Spectrum of daylight and sky type

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Keywords: daylight, spectral characteristics, sky type

1. INTRODUCTION

Spectral characteristics of daylight in conjunction with internal lighting change during the day and subconsciously affects on the people in the room. When we want to understand the interior spaces in terms of overlapping spectra of the daily and artificial light, is necessary to carefully examine the spectral characteristics of the daylight at various situations, not only in the overcast sky. In the future we will not be interested how much amount of daylight will be in interior, but the design of lighting systems will be addressed and will to find optimal value of the individual components of the spectral characteristics of artificial light sources and daylight, that the physiological and psychological point of view was best for man.

2. HISTORICAL DEVELOPMENT OF SPECTRAL CHARACTERISTIC FROM THE VIEWPOINT OF LIGHT TECHNIQUE

At the end of the 19th century, Vogel, [1], executed first measurements of spectral distribution of solar radiation with the selected benchmarking flame of kerosene lamp standard. Initial measurements were experimentally simple, performed for a limited range of wavelength with measurement step more than 20 nm. Nichols & Ives [2, 3] processed the measurement of spectral distribution of daylight and they normalized measured spectrum to a defined light source and to the sensitivity of the human eye. Between years 1912 to 1923, the shape of the spectral characteristics of sunlight changed, and began to resemble the shape of the today spectrum, with the exception of selected properties of the atmosphere, which were discovered later. For example, Ornstein et al. [4], calculated the spectral distribution including the altitude of sun and cloud conditions. Deirmendjian and Sekera, [5], found a dependence of the spectral distribution of diffuse radiation from different heights zenith angle. Interesting were comparisons of solar radiation on the northern and southern sky. The measurements were then used in the standardization of the spectral distribution of solar radiation. Henderson and Hodgkiss, [6], recommended normalization of the spectral characteristics at λ = 560 nm. Judd et al. [7], determined the spectral distribution of daylight, which is recommended today, and later were mathematically interpolated values at interval 5 nm. In 2001, Hernandez - Andrés et al. [8] made a clear measurement of the sky type. Measurement of the sky type was based on then current standard of CIE. The authors focused mainly on reconstruction of the spectral characteristics of daylight sky hemisphere by measuring individual elements. Measurements accomplished in 44 elements, at different azimuths and almucantarats. With experimental measurements and calculations originated a wide ranges of models of spectral characteristics.

3. SPECTRAL CHARACTERISTICS OF DAYLIGHT

Daylight is part of sunlight, which human eye perceives in the interval of approximately 380 to 780 nm. The sun radiates most intensely at a wavelength of 501 nm, which is very close to the maximum spectral sensitivity of the human eye *V(λ)*. Spectral composition of daylight indicates that the filtering of certain constituents of solar radiation occurs in the atmosphere. In particular, action of processes light of absorption and scattering on the particles and molecules in the atmosphere. Each source has own characteristic spectral curve. Daylight is specific in that curve changes during the day. Emitted light from the Sky and the Sun varies not only in the intensity of radiation, but also changes the shape of the spectral characteristics. Daylight is represent the linear absorption spectrum, which can be described as radiant flux Φ_e [W], defined as

$$\Phi_e = \int_{\lambda_1}^{\lambda_2} \phi_{e,\lambda} (\lambda_i) \Delta\lambda \qquad (1)$$

where $\Phi_{e,\lambda}$ is the spectral radiant flux density [W / nm], $\Delta\lambda$ is the length of interval wavelength [nm]. The radiant flux belong the each wavelength, which indicates the amount of energy. CIE defines the phases of daylight, labeled D, coordinates of chromaticity and color temperature, table 1.

Table 1 Temperature and coordinates of chromaticity of standard light sources of daylight according to CIE, [9].

Standard	CIE 1931 2°		CIE 1964 10°		T [K]
	x	y	x	y	
D50	0,34567	0,35850	0,34773	0,35952	5003
D55	0,33242	0,34743	0,33411	0,34877	5503
D65	0,31271	0,32902	0,31382	0,33100	6504
D75	0,29902	0,31485	0,29968	0,31740	7504

The transitions between colors in the spectrum of daylight are continuous, so it is not possible set range of single wavelength of colors. Daylight provides the best perceived color and space, but also creates the best visual conditions, comfort and well being. It is well known relation intensity lighting and the composition of daylight and with biological rhythms of man, in the case when is lack in part of spectrum of artificial sources that so may present health problems.

Spectrum daylight changes very quickly and it is not possible to perfectly predict what will have the spectral characteristics shape, an example of changes correlated color temperature (CCT), figure 1, and as a dynamic system is changing with the position of the observer. Predicting the spectral characteristics allowing us to partly atmospheric - physical models, but they are not tied to the needs of lighting techniques. Discovering the spectral characteristics of the various states of the sky, we gain an overview their properties.

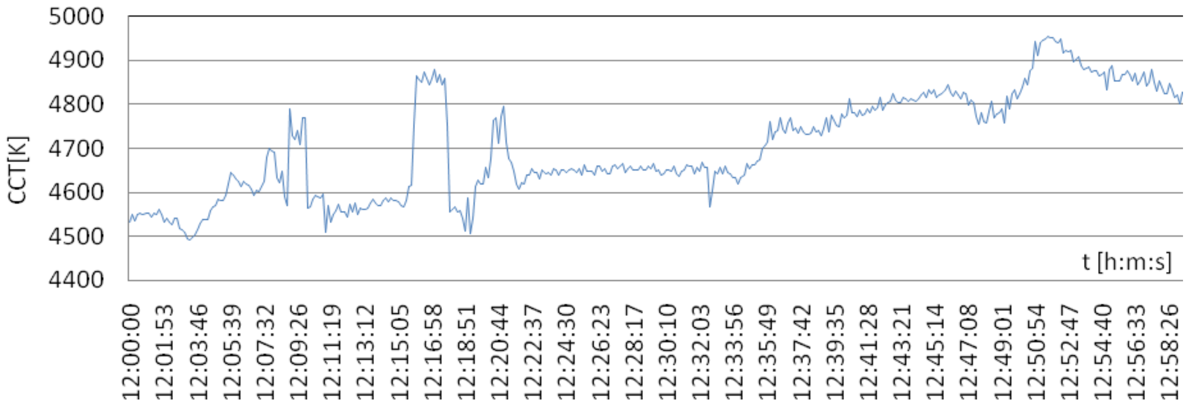


Figure 1 Changes in CCT of daylight for one hour.

In the following tests will be presented spectral characteristics of daylight in terms of lighting techniques, which will be evaluated and be traceable to the sky types defined by the CIE.

4. MEASUREMENTS AND RESULTS OF MEASUREMENTS OF SPECTRAL CHARACTERISTICS

The solution for determining the spectral distribution is based on numerical calculations and experimental measurements, the description is on figure 2. Model proposed Chain et al., [10], which set the dependence of luminance and color temperature in various situations on sky.

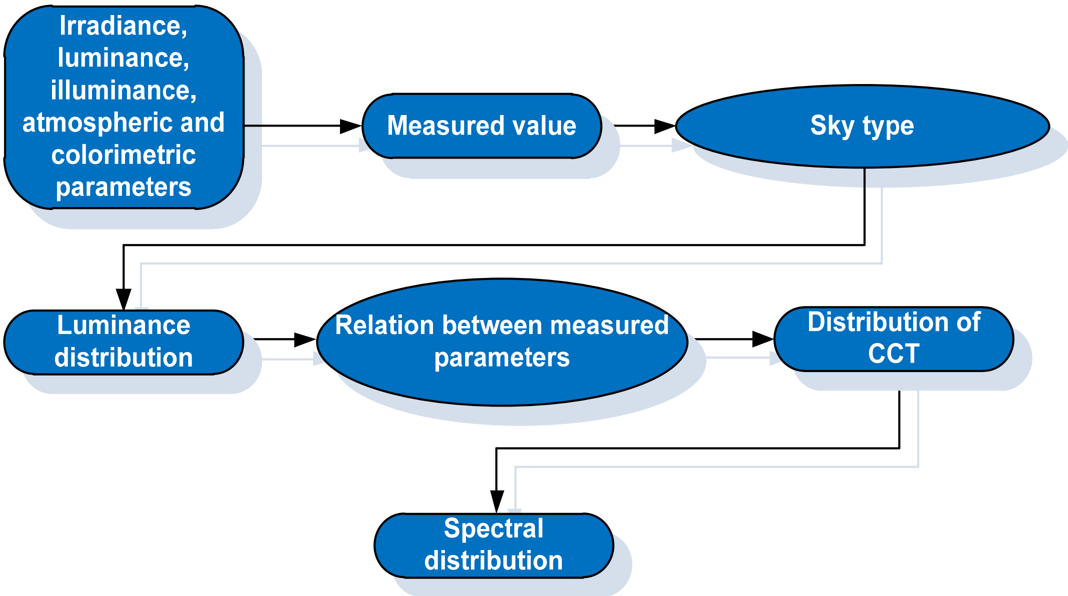


Figure 2 Comprehensive measurement and evaluation of spectral characteristics. [10]

The validity of these expressions on the current model of sky types according to CIE S011 / E: 2003, table 2, is not verified, since the solution is valid for sky types expressed by Perez. This sequence chain measurement and evaluation, indicates how verify measured data of the sky type in terms of spectral characteristics.
Choice of input variables is an important element, since there befall of two areas of the measurement: specific parameters sky type and evaluation of their measurements. For accurate measurement of the spectral characteristics of sky type, we must measure all elements of the sky. Expression of all spectral values of the sky, we are near to the actual issuance of the spectral characteristics of the Sky system.

Table 2 Description of the sky types, [11].

Sky	Description of luminance	Sky	Description of luminance

type	distribution	type	distribution
I.1	CIE Standard Overcast Sky, alternative form Steep luminance gradation towards zenith, azimuthal uniformity	IV.2	Partly cloudy, with the obscured sun
I.2	Overcast, with steep luminance gradation and slight brightening towards the sun	IV.3	Partly cloudy, with brighter circumsolar region
II.1	Overcast, moderately graded with azimuthal uniformity	IV.4	White-blue sky with distinct solar corona
II.2	Overcast, moderately graded and slight brightening towards the sun	V.4	CIE Standard Clear Sky, low illuminance turbidity
III.1	Sky of uniform luminance	V.5	CIE Standard Clear Sky, polluted atmosphere
III.2	Partly cloudy sky, no gradation towards zenith, slight brightening towards the sun	VI.5	Cloudless turbid sky with broad solar corona
III.3	Partly cloudy sky, no gradation towards zenith, brighter circumsolar region	VI.6	White-blue turbid sky with broad solar corona
III.4	Partly cloudy sky, no gradation towards zenith, distinct solar corona		

4.1 Testing and results of the spectral characteristics of the sky types

Measurement of the spectral characteristics of daylight took place a long time in several seasons and different climatic conditions. Measurements were performed at noon and afternoon, because morning smog causes changes in the atmosphere. Measured parameters were global horizontal irradiance *(G_V)*, and this corresponding diffuse horizontal irradiance *(D_V)*, where was used correction method by Drummond, [12], on the shadowing element. At the same time were measured also colorimetric parameters. Total number of measurements of spectral irradiance is 400, figure 4, where the sky types were determined on the basis of proportional coefficient L_Z / D_V, figure 3. Method is based on the computation of the ratio between the zenith luminance and the diffuse horizontal illuminance obtained from the measurements. The value is compared with the theoretical value of 15 CIE sky types. If the value is in the range 2,5 %, there is probability of compliance. When we will use proportional coefficient direct horizontal illuminance *(P_V)* and extraterestrial horizontal illuminance *(E_V)* P_V / E_V, we will reaching the same result identification of types of sky, as it applies

$$P_V = G_V - D_V \qquad (2)$$

Measurements were performed for different solar altitude γ_S and they cover different situations in the sky.

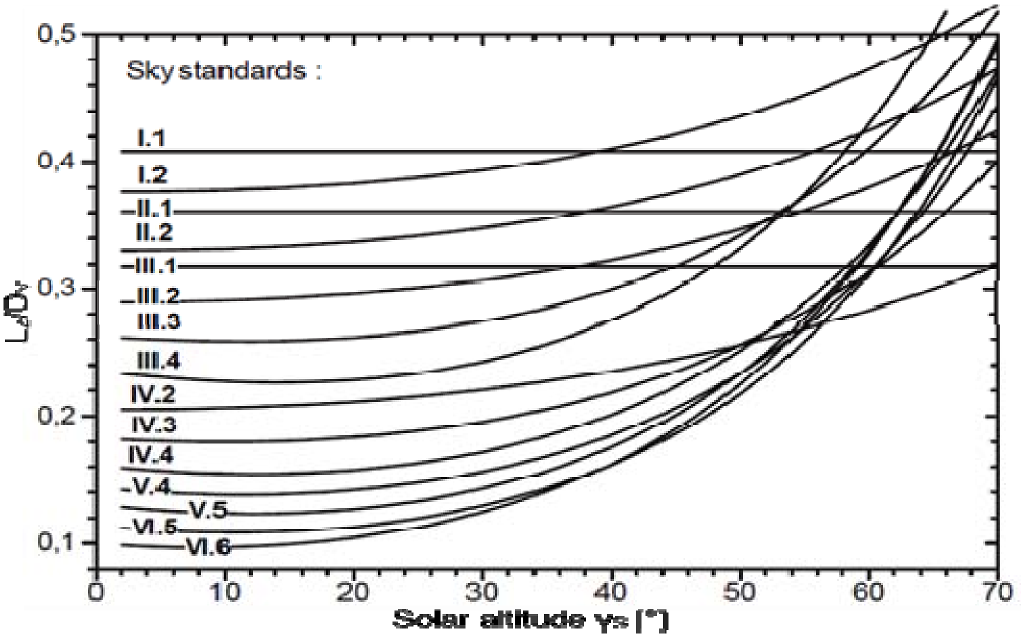


Figure 3 Sky types identification by L_Z / D_V [13].

To measure was chosen low cost device spectrophotometer Ocean Optics USB2000 with spectral range of measurement from 175 to 874 nm. Previous measurements [14], we proved that the instrument for measuring daylight has expanded uncertainty U = 7.26% for k = 2, which advises the device to the group C categories based on instrumentation for measuring solar radiation under the WTO [15]. In previous contribution, we determined coefficient to calculate the luminance for this device. At measurements we were used neutral density filters of known spectral transmittance value of 13.82% and 31.82%. All measurements were worked on the base of recommended procedures and methods.

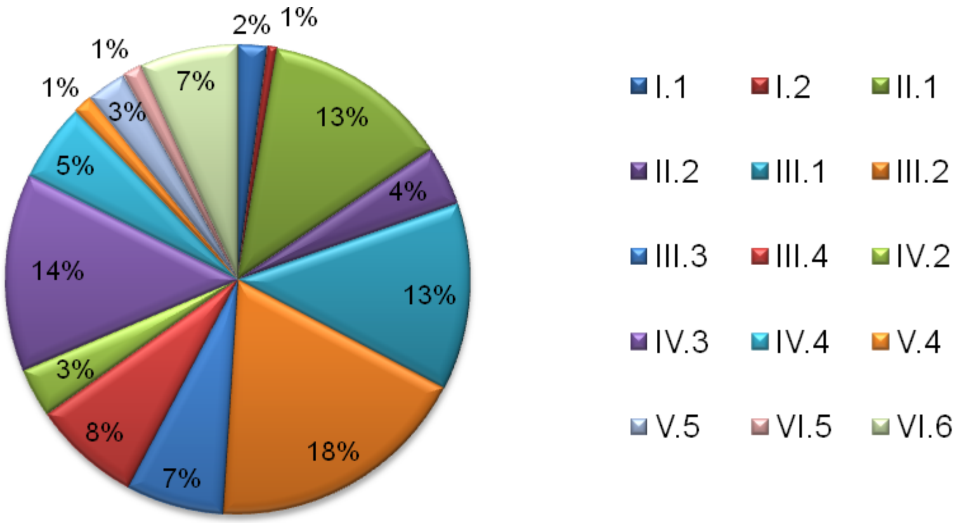


Figure 4 Percentage values of measure of sky types.

Situations without direct sunlight accounted for 33% of the total number of measurements, situation with direct sunlight are in 17% cases, partially covered sky clouds occurred in 50% of measured values.

CIE defines a numerical method for calculating the spectral characteristics based on the value of color correlated temperature *T* [K], [9]. Coordinates of chromaticity daylight x_D, y_D were evaluated based on measurements of global solar radiation and the replacement of CCT, figure 6. The value of color temperature has been chosen as an indicator of the type of the sky. Graph, figure 5, indicates the average value of chromaticity different types of sky. Sky type IV.4 showed average chromaticity 7089 K, which is compared to the remaining types higher.

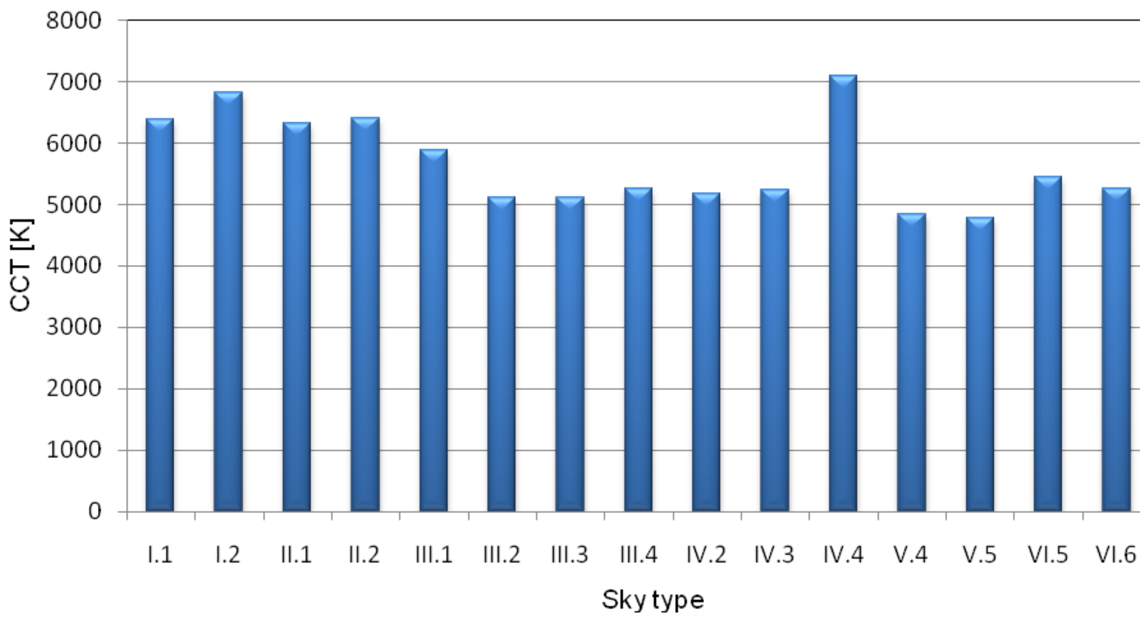


Figure 5 Values of CCT of sky types on the basis ratio L_z / D_v.

Table 3 Average values of sky types CCT.

Sky type	I.1	I.2	II.1	II.2	III.1	Average
Average CCT [K]	6387	6831	6320	6415	5887	6368
Standard deviation [%]	4,99	6,30	18,54	5,56	0,61	3,32
Sky type	**III.2**	**III.3**	**III.4**	**IV.2**	**IV.3**	**Average**
Average CCT [K]	5105	5107	5261	5166	5227	5173
Standard deviation [%]	19,46	0,53	2,42	12,95	0,34	1,09
Sky type	**IV.4**	**V.4**	**V.5**	**VI.5**	**VI.6**	**Average**
Average CCT [K]	7089	4847	4754	5454	5255	5485
Standard deviation [%]	4,73	1,91	0,92	12,83	0,08	11,69

CCT of different sky types is variable and for different types have been reported standard deviations table 3. Tolerances are indicating the variance values for a each type of sky. For the type VI.6 was recorded deviation 0.08%, which represents more than 99.9% identity CCT for a clear sky, opposite this the sky type III.2 shows ~ 20% of the variance values of CCT.

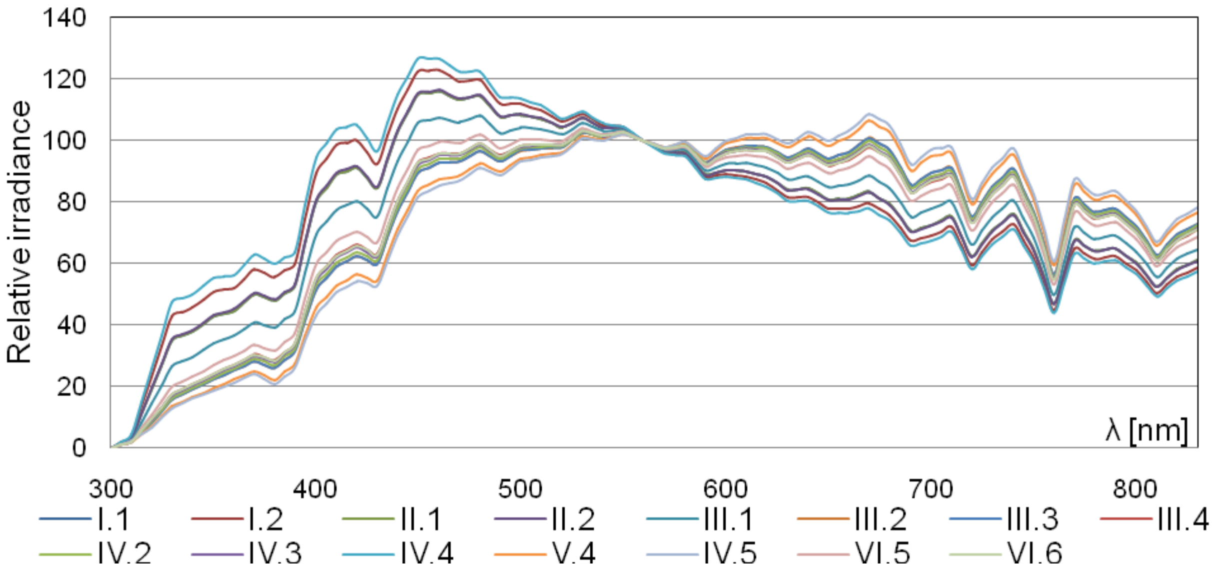


Figure 6 Average spectral characteristics of the sky types.

Global irradiances were measured with colorimetric parameters, we checked the condition of the distance DC < 5.4 * 10^{-3} daylight from black body locus (BBL), figure 7. All values, that did not meet criterion about distance from BBL, they were excluded from test.

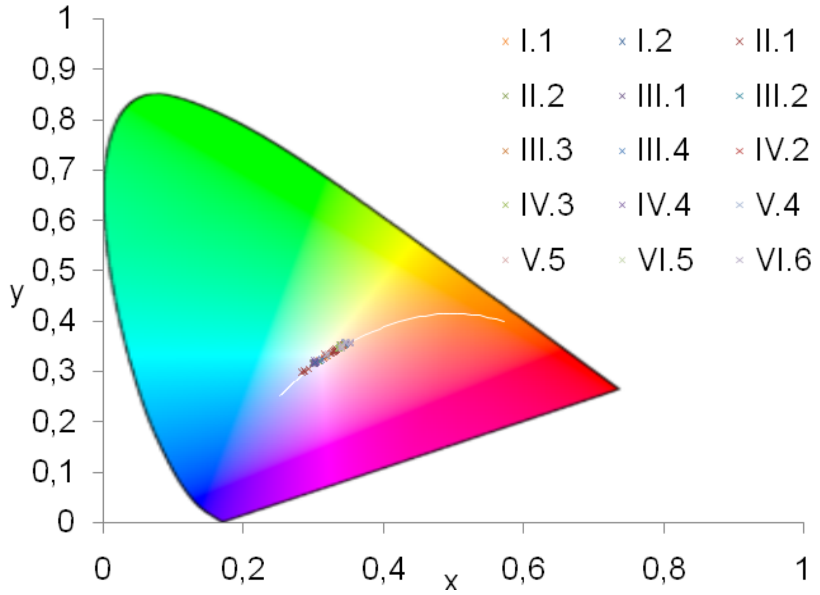


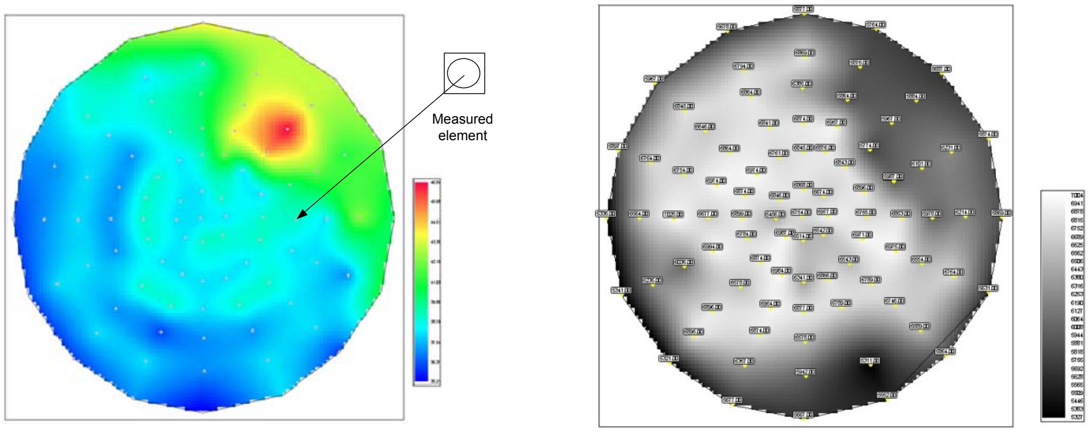
Figure 7 Chromatic diagram CIE XYZ. Around BBL are marked coordinates of the measured sky types.

When the sky types will divide into categories without direct sun, direct sun and overcast sky types, then we have value for category without Sun is CCT 6328 K, which corresponds to the standard D65. Category of sky types with direct sunlight have CCT 5485, that is near the D55 standard and the situation with scattered partially clouds can attributable to the standard D50, table 3.

4.2 Testing and results of the spectral characteristics of the elements sky

Measurements were made in the network of 89 points, while zenith element was measured at the beginning and end of measurement for control of equal value. We used 2° observer and were measured radiation, photometric and colorimetric values. In the test was used tube with 10° optical element. Measurements were carried out for all almucantarats 0° to 90° with step 15° and the azimuth from 0° to 360° in steps of 22.5°. Scan was obtained in 7 minutes. Identification of the sky type, figure 9, was carried out by the proportional coefficients, and the results were $G_v / E_v = 0.19$, $D_v / E_v = 0.19$ and $L_z / D_V = 0.40$ for given γ_S. The coefficients are valid for type sky I.2, which is an overcast sky with gradations of brightness and increased brightness at the sun. Between the individual elements was carried out approximation of values, figure 8.

Each point in the sky hemisphere is emitting spectral characteristic. Amplitude and its spectral lines will change depending on the current position on the hemisphere.



(a) (b)

Figure 8 (a) Luminance distribution on the sky type. (b) CCT distribution in the individual elements.

Perceptible influence of Sun over the cloud of type stratus at southern sky CCT slightly increased. Coordinates of chromaticity obtained by the CIE algorithm with resolution of 5 nm are shown in figure 9.

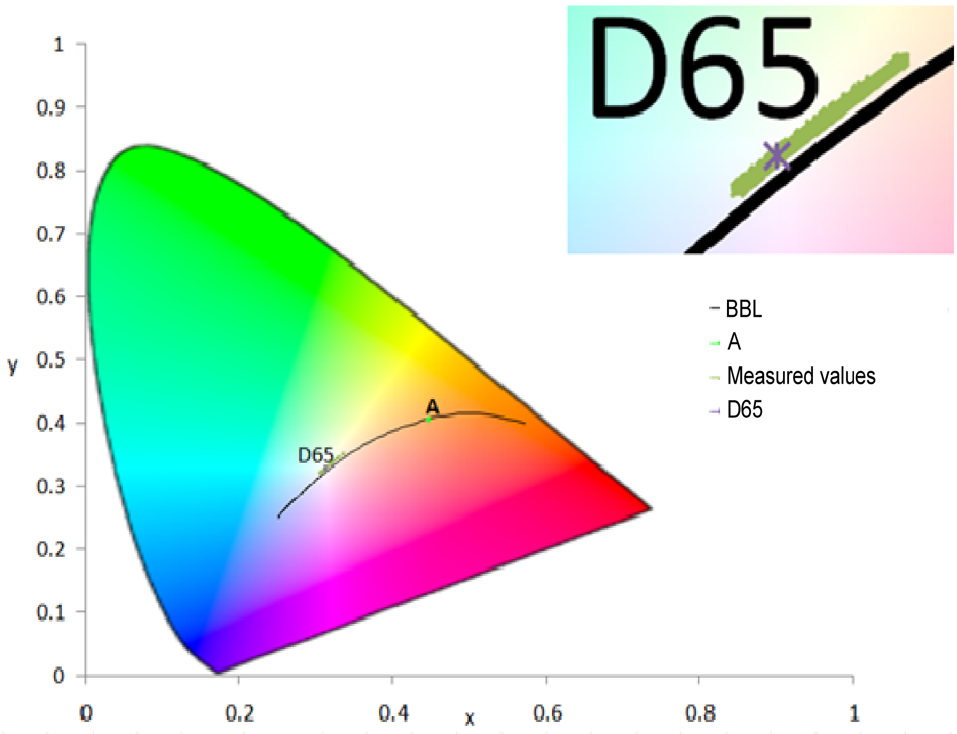


Figure 9 Coordinate of chromaticity of daylight measured on the sky type.

When measure the sky type is recorded interval of color temperature from 5 311 K on the horizont to the value 7025 K on the hemisphere, figure 10. This represents a significant difference of variance in terms of individual elements on the sky. Mean

CCT was 6450 K, with a standard deviation of 6.86% and the coordinates of chromaticity are x_D = 0,3135 and y_D = 0,3299.

Value CCT of type I.2 in the previous test was 6830 K. With Retroactive check, is assessment of sky type on base of elements fall into the category of sky I.2, considering the calculated a standard deviation.

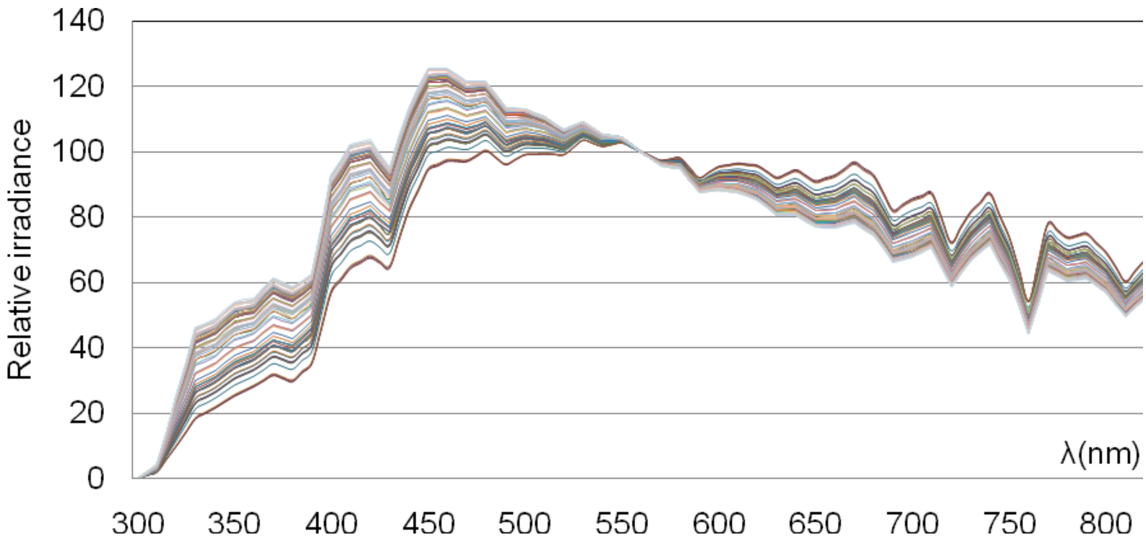


Figure 10 Spectral characteristics of 89 elements in the sky type.

With measurement of almucantarats we will achieve an accurate understanding lighting values and their distribution on the hemisphere. Collectivizing data from measurements we can be achieved creating sets of spectral characteristics for under CIE sky types. Often we encounter with defining the expression of daylight by coordinates of chromaticity. In assessing in view of the sky types, we could be explored the location of coordinates of chromaticity in various types of sky, eventually elements on the hemisphere and to examine the distribution of coordinates of chromaticity.

5. CONCLUSION

Spectral characteristic of daylight can be predestinated mathematically, but it is difficulty on processing of the amount of data, computing capacity and complexity of the calculations. Consideration of all components are affecting the real scattering and absorption in the solar spectrum, we come to the conclusion that it is possible to express the spectrum daylight simplified relationships, verified by experimental measurements. Currently there is no exact mathematical model for solving the spectral characteristics of daylight, or solar radiation. Atmospheric models are sufficiently precise, more focused on physical expression of daylight, but are not linked to the needs lighting techniques. Spectral characteristic of daylight is defined by CIE standard, which is affected by using only two vectors in the calculation.

Measuring the sky, we have shown how a sky system dynamically changes the spectral characteristics. With parameterization of results we will be closer to knowing the different types of defined sky. More precision conclusions we reach a greater number of measurements.

On the decomposition of the spectral characteristic of daylight indoors has influenced by transmission material and with structure of material. Those facts it will be necessary in the future to take into account in design of lighting spaces, we should therefore be thoroughly familiar with the spectra of daylight.

Acknowledgment

Work was supported by the Operational Programme "Research and Development" and the European Fund for the project ITMS 26220220150, entitled "Research Center of Light and lighting technology."

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