The impact of ambient temperature on the spectral characteristics of LED sources in the context of astronomical observations of the night sky

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Abstract—The Spectral Power Distribution (SPD) of artificial light sources is crucial in determining the extent of night sky degradation due to light pollution. External temperature affects the properties of LED lamps, including their SPD. In this study, we investigated the impact of ambient temperatures ranging from -25°C to 25°C on the spectral characteristics of 14 LED sources used in outdoor lighting. The obtained SPDs were then used to calculate the Scotopic Sky Luminance Ratio index, enabling the assessment of changes in night sky degradation.

The Member States of the EU must improve energy efficiency in the external lighting sector. LED technology, currently recognized as the most energy-efficient [1], offers significant opportunities in this regard. One of the least expensive ways to modernize lighting, especially in the case of park lighting fixtures, is to replace conventional light sources with LED sources [2, 3]. Sometimes, LED sources are proposed as a substitute for traditional light sources in street lighting. However, LED sources should not be installed in place of high-pressure sodium lamps in lighting fixtures with a reflector system designed for such lamps. This is because such a system may not meet the requirements for street lighting outlined in Polish standards.

Artificial lighting has many critical outdoor applications, enabling or improving human activities at night. However, it also leads to the adverse phenomenon known as light pollution (LP). The LP may be harmful to living organisms [4, 5] but has a detrimental impact on the night sky as well. Artificial light at night (ALAN) scatters in the atmosphere, causing the night sky to increase in brightness [6]. The contrast between the background and celestial object decreases as the sky becomes brighter. When the level of contrast is insufficient, conducting astronomical observations becomes challenging or even impossible. Artificial light is, therefore, a significant obstacle to professional astronomy, and, in addition, it negatively influences the general public's perception of the night sky [7]. In a broader sense, we are dealing with the degradation of the night landscape, as the sky is an integral part of it.

The transition from older artificial light sources, like sodium laps, to LED sources may amplify the problem of the degradation of the night sky due to two factors. The first one is related to the spectral power distribution of artificial light sources and light scattering. The most popular light source in outdoor lighting is a white LED, consisting of a blue diode covered with a phosphor. Such LED source emits a significant amount of light in the blue range of the spectrum. Short-wavelength light, i.e., blue, is scattered significantly more by the atmosphere than long-wavelength light [8].

The second factor is associated with the characteristics of human vision. In the case of observations by the general public of the night sky, they are made with eyes adapted to scotopic vision, which is more sensitive to short-wavelength light [9].

As demonstrated by [10], replacing discharge lamps with LED sources may significantly increase the brightness of the sky due to these two factors. However, another factor might influence the general public's perception of the state of the night sky, i.e., ambient temperature.

Light source manufacturers provide photometric and colorimetric parameters for an ambient temperature of 25°C. However, changes in ambient temperature significantly impact the properties of lamps [11, 12]. This is particularly important for light sources installed in outdoor lighting fixtures. These lamps operate in both summer and winter, exposing them to varying ambient temperatures.

One characteristic feature of LED sources is that ambient temperature induces changes in the SPD [12]. As far as we know, this factor has not yet been considered in studies of the impact of LED sources on the brightness of the night sky. In this paper, we try to fill this gap.

Fourteen LED sources for park lighting fixtures were placed in a climatic chamber to determine their SPD for ambient temperatures ranging from –25°C to 25°C with a step of 5°C. The results are shown in Fig. 1.

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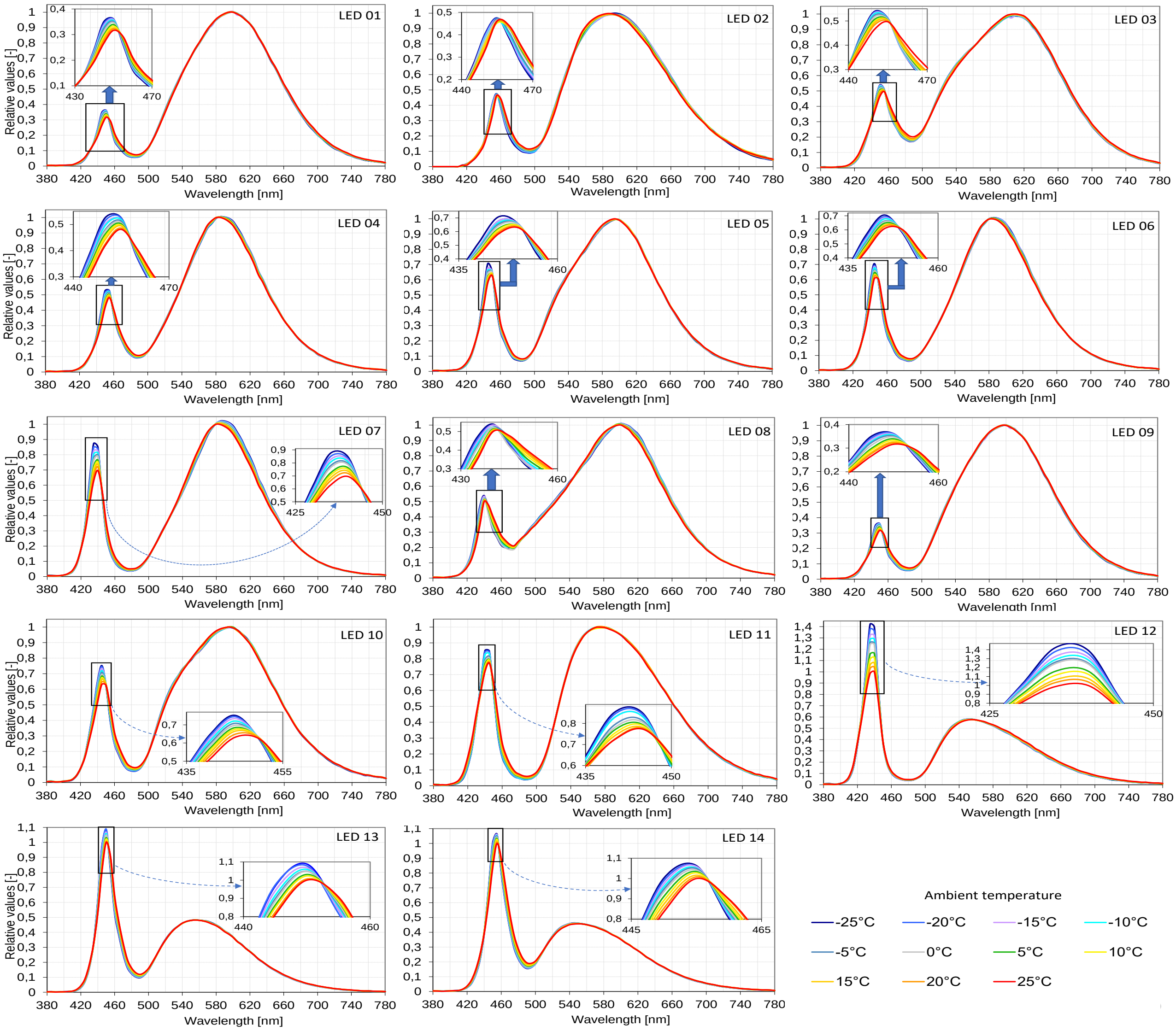

Fig. 1. Relative spectral characteristics of 14 LED sources for various ambient temperatures.

Most of the analyzed light sources (LED01–LED11) produce warm white light, which is desirable for minimizing the undesirable phenomenon of increasing night sky brightness. According to the European standard EN 12464-2:2014, warm light sources have a corrected color temperature (CCT) value below 3300 K. The last three LED sources have the following CCT values: LED 12 is about 5000 K, LED 13 is approximately 6600 K, and LED 14 is around 7300 K.

The most significant changes in SPD due to ambient temperature occur below 500 nm, which is the wavelength range most susceptible to atmospheric scattering. In some cases, we see an apparent increase in spectral power around 440–450 nm. The phenomenon is described in the literature [12]. To assess the impact of this change on the perceived brightness of the night sky during visual observations, we devised an index called the Scotopic Sky Luminance Ratio (SSLR), which is expressed by the following equation.

$$SSLR = \frac{\int_{380nm}^{780nm} S(\lambda)_n V'(\lambda)\,\lambda^{-a}\, d\lambda}{\int_{380nm}^{780nm} S(\lambda)_{n\_25} V'(\lambda)\,\lambda^{-a}\, d\lambda}, \quad (1)$$

where $S(\lambda)_n$ is the normalized spectral power distribution of an LED source at a given ambient temperature T, $S(\lambda)_{n\_25}$ – the normalized spectral power distribution of an LED source at T=25°C, $V'(\lambda)$ – spectral luminous efficiency function for scotopic vision, λ^{-a} – atmospheric scattering. We assumed a=2.0 as typical for areas with more air pollution (e.g., urban areas) [13]. This is because artificial light sources are typically associated with inhabited areas, where a higher concentration of aerosols often exists, which will result in more significant light scattering.

The spectra were normalized to eliminate variations in the luminous flux among the studied LEDs and different temperatures. Such normalization allows us to concentrate our analysis solely on temperature-induced changes in the spectral characteristics of LED sources, i.e., the shape of their spectrum.

$$S(\lambda)_n = \frac{S(\lambda)}{\int_{380nm}^{780nm} S(\lambda)_{n\_25} V(\lambda)\, d\lambda}, \qquad (2)$$

where $S(\lambda)$ is the unnormalized spectral power distribution of an LED source, and $V(\lambda)$ – spectral luminous efficiency function for photopic vision.

The SSLR index has a simple interpretation. Its SPD at T=25°C serves as the reference state for a given LED source. Thus, for all the studied LED sources at T=25°C, the SSLR equals 1.0. A value of the index greater than 1.0 indicates that the perceived brightness of the night sky is higher than in the reference state. On the other hand, a value less than 1 indicates a darker sky.

The SSLR values for all 14 examined LED sources at all applied temperatures are presented in Fig. 2.

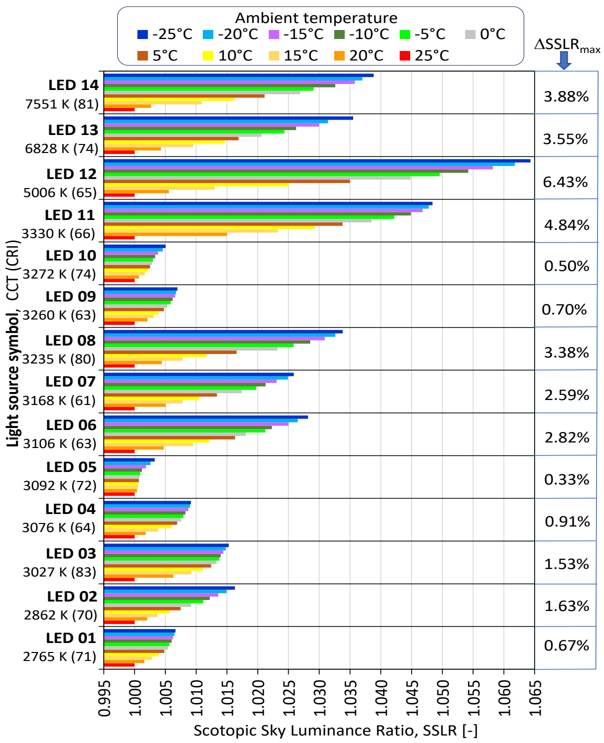

Fig. 2. Graphic visualization of calculated SSLR indices for 14 LED lamps operating at various ambient temperatures.

Under the light source symbol, the correlated color temperature (CCT) values and the overall color rendering index (CRI) are given on the vertical axis. The given values (CCT and CRI) refer to an ambient temperature of 25°C.

For each LED source, the lowest index value is at T=25°C (SSLR=1.0) and increases with decreasing temperature. Thus, we expect that the perceived brightness of the night sky will be higher in winter than in summer. Generally, the relationship between temperature and SSLR is non-linear. Moreover, the maximum determined increase in the index,

$$\Delta SSLR_{max} = \left(SSLR_{T=-25^oC} - SSLR_{T=25^oC}\right)\cdot 100\% \qquad (3)$$

varies for different sources, ranging from 0.33% (LED05) to 6.43% (LED12). We found no correlation between $\Delta SSLR_{max}$ and CCT and between $\Delta SSLR_{max}$ and CRI. Thus, providing a simple mathematical formula for calculating SSLR for any LED and chosen ambient temperature is impossible. The only way to determine SSLR is through laboratory measurement.

The key finding of our study indicates that the SSLR index shows minimal variation across the range of air temperatures recorded in Poland throughout the year [14]. During the coldest winter nights, SSLR is expected to show only a minimal increase, not surpassing a few percent compared to the warmest summer nights.

In summary, temperature-induced changes in the spectrum shape of LED sources are not expected to play a significant role in the degradation of the night sky as perceived in visual observations. It should be noted that this conclusion applies under the assumption of constant luminous flux (see eq. 2). This assumption is not purely theoretical. In practice, the luminous flux of LED sources could be maintained at a constant level through smart control. However, it is impossible to influence the change in the spectrum's shape.

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