Simulation of sky luminance according to CIE standard DS 011.2

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1. Abstract

For over half a century, the experts have been trying to describe the daylight and sky luminance distribution with different models. Different approaches were used to describe the luminance of sky in different weather and climatic conditions. But until recently only two types of sky had been standardised: The CIE Standard Clear Sky and Overcast Sky. As the use of daylight is gaining on importance in the lighting design, the TC 3 at CIE also started drafting a standard description of other types of sky between clear and overcast sky. The new standard has been adopted in March 2003 and it will be used in calculations of lighting conditions in interiors lit by natural daylight. In the paper, the new CIE standard is described together with two computer programmes developed in our laboratory. The first programme is used for calculation of the position of the sun according to the point of observation on the earth and time (date). The position of the sun is then used in the second programme for calculation of the sky luminance distribution according to the proposed standard. The programme calculates the luminance of 77 patches representing the sky vault. The luminance of this sky model will then be used for calculating lighting conditions in interiors lit by daylight.

Index terms— daylight, calculating sky luminance, CIE standard, clear sky, overcast sky,

2. Introduction

Natural light has always played an important role in human life. Our life and work are still very much connected with daylight, although we are able to illuminate interiors with artificial light. The human rhythm of work and rest and the chemical processes in our body do follow the sun's path on the sky. Lack of visual contact with the sun has a depressive effect on people. People lose track of time and the will to work. This is why natural light is so important for interiors and has a significant influence on the appearance of such spaces and quality of life in these premises.

It is necessary to be familiar with the daylight that is coming into a room through windows or window openings to design buildings and lighting in an appropriate way, knowing the daylight is also important when simulating and modelling power losses for air-conditioning. When calculating daylight in indoor spaces we face different problems. Daylight is depending on the date and hour of calculation, on orientation of the window(s) or window openings, on location of the building (geographical latitude) and above all on the type of sky, clear or overcast. To calculate the contribution of daylight in indoor lighting it is necessary to know the distribution of sky luminance for different climatic conditions, for different sky conditions and different times. Time and climatic functions are relatively simple to describe, but there are problems with describing different sky conditions. Most of the programmes for daylight simulations calculate daylight only for two sky conditions. The first one is CIE clear sky, the second is CIE overcast sky. Measurements made in the last 20 years have shown that calculating with only two different sky conditions is not satisfactory any more.

The focus of the work of the CIE Technical Committee 3 was to describe and define most frequent sky conditions. Authors, who have been working on this field for longer time, have described a number of different sky conditions between clear and overcast [3],[4]. The outcome that describes relative sky luminance was adopted as a CIE standard in March 2003.

3. Standardisation of sky luminance distribution

The first CIE standard for nonuniform sky luminance distribution was described by Moon and Spancer in 1942. Changes of luminance from horizon to zenith in ratio 1:3 were described by trigonometric function:

$$\frac{L_\gamma}{L_Z} = \frac{1 + 2 \cdot \sin\gamma}{3} = \frac{1 + 2 \cdot \cos Z}{3}, \qquad (1)$$

where:

L_γ is luminance of a sky element in cd/m^2,

L_Z is luminance of zenith in cd/m^2,

γ is angle of elevation of a the sky element above the horizon,

Z angular distance between the sky element and zenith ($Z = 90^0 - \gamma$).

The luminance distribution of clear sky was described by Kittler and was, together with CIE overcast sky, published as ISO/CIE standard in 1996 [8].

$$\frac{L_\gamma}{L_Z} = \frac{(1 - e^{-0.32/\sin\gamma})(0.91 + 10 \cdot e^{-3\chi} + 0.45 \cdot \cos^2 \chi)}{0.274 \cdot (0.91 + 10 \cdot e^{-3Z_S} + 0.45 \cdot \cos^2 Z_S)}, \qquad (2)$$

where:

χ is angular distance between a sky element and sun,

Z_S zenith distance of the sun.

In March 2003 a new ISO/CIE standard was published. The new standard is an outcome of the CIE TC 3-15's work. It's based on measured data in Tokyo, Barkeley and Sydney. Different sky conditions are arranged in 15 sky types, 5 for clear sky, 5 for overcast sky and 5 for partly overcast sky. Sky types are described by use of gradation and indicatrix function.

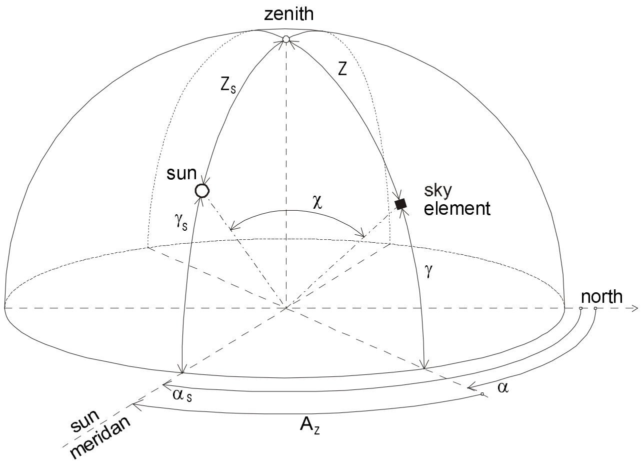

Fig. 1. Angles defining position of a sky element and the sun.

4. Calculation of relative sky luminance using the new CIE standard.

Position of the sun, the sky element and also parameters *a, b, c, d, e*, which describe climatic conditions, are input data. The position of the sky element is described by zenith angle Z and difference in the azimuth between the solar meridian and the sky element (see Fig. 1) and (3).

$$\chi = \arccos(\cos Z_S \cdot \cos Z + \sin Z_S \cdot \sin Z \cdot \cos Az), \tag{3}$$

where:

$$A_Z = |\alpha - \alpha_S|.$$

Relation between the luminance of a sky element L_γ and the luminance of zenith L_z is described by equation from former CIE standard for clear sky.

$$\frac{L_\gamma}{L_Z} = \frac{f(\chi) \cdot \varphi(Z)}{f(Z_S) \cdot \varphi(0)} \tag{4}$$

The luminance gradation function φ connects the luminance of the sky element and its zenith angle:

$$\varphi(Z) = 1 + a \cdot \exp(\frac{b}{\cos Z}), \tag{5}$$

where

$$0 \le Z \le \frac{\pi}{2}$$

and in horizon:

$$\varphi(\pi / 2) = 1$$

Equation (4) also applies its value in zenith, which is:

$$\varphi(0) = 1 + a \cdot \exp(b) \tag{6}$$

Function *f* is a scattering indicatrix function, which connects relative luminance of a the sky element and the angular distance between the sky element and the sun.

$$f(\chi) = 1 + c \cdot \left[\exp(d\chi) - \exp(d\frac{\pi}{2}) \right] + e \cdot \cos^2 \chi \tag{7}$$

Its value in zenith is:

$$f(Z_S) = 1 + c \cdot \left[\exp(dZ_S) - \exp(d\frac{\pi}{2}) \right] + e \cdot \cos^2 Z_S \tag{8}$$

Parameters *a, b, c, d* and *e* for standard types of sky are listed in Table 1.

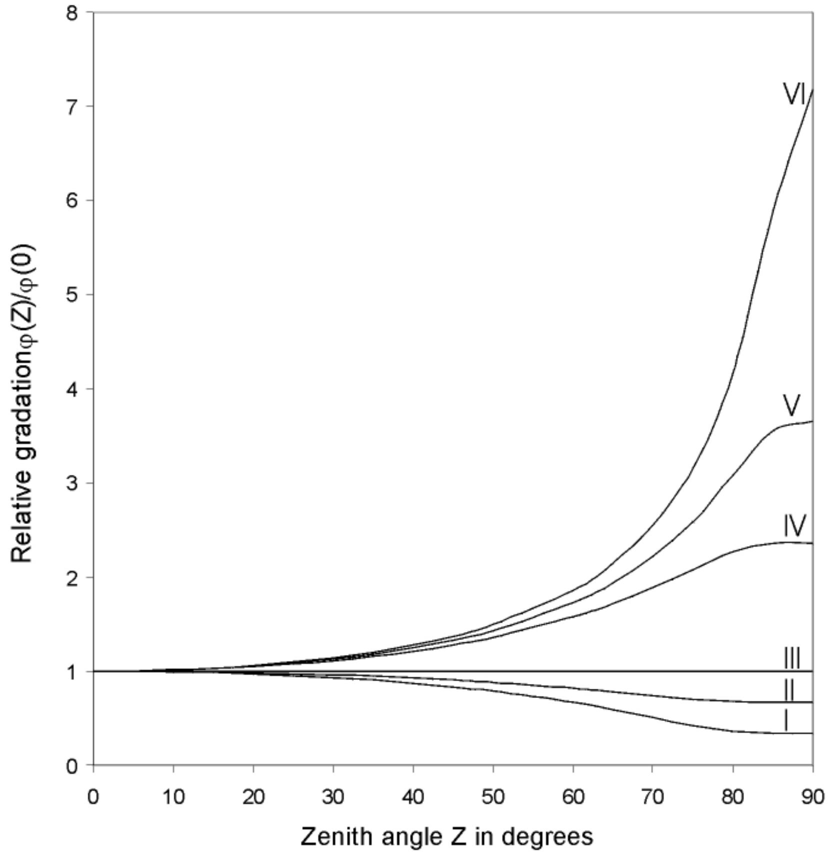

Fig. 2. Standard gradation function groups

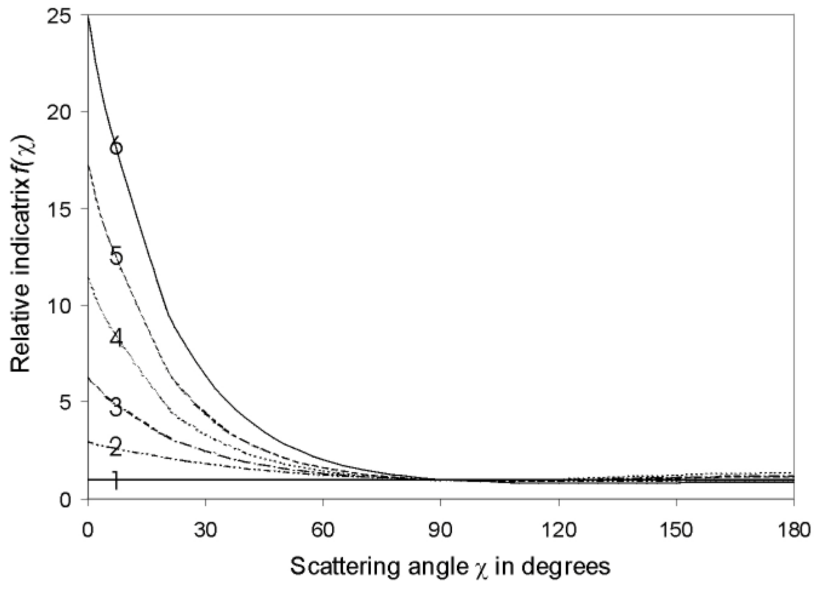

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Fig. 3. Standard indicatrix function groups.

5. Standard parameters

For indoor illuminance calculation, energy analysis, window design, glare control and other purposes we must choose parameters for (5) –(8) from Table 1. In the table we can find 15 different types of standard sky luminance distributions. Sky types are based on 6 groups of parameter *a* and *b* values, which describe gradation function and 6 groups of parameter *c, d,* and *e*, which describe indicatrix function. Resulting waveforms are shown on Fig. 2 and Fig. 3.

The set of standard skies is a realistic way to model and simulate daylight. The new set will be used in simulating indoor illuminance calculations and also in future climatic calculations and simulations. The new standard brings closer evaluation of environmental intervention in both environmental and economic way.

TABLE 1: STANDARD PARAMETERS

Type	Gradation	Indicatrix	*a*	*b*	*c*	*d*	*e*	Description of luminance distribution
1	I	1	4	-0.7	0	-1	0	**CIE Standard Overcast Sky, alternative form** Steep luminance gradation towards zenith, azimuthal uniformity
2	I	2	4	-0.7	2	-1.5	0.15	Overcast, with steep luminance gradation and slight brightening towards the sun
3	II	1	1.1	-0.8	0	-1	0	Overcast, moderately graded with azimuthal uniformity
4	II	2	1.1	-0.8	2	-1.5	0.15	Overcast, moderately graded and slight brightening towards the sun
5	III	1	0	-1	0	-1	0	**Sky of uniform luminance**
6	III	2	0	-1	2	-1.5	0.15	Partly cloudy sky, no gradation towards zenith, slight brightening towards the sun
7	III	3	0	-1	5	-2.5	0.3	Partly cloudy sky, no gradation towards zenith, brighter circum solar region
8	III	4	0	-1	10	-3	0.45	Partly cloudy sky, no gradation towards zenith, distinct solar corona
9	IV	2	-1	-0.55	2	-1.5	0.15	Partly cloudy, with the obscured sun
10	IV	3	-1	-0.55	5	-2.5	0.3	Partly cloudy, with brighter circumsolar region
11	IV	4	-1	-0.55	10	-3	0.45	White-blue sky with distinct solar corona
12	V	4	-1	-0.32	10	-3	0.45	**CIE Standard Clear Sky, low illuminance turbidity**
13	V	5	-1	-0,32	16	-3	0,3	**CIE Standard Clear Sky, polluted atmosphere**
14	VI	5	-1	-0,15	16	-3	0,3	Cloudless turbid sky with broad solar corona
15	VI	6	-1	-0,15	24	-2,8	0,15	White-blue turbid sky with broad solar corona

6. Luminance distribution calculation tools

The new standard has set new parameters and also new methods for calculating indoor illuminance in different climatic conditions. These basics should be included in all new programmes that calculate daylight. That is why we started to build a software that will calculate sky luminance distribution regarding the new standard.

The software comprises of two modules. The first, Sun, calculates exact location of the sun in the sky, the second, Sky, calculates luminance distribution regarding the position of the sun and other input data.

7. Module Sun

The first input datum for luminance distribution calculation is the position of the sun. Positions of every planet or star including the sun, depend on the time of observation and the location of observation on the earth.

Using a set of equations [13] we built a programme code that calculates the position of the sun, the rise and set times, and the length of the day for a certain point of observation on the earth. The position of the sun is exactly described by altitude γ_s and azimuth α_s. Altitude and azimuth are given in degrees. Time data are expressed in local time, which contributes to easier further calculations.

Figure 4 shows a custom interface window of module Sun, in which the position of the sun is calculated. The location of observation (geographical longitude and latitude) can be inputted as numeric values in adequate fields or using World map (see Fig. 5) to select appropriate location by clicking on a certain point on the map. Beside the location of observation it is necessary to fill in the time of observation and the time zone of location.

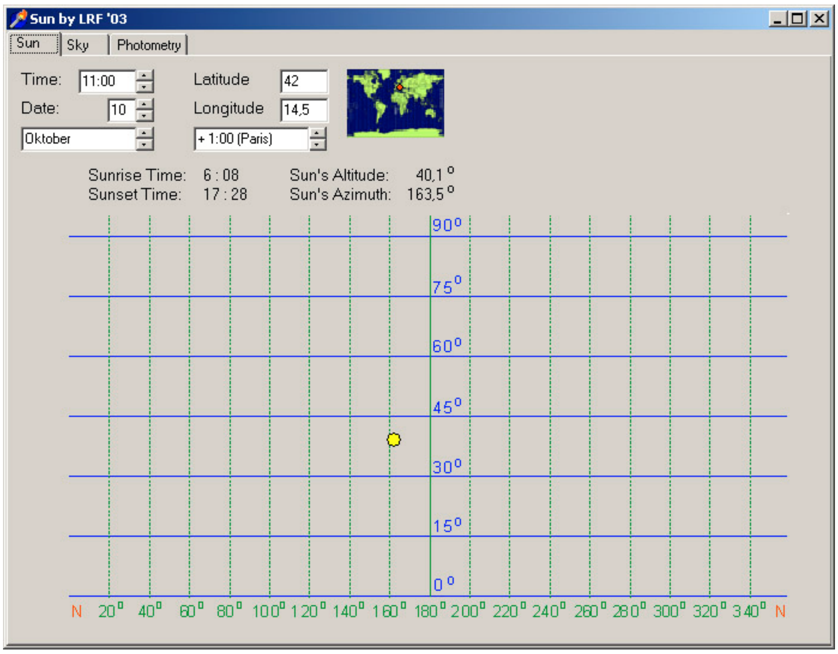


Fig. 4. Man - Machine interface of module Sun

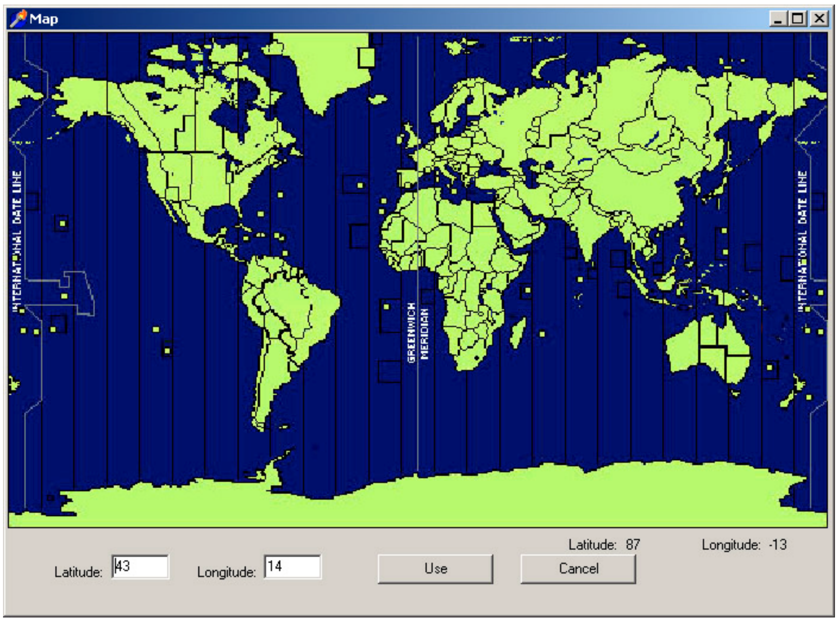


Fig 5. Using World map to select position of observation

Module Sun calculates and displays rise and set times, the angle between the horizon and the sun (altitude γ_s), and the value of the azimuth of the sun for time and location. Rise and set times only serve as control purposes. These two times set the available time interval for calculation, therefore it is impossible to calculate daylight at night, when the observed location is not lighted by the sun.

8. Module Sky

As already mentioned above, the position of the sun is an input datum for module Sky. As this module is based on the new CIE standard it is compulsory to enter in the CIE type of luminance distribution. To make choosing appropriate type of sky luminance distribution easier, we added a table where all types are listed and described. The layout of the module Sky is shown in Fig. 6, where luminance distribution for a certain moment is also graphically represented.

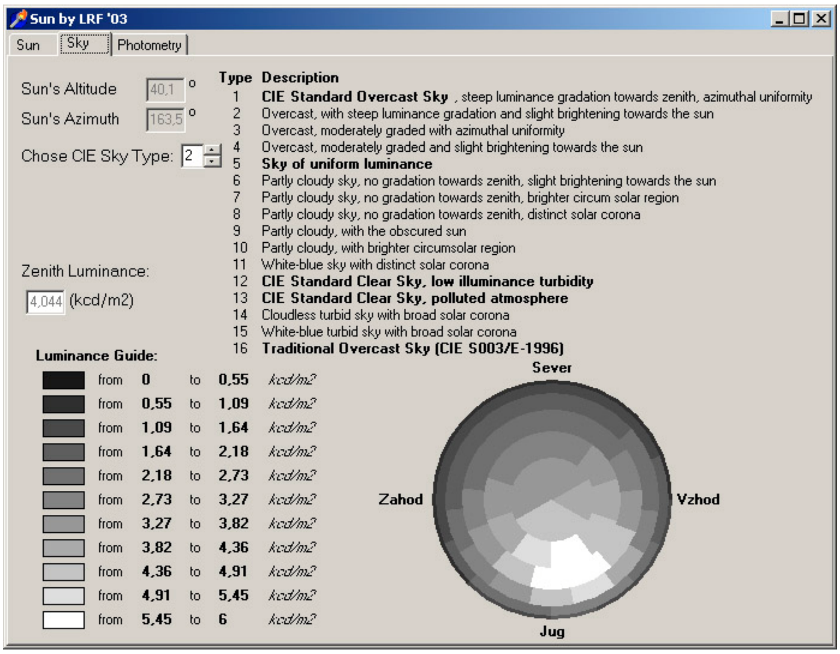


Fig. 6: Man - Machine interface of module Sky

Before calculating luminance distribution we have to divide sky into numerous patches. The sky is represented as hemisphere. The hemisphere is then divided into numerous patches that cover equal areas. In our case, we divided the sky dome into 77 patches.

To show luminance distribution in a graphical way a three-dimensional hemisphere should be flattened into a two-dimensional circle. Reduction from a three-dimensional sphere into two dimensions destroys the ratio between linear dimensions and areas. As a consequence, areas on the two-dimensional picture are not equal any longer. Figure 7 shows 77 elements of the sky dome, which are used for calculations.

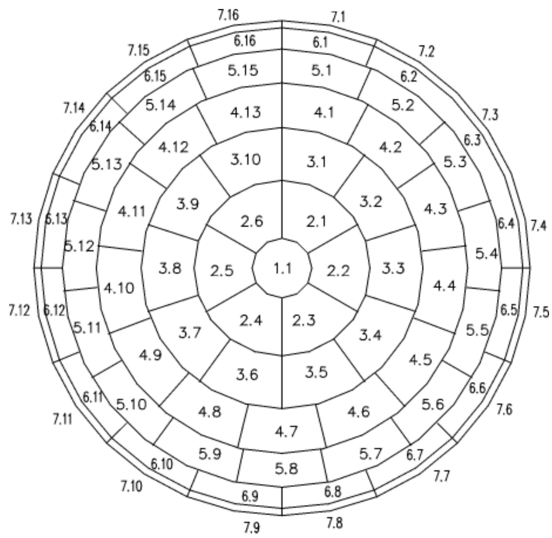


Fig. 7. Presentation of 77 sky elements

For each element azimuth α and altitude γ are calculated and later the ratio between the luminance of the element and the luminance of zenith is calculated using (1) - (8). For calculating the absolute value of the luminance of the sky element it is necessary to know the exact zenith luminance. Zenith luminance is defined with (9) - (15).

$$L_Z = \exp(A \cdot Nevg^5 + B \cdot Nevg^4 + C \cdot Nevg^3 + D \cdot Nevg^2 + E \cdot Nevg + F), \tag{9}$$

where:

$$A = 18.373 \cdot \gamma_S + 9.955 \tag{10}$$

$$B = -52.013 \cdot \gamma_S - 37.766 \tag{11}$$

$$C = 46.572 \cdot \gamma_S + 59.352 \tag{12}$$

$$D = 1.691 \cdot \gamma_S^2 - 16.498 \cdot \gamma_S - 48.670 \tag{13}$$

$$E = 1.124 \cdot \gamma_S + 19.738 \tag{14}$$

$$F = 1.170 \cdot \ln(\gamma_S) + 6.369. \tag{15}$$

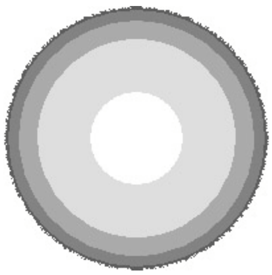
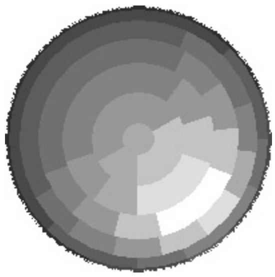
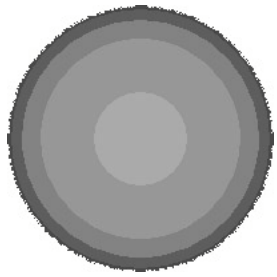
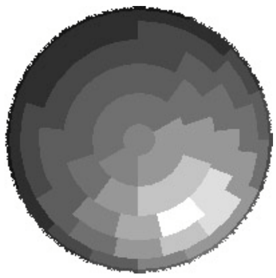
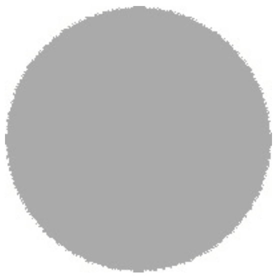
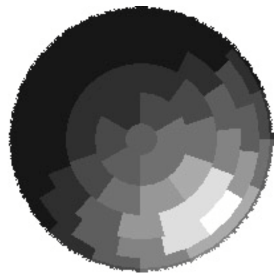
Parameter N_{evg}, used in equation (9) is dependant on the type of luminance distribution and is defined with table 2.

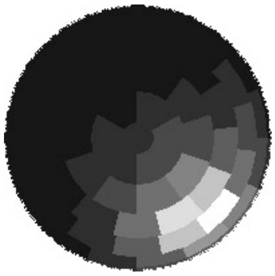
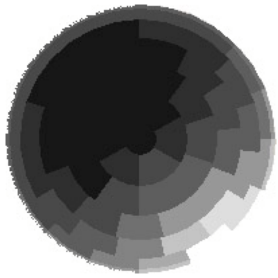
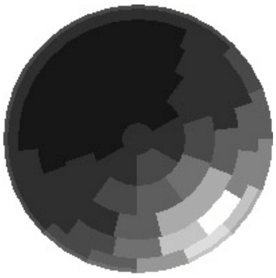
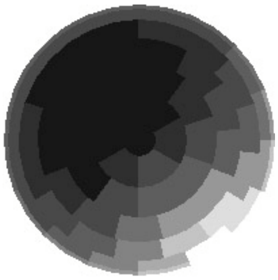
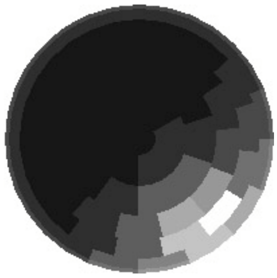
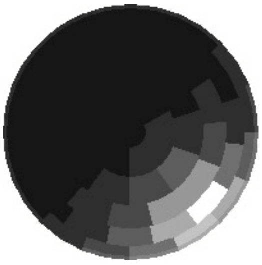
TABLE 2: PARAMETER $\mathbf{N_{evg}}$ FOR DIFFERENT SKY TYPES

Type	N_{evg}	Type	N_{evg}	Type	N_{evg}
1	0,15	6	0,5	11	0,8
2	0,2	7	0,5	12	0,9
3	0,2	8	0,6	13	1
4	0,3	9	0,6	14	1
5	0,4	10	0,7	15	1

The calculated absolute value of zenith luminance can be inserted into (4) and the absolute luminance of each sky element is calculated. After the calculation is performed, a graphical representation of sky luminance distribution can be drawn and each sky element is rendered. The brightest sky element is coloured in white, and the darkest element is coloured black. All other sky elements are coloured in ten shades of grey. To visualise the graphical representation of sky luminance distribution, let us look at Table 3, where all types of sky luminance distribution are collected. In this case $\alpha_s = 140^0$ in $\gamma_s = 40^{\ 0}$.

TABLE 3: 15 LUMINANCE DISTRIBUTION TYPES AND GRAPHICAL PRESENTATION FOR CASE OF $A_S=140^0$ IN $\gamma_S=40^{\ 0}$

Sky Type 1  **CIE Standard Overcast Sky,** Steep luminance gradation towards zenith, azimuthal uniformity	Sky Type 2  Overcast, with steep luminance gradation and slight brightening towards the sun	Sky Type 3  Overcast, moderately graded with azimuthal uniformity
Sky Type 4  Overcast, moderately graded and slight brightening towards the sun	Sky Type 5  **Sky of uniform luminance**	Sky Type 6  Partly cloudy sky, no gradation towards zenith, slight brightening towards the sun

Sky Type 7  Partly cloudy sky, no gradation towards zenith, brighter circumsolar region	Sky Type 8  Partly cloudy sky, no gradation towards zenith, distinct solar corona	Sky Type 9  Partly cloudy, with the obscured sun
Sky Type 10  Partly cloudy, with brighter circumsolar region	Sky Type 11  White-blue sky with distinct solar corona	Sky Type 12  **CIE Standard Clear Sky, low luminance turbidity**
Sky Type 13  **CIE Standard Clear Sky, polluted atmosphere**	Sky Type 14  Cloudless turbid sky with broad solar corona	Sky Type 15  White-blue turbid sky with broad solar corona

9. Conclusion

Daylight is more and more important when indoor design is in question, not only when planning lighting but also when designing climatic conditions in a room. For a correct evaluation of daylight contribution it is necessary to have an appropriate and world-wide used method for calculating sky luminance distribution. Only a standardised method can give comparable results using different software. As the new standard has just been adopted, we expect that a great number of different programmes will be designed.

To stay in contact with up-to-date research activities, we developed the two modules mentioned in the article that will serve as a base for further modules for calculating indoor illuminance.

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