák [9]	1852	2421	641	759

Table 3: Mean Absolute Deviation (MAE) and Root Mean Square Deviation (RMSE) between measured and predicted values for clear and overcast sky conditions.

The comparison between the modelled and measured data for clear sky conditions shows no significant variation of the resulting RMSE and MAE for all fittings. All models show relatively high MAE and RMSE values. For overcast skies the model introduced by Chain, Dumontier and Fontoynont [7], performs best. The relationship between the computed and the measured *CCT*s for Chain [8], and Rusnák [9] are comparably good. The comparison showed that the Takagi *et al*. [6] model is unreliable for overcast skies.

Conclusions

In this paper, we presented a differentiated colorimetric approach based on direction specific spectral data. The review of existing spectral sky models showed that further improvement in the measurements and validation of the models is needed. Based on a large dataset of spatially, spectrally and temporally resolved measurements gathered at the TU Berlin a comparative analysis between the predicted and measured data was conducted. This comparison showed that the fittings for overcast condition from Chain, Dumontier and Fontoynont [7], Chain [8] and Rusnák [9] were performing comparably well, whereas the Takagi *et al*. [6] model is unreliable for this sky state. For clear skies no significant variation in MAE and RMSE values between the models was visible. The study revealed that for clear sky conditions a further analysis with a division into smaller *CCT* range categories is needed. The approach of Chain [8] and Rusnák [9] will be pursued further. The spectral sky models will be further refined and validated through TU Berlin measurements. The spectral sky models should be validated for different locations.

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