The New Generation of an Artificial Sky: Simulating Various Overcast Sky Conditions

Stanislav Darula
Institute of Construction and Architecture, Slovak Academy of Sciences
Bratislava, Slovak Republic
usarsdar@savba.sk

Richard Kittler
Institute of Construction and Architecture, Slovak Academy of Sciences
Bratislava, Slovak Republic
usarsdar@savba.sk

***Abstract*—During 1994 – 98 at the CIE IDMP Bratislava one minute illuminance and zenith luminance were gathered. Their analyses have detected groups of overcast ISO/CIE sky types 1 – 6. The renovation of the illumination system in the ICA SAS artificial sky was upgraded using new dimmable LED lamps enabling to simulate several overcast sky luminance distributions in cd/m^2 and absolute horizontal illuminance levels in kilolux at the ground.**

The artificial sky calibrations include checks of luminance patterns with standard luminance gradations using fish-eye images taken by a calibrated camera. Measured zenith luminance with horizontal illuminance were determined as reference levels to find the range of Sky Intensity Scale Factors which enable to determine skylight illuminance in klx depending on solar altitudes. Contribution discusses possibilities to simulate daylight standard conditions in an artificial sky considering current trends, i.e. verification daylight measurements in relative units and also in physical units lux and cd/m^2.

***Index Terms*-- Daylighting, artificial sky, model measurements.**

Introduction

Totally diffuse overcast skies under dark and rainy situations were historically considered as the worst feeble daylight sources without any sunlight and with low luminance distributions resulting in minimal horizontal illuminance available outdoors especially during sunrise or low solar altitudes. In early daylight photometry these were assumed to have equally uniform and unity luminance all over the whole the sky vault as defined, [1]. After the first luminance measurements during the first half of the 20th Century [2] the gradually increasing luminance pattern from horizon to zenith 0.33:1 was standardised in [3] while recently a set of fifteen standard skies were adopted in [4] and [5] containing homogeneous sky types from overcast, cloudy to clear skies under different turbidity conditions.

Due to actual low visibility, environmental reasons as well as energy saving policies worst overcast skies are accepted as critical criteria for window design and daylighting of the interior working places and therefore previously were preferred for the simulation in artificial skies for research on architectural models using the 20th Century equipment [6] and experiments were done under stable chosen overcast sky simulations in relative terms using Sky or Daylight Factors.

Recently new accurate measurements of the extraterrestrial solar irradiance and illuminance incoming towards the Earth globe enabled to define the Luminous Solar Constant 133.8 klx [7], transmittance and scattering of solar beams as well as both the gradation and indicatrix functions determining the sky luminance patterns. At the same time regular measurements of daylight illuminance and zenith luminance in minute steps worldwide organized under the CIE International Daylight Measurement Programme (IDMP) with sky scanner data and fisheye photo images were analysed to determine typical daylight sources in absolute physical units [8] and [9].

New theoretical findings [4] and [5] and new LED lighting systems allow to simulate daylight sources also in the laboratory under the artificial sky even in absolute physical units. Since 1974 [10] is in operation the hemispherical artificial sky in the Institute of Construction and Architecture Slovak Academy of Sciences (ICA SAS). During its renovations the old incandescent reflectors were removed and a new LED lighting system was installed while currently the sky is calibrated with respect to [4] and [5] recommendations.

Various overcast sky situations measured during the CIE IDMP

When analysing five year data gathered during 1994-1998 at the Bratislava CIE IDMP general station under various overcast sky conditions and different solar altitudes [11] the following circumstances were discovered:

- Evaluating 5-minute data was done according to the categorisation parameter $L_{vZ}/E_{v,d}$ (i.e. zenith luminance to horizontal diffuse sky illuminance) to define values measured within the 2.5% strip region belonging to ISO/CIE sky types 1, 3 and 5 as well as for those identifying ISO/CIE sky types 2, 4 and 6. Following the survey based on the parameters $L_{vZ}/E_{v,d}$ and solar altitude γ_s the disputable cases close to the intersection regions with other sky types within solar altitudes 37-40 degrees and 54 - 60 degrees were excluded.
- The number of overcast sky groups within the ISO/CIE sky types 1 – 6 were selected in the prevailing small strips ± 0.01 of $E_{v,d}/E_{vo,h}$ (i.e. horizontal diffuse sky illuminance at ground level to horizontal extraterrestrial illuminance) separating very often occurring cases from infrequent ones. So the total number of occurring cases in every sky type characterizes the frequency of this sky type in Bratislava during the five years period, while the most often occurring atmospheric transmittance associated with a certain ISO/CIE sky type is indicated by the highest number of cases within the ± 0.01 strips of $E_{v,d}/E_{vo,h}$ in Table 1.

TABLE I. OCCURRENCE OF FIVE MINUTE OVERCAST SKY CASES IN A FIVE YEARS PERIOD AT BRATISLAVA.

ISO/CIE Overcast sky	Number of all cases	Number in $E_{v,d}/E_{vo,h}$ range			
No	*Total*	*0.05±0.01*	*0.1±0.01*	*0.15±0.01*	*0.3±0.01*
1	9716	300	600	450	75
2	12432	400	630	520	140
3	11506	275	500	360	205
4	8042	130	210	255	215
5	5777	50	140	170	180
6	5415	75	115	100	160
Sum	52888	1230	2195	1855	975

It is evident that for Bratislava are characteristic ISO/CIE sky types 2 with the highest occurrence number average of all overcast sky types 1 – 6 and are most frequent with a very low transmittance of the atmosphere with a thick overall cloudiness of 0.1, i.e. around 10% of the incoming extraterrestrial flux passing the fictitious horizontal plane at the outer atmospheric border.

The sky luminance patterns of each ISO/CIE overcast sky is different, but sky types 1, 3 and 5 because of uniform unity scattering have only different gradations from horizon to zenith and have the same luminance around all azimuth sky circles, while sky types 2, 4 and 6 besides gradation differences are characteristic due to small indicatrix changes depending on the hidden sun position defined by the momentary solar altitude and azimuth.

INOVATION OF THE ARTIFICIAL SKY INCLUDING THE LED LIGHTING SYSTEM

As already mentioned in the general paper [12] all ISO/CIE overcast skies have a perfect even and smooth luminance patterns without any extreme or patchy luminance irregularities because the solar position and sun beams are either absolutely hidden or diffusely dispersed by the overcast cloud layers. During the renovation of the Bratislava artificial sky several new features applying the LED luminaire system were already described [13] including the placement and direction of 58 LED reflectors equipped by diffuse filters enabling rough conditions to simulate various sky luminance patterns.

Specific conditions were documented during the artificial sky calibration analysing the fish-eye photo images. For the case of Bratislava artificial sky simulation in 2016 the equisolid projection of the camera lens was tested [14]. Overall luminance calibration was done in the laboratory of the Faculty of Electrical Engineering and Communication University of Technology in Brno [15]. To avoid vigneting effect of the fisheye lens the smallest aperture was set [16] and the lens cap and the adapter ring were removed when taking all images.

Thus during the first step of the calibrating procedure the new LED lamps with diffuse filters were tested in the artificial sky and using the DALI dimming adjustments were set to simulate the gradation and indicatrix characteristics of each of the six ISO/CIE overcast skies. Utilizing the DALI possibilities to set the overcast sky luminance patterns the overall scaling of the rising luminance followed in accordance to the ratios $E_{v,d}/E_{vo,h}$ in Table 1. Evidently, the darkest illuminance levels occur under sky types 1 and 2 in the range $E_{v,d}/E_{vo,h}$ = 0.05 – 0.15 with the maximal frequency 0.1. Even sky type 3 is still characteristic with this maximal frequency 0.1, but a relative rise towards 0.15 is already noticeable, which becomes the frequency for ISO/CIE sky type 4.

Under the uniform sky type 5 and 6 are remarkable brighter skies with $E_{v,d}/E_{vo,h}$ = 0.25 to 0.30. So, the DALI setting of the calibrated sky patterns should also follow these slight changes in brightness from darker to brighter illuminance levels.

CALIBRATION OF OVERCAST SKIES

Of course the obvious priority should be given to standardised sky types especially the CIE Overcast Sky type 1 not only to reproduce its gradually increasing luminance pattern but also frequent illuminance levels on the unobstructed exterior horizontal ground. After long term one-minute data gathered at the CIE IDMP Bratislava general station based on evaluated measured illuminance values during first five years 1994 – 1998 [11] indicate that frequent sky type 1 conditions occurred when $E_{v,d}/E_{vo,h}$ = 0.1 even while the range corresponded approximately with the ratio 0.05 – 0.2 with the mean 0.154 and mode 0.094 exactly. Due to the occurrence of sky type 1 mainly during the winter season the largest number of such cases were under the solar altitude 28° especially during its whole day presence. Most frequently the zenith luminance was in the range L_{vZ} = 1 - 2 kcd/m^2 and exterior horizontal illuminance were around $E_{v,d}$ = 6.3 klx [2]. If in accordance to other sky types, the assumed solar altitude γ_s would be 20° with the $E_{v,d} \approx$ 4.5 klx or at solar altitude γ_s = 30° the exterior illuminance could be $E_{v,d} \approx$ 6.7 klx. However, the ratio $L_{vZ}/E_{v,d}$ was close to 0.408.

Quite similar conditions are associated with ISO/CIE sky types 3 and 5 but except the extended gradation the ratios $E_{v,d}/E_{vo,h}$ are slightly higher. For the sky type 3 the most frequent $E_{v,d}/E_{vo,h}$ = 0.1 – 0.125 within the range 0.08 – 0.2 with a mean 0.186 and mode 0.114.

For the sky type 5 representing the Lambertian luminance distribution a special attention has to be given for its uniformity although it is not as frequent as the rest of overcast sky types in the Bratislava 1994-98 set. However, these foggy overcast skies are rather brighter in the wider range $E_{v,d}/E_{vo,h}$ = 0.1 – 0.4 with a mean 0.219 and mode 0.226. In spite of the perfect uniformity the luminance level is dependent on solar altitude in the wintertime $\gamma_s \leq 35°$ with low zenith luminance L_{vZ} under 5 kcd/m^2 and recommended $E_{v,d}/E_{vo,h}$ = 0.2, thus $E_{v,d} \approx$ 15 klx in wintertime, but $L_{vZ}/E_{v,d}$ was close to $1/\pi$ = 0,3183.

In case of the overcast artificial sky calibration it is important to note that the gradation and indicatrix distributions as well as $L_{vZ}/E_{v,d}$ ratios are not dependent on solar altitude, but all are simultaneously linked with the intensity level expressed by the $E_{v,d}/E_{vo,h}$ ratios determining the transmission, i.e. penetration of the densely overcast atmosphere. Therefore it is possible to choose the basic reference L_{vZ} and $E_{v,d}$ level at any solar altitude in the calibration to decide the relative skylight Intensity Scale Factor for the particular ISO/CIE standard sky type. When such a reference scaling is valid as calibrated for a specific sky type under a specific solar altitude and the actual or typical reference $E_{v,d}/E_{vo,h}$ precisely calculated, while the calibrating $E_{v,dm}$ is measured, then the reference diffuse/skylight Intensity Scale Factor *RISFd* is

$$RISFd = E_{v,d} / E_{v,dm} \tag{1}$$

which means that the real exterior illuminance $E_{v,d}$ is reduced in its intensity in relation to

$$E_{v,d} = E_{v,dm}\, RISFd \tag{2}$$

However, for the calibrated reference point the value of *RISFd* = 1 could be best to find for the chosen or typical ratio *RISFd* = $E_{v,d}/E_{vo,h}$ and when the gradation and indicatrix function for the specific ISO/CIE standard sky type was calibrated first, thus the *RISFd* = 1 has to be if

$$\gamma_{s,c} = \arcsin \frac{E_{v,dm}}{133800\, E_{v,d} / E_{vo,h}} \tag{3}$$

Thus a calibrating diagram for any solar altitude in the range 0 – 65° can be calculated defining the diffuse Intensity Scaling Factor which is given by the ratio of the actual solar altitude to the sine of the reference point *RISFd* = 1, i.e

$$ISFd = \frac{\sin \gamma_s}{\sin \gamma_{s,c}} \tag{4}$$

while the scale *ISFd* in integers can be calculated for any solar altitude γ_s as:

$$\gamma_s = \arcsin\left(ISFd \sin \gamma_{s,c}\right) \tag{5}$$

as applied for the scale in Fig. 1.

Which means that the real horizontal illuminance $E_{v,d}$ in lux is

$$E_{v,d} = ISFd\ E_{v,dm} \quad \text{[lx]} \tag{6}$$

EXAMPLE OF CALIBRATING ISO/CIE SKY TYPE 5

In the first step the very even luminance distribution on the whole sky vault was adjusted using the DALI dimming system as roughly documented in Fig. 2.

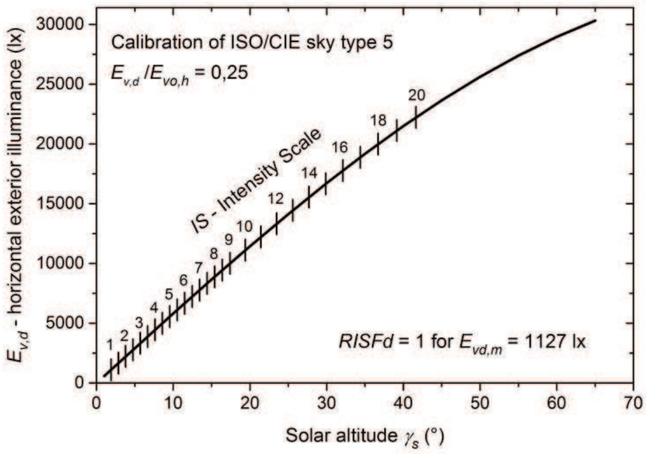

Figure 1. Calibration diagram for ISO/CIE sky type 5 defining intensity scale

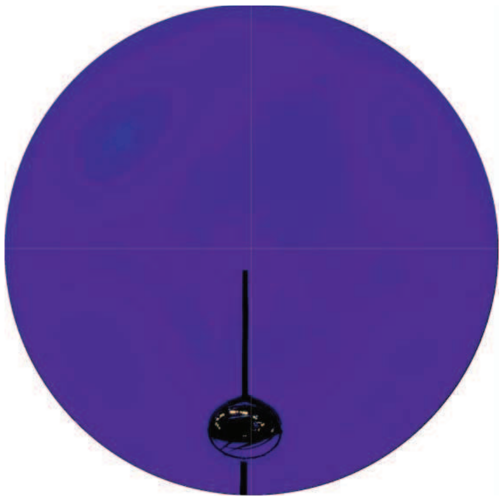

Figure 2. Fisheye luminance map of ISO/CIE sky type 5 in the ICA SAS artificial sky.

Using the program ASC V2.2 [17] further test of the gradation and indicatrix distributions are documented in Fig. 3 and Fig. 4.

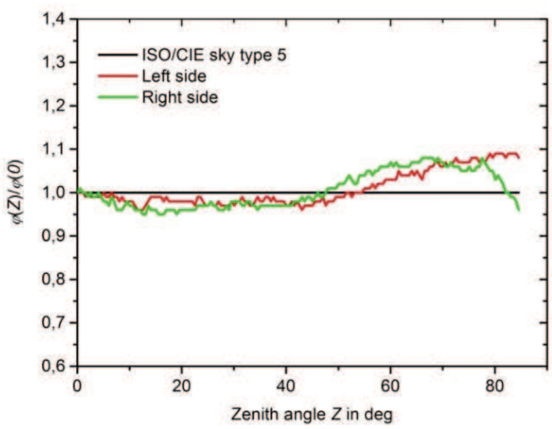

Figure 3. Theoretical and measured gradation function in the ICA SAS artificial sky.

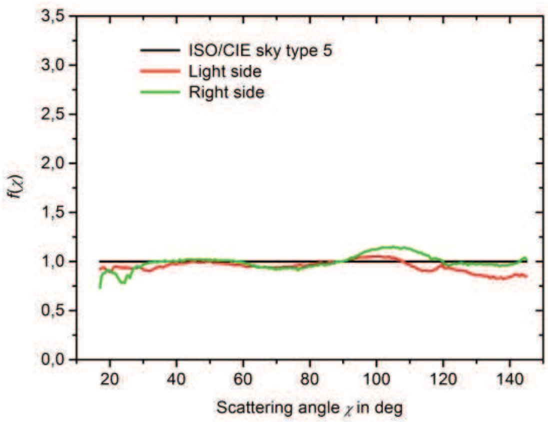

Figure 4. Theoretical and measured indicatrix function in the ICA SAS artificial sky.

Average deviation 3.05% between theoretical sky luminances and their simulation documented from the fisheye image was calculated from 323 sky elements. Zenith luminance 354,17 cd/m^2 was measured by calibrated digital camera while value of 354,9 cd/m^2 was measured by luminance meter Minolta Konica 1° and $E_{v,d}$ = 1127 lx was measured by illuminance meter Konica Minolta T-10A then measured ratio of $L_{vz}/E_{v,d}$ is 0.3149 very close to the theoretical value 0.3183.

CONCLUSIONS

The renovated Bratislava artificial sky will serve for daylight research or tests of architectural models as an accurate laboratory instrument modelling skylight and/or sunlight conditions under the whole range of ISO/CIE sky type standards with stable and accurately simulated frequent circumstances world-wide either under standard overcast, sunless cloudy or clear skies without or with sunlight with the possibility to simulate by the real sky types standardised by ISO/CIE. Contrary to older artificial skies the relative Daylight Factor evaluation system is replaced by luminance and illuminance measured in absolute units respecting their reduction in calibrated intensity scales.

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