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Modelling of Daylight Sources in the Artificial Sky

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Abstract. Daylight in nature is characterized by daily permanent changes of sunlight and skylight. Real measurements of daylight availability are showing that different daylight exterior illuminance for building interiors can be expected each minute. This brings some complications in the window design and the choice of criteria for daylight evaluations. There are several ways how to find basic conditions and typical relations combining sunlight beam with diffuse skylight from the whole sky vault. The older assumption considered that interiors have to be sufficiently illuminated under the worst overcast conditions. The newer approach is based on the utilization of daylight in specific localities and the determination of changes in sunlight and skylight occurrence probability. Therefore, both daylight sources are researched in detail specifying sky luminance distributions and sun influences to find conditions for their simulation in laboratory facilities. The most sophisticated equipment to study daylighting in exterior and interior architectural spaces are artificial skies with the artificial sun. These have to be precisely calibrated with a verified zenith luminance and horizontal illuminance levels by theoretical calculations and checked by experimental measurements. Reference daylight conditions defined in the ISO/CIE 15469:2004 standard have to be respected with trials to determine natural sun and sky as sources of daylight in the real environment and modelling these in the artificial sky in a certain intensity scale. This paper presents the method and results of modelling daylight applying electrical light sources in artificial sky which is installed in the Institute of Construction and Architecture, Slovak Academy of Sciences (ICA SAS) and discusses possibilities of their simulation in laboratory conditions.

Introduction

Daylighting design and its evaluation in building interiors are based on the criteria formulated in standard [1] in Slovakia. The same daylight conditions are standardized in another national standards, e.g. in Czech Republic, Germany or U.K. [2-4]. All of these documents respect daylight conditions under an overcast sky based on the Daylight Factor criterion. Since the CIE IDMP program was started [5] a lot of stations over the world have measured exterior illuminances and irradiances and other parameters describing daylight climate [6-9]. It was proved that daylight conditions continually change while sequence of various situations create specific conditions for illumination of interiors in a locality [10-12]. To effectively study this variability the classification of typical/prevailing exterior daylight conditions was proposed by several authors [13-15]. Daylight on the Earth is the product of two basic sources: - sun/sunlight and - sky/skylight. The distribution of sky luminances in relative terms is prescribed in the standard [16] which was adopted by ISO in 2004 and can be applied as an input to calculations of interior skylight under sky conditions representing situations from overcast through quasi-cloudy to clear. During sunny situations sun as a light source is determined by its extraterrestrial luminous flux that can be several times decreased resulting in exterior illuminance at the ground level. So, generally the global daylight levels can be expressed as:

$$E_{v,g} = E_{v,d} + E_{v,s}. \qquad [lx] \qquad (1)$$

where $E_{v,g}$ – global horizontal illuminance in lx,
$E_{v,d}$ – diffuse/sky horizontal illuminance in lx,
$E_{v,s}$ – direct/sun horizontal illuminance in lx.

The proportion between $E_{v,g}$ and $E_{v,d}$ values depends on the sky diffusivity index $E_{v,d}/E_{v,oh}$ and luminous turbidity factor T_v, where $E_{v,oh}$ is the extraterrestrial horizontal illuminance. Both parameters can be derived from regular exterior illuminance measurements and determined for a locality or can be estimated after [17]. If skylight should be simulated according to the ISO/CIE Standard General Sky in an artificial sky the parametrization of sky luminance distribution in relative or physical units should be applied. Calculation of arbitrary sky luminance L_a in a certain sky element is based on the multiplication of relative gradation function φ and indicatrix function f as follow:

$$\frac{L_a}{L_z} = \frac{f(\chi)\,\varphi(Z)}{f(Z_s)\,\varphi(0)} \qquad (2)$$

where L_z the zenith luminance,
$\varphi(Z)$ the luminance gradation function relates the luminance of a sky element to its zenith angle,
$\varphi(0)$ the luminance gradation function at the zenith,
$f(\chi)$ luminous scattering indicatrix function which relates the relative luminance of a sky element to its angular distance from the sun,
$f(Z_s)$ luminous scattering indicatrix function at the zenith.

There are several possibilities to verify daylight design and evaluate its solutions in point of view visual environment. The virtual sky developed by [18] allows to simulate daylight ISO/CIE sky sources [16] for computer applications. Verification of daylighting solutions in models using measurements was usually the main aim of construction of the artificial sky equipment. Daylighting measurements can be carried out in situ in real architectural spaces [19] or in laboratory under artificial skies when only architectural design documentations are available [20-23].

Artificial skies are simulators of daylight sources in which the physical models in a certain dimensional scale daylighting can be tested and evaluated under stable and defined daylight conditions. The precision of model measurements depends on the generated sky luminance distribution by the electric lighting system, the construction of models in which daylighting should be measured as well as quality of measuring instruments.

The hemispherical artificial sky domes [20, 24 - 27], simulators [21, 23] or reflectors [27] are facilities available in European laboratories for model daylight measurements. The operation of artificial sky in Bratislava was started in 1973, [28]. Its lighting system consisted of two separate circuits, first consisting of 500 W fittings and four 2000 W spotlights simulated overcast skies and second circuit with 500 W fittings and rectangular 1000 W studio floodlights simulated clear sky. The parabolic mirror illuminated by a halogen lamp and candle lamps located behind the mirror artificial sun were components of the artificial sky modelling the sun and a solar corona. This lighting system was controlled by transductor dimmer circuits. Energy consumption for operation of the Bratislava artificial sky was very high. Its technical solution was obsolete based on the manual operation. Moreover, incandescent light sources are not replaceable and available now because of finish their production. Therefore, the refurbishment of the lighting system by new LED lamps was necessary and started in 2014. This brings also the opportunity to carry out the simulations of all ISO/CIE sky types to set their sky luminance distributions in the artificial sky and to decrease energy consumption during daylight experiments.

Basic assumptions for calibration of artificial sky and electric lighting system

When adjusting an advantageous electrical illumination system to simulate many ISO/CIE sky standard luminance patterns [16] in the artificial sky there are several possibilities as:

- different arrangement of lamps or their groups on the artificial sky floor,
- directing chosen sources to certain spots onto the sky vault,
- choosing lamps with different angular coverage of some parts of the sky,
- utilizing the sophisticated dimming system to regulate the output of some lamps,
- dimming considerably the solar corona sources and the artificial sun,
- simulating smooth and fluent sky luminance patterns as close to ISO/CIE sky types, [16],
- calibration and setting-up the dimming system to achieve the most true reproduction of the gradation and indicatrix modelling,
- calibration and prescription the intensity scaling of skylight luminances to get the resulted horizontal illuminance level under ISO/CIE sky types in relative or absolute physical units.

All these assumptions and problems have to be settled within the calibration procedure with necessary adjustments or best chosen alternative solutions respecting national and local climate conditions.

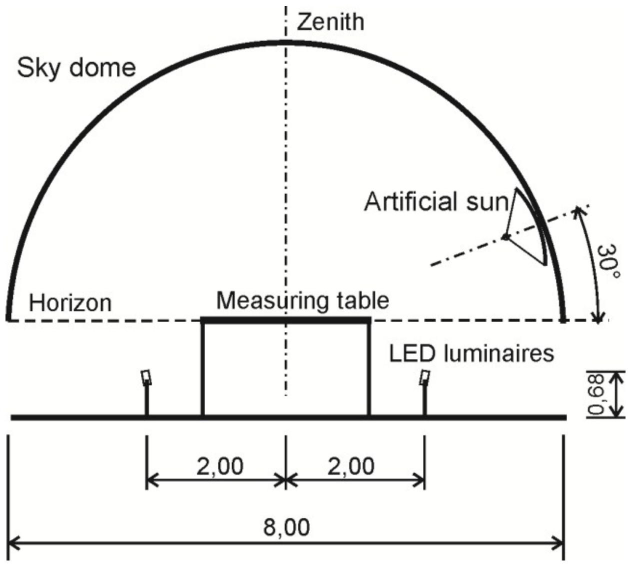


Figure 1. *Scheme of LED luminaire setting.*

Methodology

The artificial sky at the ICA SAS in Bratislava is a hemispherical dome of 8 m diameter built from reinforced concrete with inner special surface coating of the light reflectance. On the special metal holder is mounted the parabolic mirror of 1.2 m diameter illuminated by a halogen lamp simulating sunlight. This artificial sun can be located in arbitrary elevation above horizon. In the centre of the sky dome is the rotatable measuring table on which physical models can be placed. Fittings illuminating inner surface of the hemisphere produced the sky luminance distributions of the CIE overcast sky with luminance gradation 1:3 and 1:2 or the unity Lambertian sky as well as clear cloudless Kittler´s sky according to the CIE 1973 standard proposal, [28].

Currently the old luminaires are being replaced by new LED luminaires with lower energy consumption and colour temperature closer to daylight. Also inner surface of the dome was coated by new special plaster producing diffuse light and reflectance independent from wavelength. The first simulations of ISO/CIE overcast skies resulted in the location of the LED luminaires as is shown in Figure 1. Each of luminaire has to be directed to the determined specific sky element in such a way that the intensity of each electric light source can be adjusted by dimming to values related with target luminance $L_{a,t}$ of this sky element, so it can be described as:

$$L_{a,o} = f\left[P(x,y,z,\alpha,\gamma), I(\chi),\ L_{a,t}\right] \qquad [\text{cd.m}^{-2}] \tag{3}$$

where $L_{a,o}$ luminance produced by luminaire, cd.m^{-2},

$P(x,z,z,\alpha,\gamma)$ position function expressed by x, y, z and direction of azimuth α, from sun meridian and the elevation γ of the luminaire measured from horizon,

$I(\chi)$ luminous intensity curve of the luminaire,

$L_{a,t}$ target luminance, calculated sky luminance of ISO/CIE sky type, cd.m^{-2}.

The key factor of adjusting of the luminaire intensity is its dimming range and target elemental sky luminance $L_{a,t}$ caused by technical lighting system limitation. When angular distance between illuminated sky elements will be close, then homogeneity of simulated sky luminance will be more exact. Therefore, it is important to determine precisely the redistribution of sky elements on the hemisphere surface which has to be illuminated.

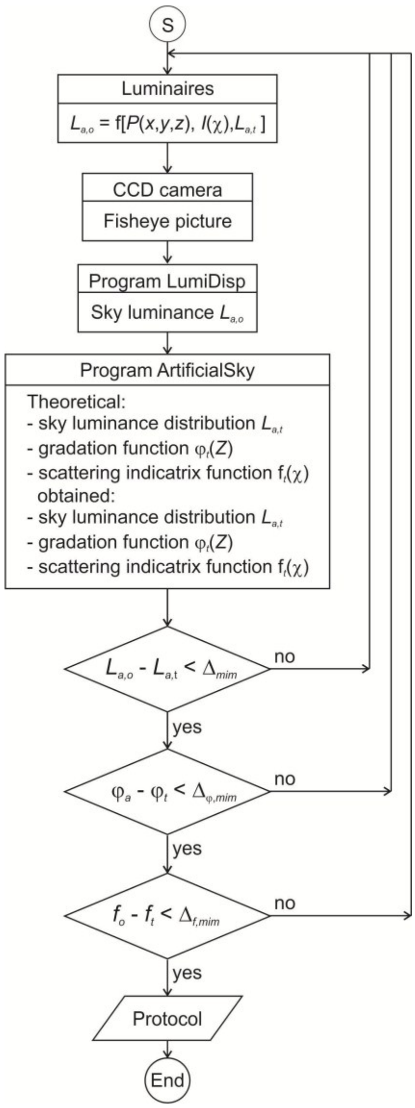


Figure 2. *Flow chart of the sky luminance calibration in the artificial sky.*

There are several possibilities how to verify the relevance between simulated and target sky luminance distributions. The proposed procedure in form of a flow chart presented in Figure 2 can be effectively applied to comply the required parameters during ISO/CIE standard calibration process. In refurbishment of lighting system in Bratislava artificial sky were proposed three calibration parameters: luminance maps of the sky samples, ISO/CIE gradation functions φ and indicatrix functions f. The first step of procedure contains the calculation of target sky luminances $L_{a,t}$ in determined sky elements a. In the second step is to take photo pictures by fisheye lenses with the CCD camera calibrated for luminance measurements enable to represent sky patterns from the exact centre of the sky dome. The CCD camera Nikon D80 equipped with Sigma Lens 4.5 mm f/2.8 EX DC Circular Fisheye calibrated for luminance measurements in the Faculty of Electrical Engineering and Communication, Brno University of Technology was used. Next, the sky luminance maps were produced by appropriate software, in our case by software [30], which was adopted to photometry of the LED sources applied in the new lighting system. In Figure 3 is shown LED luminaire and its reflector equipped by filter. To simulated levels of luminance on the dome surface several tests of light intensities and diffusion of filters had to be carried out. In Figure 4A is presented a luminance sample as a product of the sky illumination by one luminaire, in Figure 4B its related luminance map and in Figure 4C are documented achieved sky luminance values in the profile along the dome diameter with maximum value.

Results of evaluation of differences between sky luminance distribution $L_{a,o}$, gradation φ_o and indicatrix function f_o obtained from measurements and calculations indicate a need for correction of light intensity of LED luminaires. If these differences and standard deviations are low then the daylight source simulation as described in [16] is satisfactory for research and technical applications.

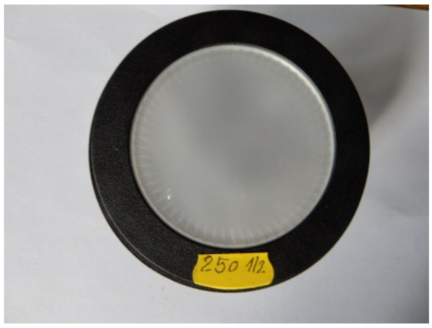
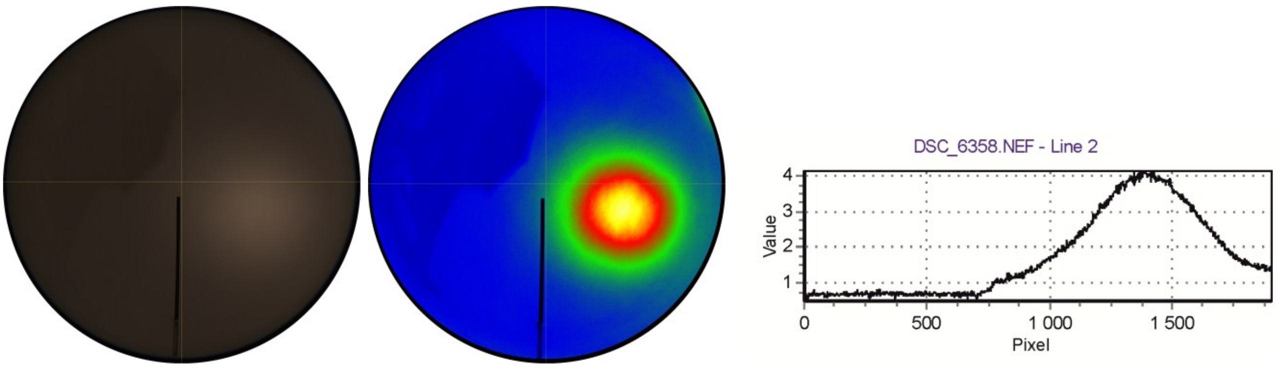


Figure 3. *LED Luminaire and its reflector with filter.*



A. B. C.

Figure 4. *A sample of illuminated dome surface by LED luminaire. A. Fisheye picture. B. Luminance map. C. Sky luminance on the luminaire meridian.*

For the calibration of the ISO/CIE Standard General Sky in Bratislava artificial sky are processed by several programs. While DALI Controller program [31] from OMS Ltd company controls intensities of luminaire sources in the scenes corresponding to sky types, the program LumiDisp converts fisheye pictures into ASCII data files which contains information about sky luminances generated by the LED lighting system. Comparison measured and target values of sky luminance distribution in determined elements with gradation and indicatrix functions is done by program ASC V2.1, [32].

Partial results

In the last century was built and up to recently operated the large hemispherical artificial sky in the laboratory of the Institute of Construction and Architecture in Bratislava. Its advantage is the simulation of daylight sources by the sky dome with plastered high reflected inner surface producing diffuse light with several sky luminance distributions.

Now the classical lighting system based on incandescent light sources and controlled by manually adjusted intensities was removed and is replaced by LED light sources controlled by DALI controller and a set of ballasts. New lighting system consists of two circuits. The circuit of LED luminaires which illuminate inner surface of the dome is separate from circuit controlled metal halide lamp of artificial sun and LED strips to simulate the sun corona. The lamps equipped by diffusers illuminate sky surface by determined intensity of each directionally orientated LED luminaires. Test of luminance homogeneity showed that 20 luminaires for illumination of the dome horizon are sufficient. The DALI controller allows to use 64 addressed which are reserved for all light located on the floor. Another DALI controller operates the circuit of artificial sky. This solution will allow to carry out daylighting experiments under standard skylight conditions as well as under coupled skylight and sunlight influences.

The scheme of both circuits and connected components for modelling daylight sources in ICA SAS artificial sky is presented in Figure 5. This scheme indicates two phases of the lighting system operation. The first phase is applied in the calibration process and adjusting daylight sources for simulation of the ISO/CIE General Standard Sky. When the computer is disconnected after the finish of calibration, the second phase of the system regular operation during experiments in models under the artificial sky and can be at any time used.

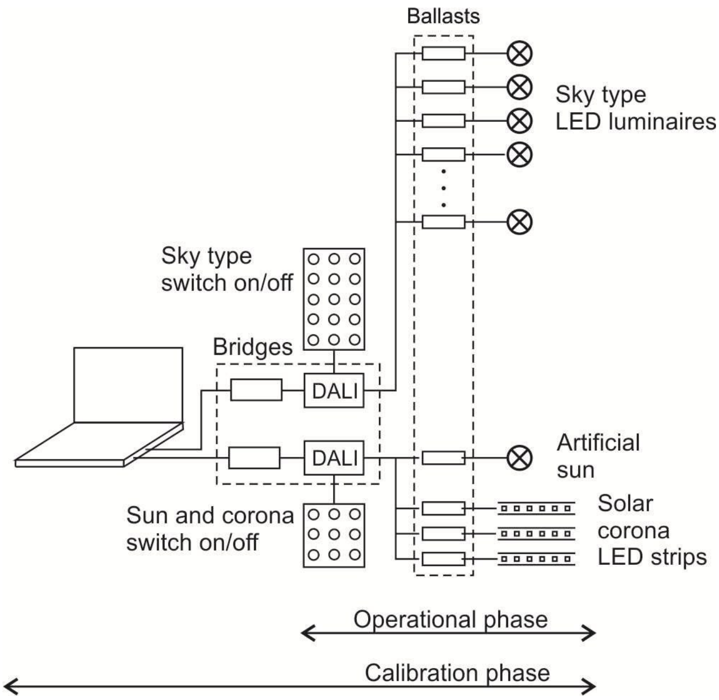


Figure 5. *Composition scheme of lighting system.*

Conclusions

In the refurbishing process of the ICA SAS artificial sky containing a parabolic artificial sun source was applied a new method of simulation and calibration of sky luminances. Several problems concerning the installation of a new LED lighting system contributing to its energy saving performance as well as more precise modelling of sunlight and skylight are described. Since 2004 the standard ISO/CIE, [16] is valid therefore new and reconstructed artificial skies have to respect standardised sky luminance distributions. Currently it is possible to model zenith luminance and exterior illuminance levels in absolute physical units which brings the opportunity also for more precise daylight solutions of artificial skies including an artificial sun.

Furthermore, recent research of new algorithms for computer programs in daylighting can be verified by their reproduction and measurements under calibrated artificial skies. Such laboratory equipment can serve for further research as well as for educational purposes or testing of novel architectural designs with complicated daylight apertures and layouts or applied daylight technologies.

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