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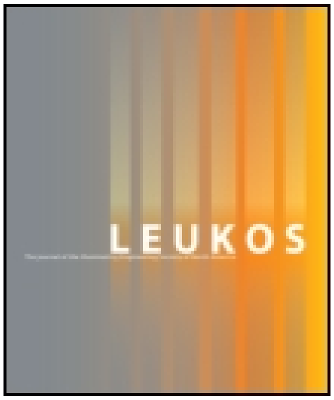

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A Methodology for Designing and Calibrating an Artificial Sky to Simulate ISO/CIE Sky Types with an Artificial Sun

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A Methodology for Designing and Calibrating an Artificial Sky to Simulate ISO/CIE Sky Types with an Artificial Sun

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ABSTRACT Artificial skies are now commonplace in laboratories for daylighting studies in university schools of built environment studies. However, these research and educational devices are often not used to their full potential because they are not calibrated to model even location-specific International Organisation for Standardisation (ISO)/CIE sky types. Nevertheless, sky luminance patterns and parallel sunbeam produced by an artificial sun in a sky simulator are required for realistic physical modeling. These facilities must be designed and calibrated in well–documented protocols to achieve the scale ratios that proportionally model real outdoor skylight and sunlight conditions. Such exacting tasks can be accomplished by respecting several technical imperatives that this article was written to elaborate and discuss.

KEYWORDS artificial sky, artificial sun, luminance and illuminance calibration, modeling of ISO/CIE sky types, sky luminance distribution

1. INTRODUCTION

The roots of current daylight photometry date from the 18th century and Bouguer's work on sunlight and luminance measurements of clear skies [Bouguer 1760] and Lambert's theoretical photometry and geometry based on simple uniform sky luminance applied to window apertures [Lambert 1760]. At the time, the Lambertian model was favored, primarily because it was more practical. In the 19th and 20th centuries, where Rayleigh [1899] explained the atmospheric scattering of sunlight, Kähler [1908], Moon and Spencer [1942], and Hopkinson [1954] studied the luminance gradation of an overcast sky, which was standardized by CIE [1955].

In the 1960s, daylight science [Walsh 1961] and the more focused research and design-oriented work by Hopkinson [1963] and Hopkinson and others [1966] regarded the overcast sky condition as a basic standard, which employed a low sky luminance for window design and daylighting evaluations. The daylight factor (D) was introduced with three components of daylighting; the direct component, called the sky component (SC), an external reflected component (ERC), and an internal reflected component (IRC). Thus, $D = SC + ERC + IRC$.

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The historic path of simulating the sky vault or its parts for physical daylighting measurements and subjective judgments of visual quality in exterior and interior spaces was made in scale models under the stable luminance environments of all manner of artificial skies reviewed by Kittler [1959]. Indoor studies employed simulated skylight conditions initially under the simple uniform luminance of the Lambertian sky to determine sky factors (*SF*), which, for practical, scaling purposes, excluded direct sunlight. Later, in order to facilitate regulation of minimum daylighting requirements, the CIE adopted the one-to-three luminance ratio, 1 horizon to 3 zenith sky luminance, often referred to as the Moon and Spencer sky [Moon and Spencer 1942]. This sky luminance distribution represents a densely overcast sky with the low luminance prevalent in Western Europe. Three components comprising the daylight factor replaced the sky factor as the standard for minimum daylighting in most European localities. In this era, a primary function of windows was to provide work and living place illuminance with or without direct sunlight.

After a new CIE initiative, studies proceeded on the relative luminance pattern of a clear sky by Kittler [1967] and resulted in the 1973 CIE standard that introduced the influences of the scattering indicatrix and gradation functions to express atmospheric turbidity in the countryside and towns. Further developments using these functions enabled homogeneous overcast, Lambertian, and clear sky patterns to be combined in the set of 15 sky types [Kittler and others 1997] and recommended in the 2003 CIE standard finally adopted by the International Organisation for Standardisation [ISO 2004].

There are numerous nonhomogeneous sky luminance distributions caused by many cloud types with different cover and layer positions on the real sky vault. Homogeneous and quasihomogeneous cases are considered elementary to simulation in an artificial sky. Current standardized real sky types from fully overcast to clear skies containing various turbidities can be modeled, with the latter cases linked with proportional sunlight either in relative or absolute units [Kittler and Darula 2014]. Construction of an artificial sky can be mirrored, diffusely reflective or transilluminated, rectilinear, hemispherical, or created by multiple lunes.

Accurate simulation of complex sunlight and skylight outdoor conditions in older artificial skies of the mirror box type is not possible because the controlled multireflected light from the mirrors that, together with the plain overhead light source, produces the luminance distribution, uniform or overcast, effectively until a model is placed against its side aperture. Diffusively reflecting hemispherical sky simulators could accommodate an artificial sun facility but still have the horizon scale error, which naturally diminishes with increased sky radius or model size reduction [Kittler 1974]. However, recent luminaire and source technological developments such as light emitting diode (LED) lamps and luminaires should facilitate greater sky luminance pattern control, flexibility, and accuracy.

Models used for photometric studies will rarely be to the same scale as the model used for subjective assessments. Therefore, if subjective evaluations are needed in the facility there is little alternative to a large dome, with its high concomitant financial and accommodation constraints that would likely confine its existence to national science laboratories, for the valuable purpose of research and monitoring the accuracy of the mathematics and computer simulation. However, if subjective assessments are not required, the model scale can be vastly reduced with much smaller photocells. One hundred-to-one model scaling was feasible with the silicon cell corrected by MacGowan [1965], thus opening the measurement assessment facilities to serious research in universities.

The first task is to document those real typical and extreme sky types and situations that could be simulated with respect to sensor size, precise and reliable measurement, and other restrictions that stem from the construction, form, and size of the available hemispherical structure, newly built or older already available for refurbishing.

Existing artificial skies with powerful reflectors placed on their inner surface or forming a virtual lune set fail to simulate fluent smooth luminance distributions and frequently permit calibration of only specific elements of the whole sky luminance patterns, and the source of parallel sunbeams from the artificial sun should be a relatively wide stream and fall on the model window apertures in an adequate intensity.

2. HORIZONTAL EXTRATERRESTRIAL SUNLIGHT AS A PARAMETRIC FACTOR OF THE DAYLIGHT ILLUMINANCE AT GROUND LEVEL

It is evident that any daylight reaching the horizontal plane at ground level is proportional to sunlight falling on a fictitious horizontal plane on the exterior of the Earth's atmosphere. Precise detection of the extraterrestrial monochromatic solar spectrum in the widest range by space satellites [Gueymard 2004] enabled the derivation of the luminous solar constant respecting the CIE standard luminous efficiency function $V(\lambda)$ for photopic human vision [CIE 1990] $E_{vo} = 133{,}334$ lx and for colorimetry as $E_{vo} = 134{,}108$ lx [Darula and others 2005]. A recommended value for daylight calculations was adopted as $E_{vo} = 133{,}800$ lx $= 133.8$ klx [CIE 1994]. This extraterrestrial illuminance constant is valid for a virtual plane perpendicular to sunbeams that is placed on the outer border of the Earth's atmosphere on April 3 and October 5, the days of the average Earth–Sun distance.

Thus, for any day with a day number J starting from January 1 as $J = 1$, the constant can be corrected with satisfactory precision by a multiplying eccentricity factor ε,

$$\varepsilon = 1 + 0.034 \cos\left(\frac{2\pi(J-2)}{365}\right). \tag{1}$$

Then daily changes, which are within ±3.3%, can be taken into account and the daily value $E_{vo,s}$ is

$$E_{vo,s} = 133.8\,[\varepsilon] = 133.8\left[1 + 0.034\cos\left(\frac{2\pi(J-2)}{365}\right)\right][\text{klx}], \tag{2}$$

The horizontal extraterrestrial illuminance $E_{vo,h}$ is given as

$$E_{vo,h} = E_{vo,s} \sin\gamma_S\,[\text{klx}], \tag{3}$$

where γ_S is the solar altitude.

At various locations on the ground the split of this extraterrestrial illuminance is measured or calculated as horizontal diffuse skylight illuminance at ground level $E_{v,d}$ or the component of only parallel sunbeam horizontal illuminance $E_{v,s}$ or all added together in the horizontal global illuminance $E_{v,g}$. Thus, for any location worldwide, the horizontal extraterrestrial illuminance can be taken as a parameter that expresses the overall momentary transmittance of the local state of atmosphere in ratios $E_{v,d}/E_{vo,h}$ and $E_{v,s}/E_{vo,h}$ or $E_{v,g}/E_{vo,h}$ and these can also express the mutual relationship of skylight and sunlight under different CIE standard skies, thus normalizing momentary levels characterizing daylight availability conditions. When regular either $E_{v,s}$ or $E_{v,g}$ and $E_{v,d}$ illuminance data are gathered, the atmospheric turbidity defined by the simultaneous relative luminous turbidity factor T_v in the direction of sunbeams can be calculated after

$$T_v = \frac{-\ln\left(E_{v,s}/E_{vo,h}\right)}{a_v\, m} = \frac{-\ln\left[\left(E_{v,g} - E_{v,d}\right)/E_{vo,h}\right]}{a_v\, m}, \tag{4}$$

where illuminance levels either $E_{v,s}$ or $E_{v,g}$ and $E_{v,d}$ respectively are measured, but in theoretical calculations $E_{v,s}$ can be also calculated after assumed atmospheric conditions

$$E_{v,s} = E_{vo,h} \exp(-a_v\, m\, T_v)\,[\text{klx}], \tag{5}$$

where the optical air mass m and the relative luminous extinction coefficient a_v are determined according to the momentary solar altitude [Kittler and others 2012].

3. DAYLIGHT HORIZONTAL ILLUMINANCE AND ZENITH LUMINANCE UNDER ISO/CIE SKY TYPES

In practical evaluations of daylight in interiors, a simplified system of the relationship simulating reality was sufficient to predetermine typical or close to prevailing conditions that were adopted as the de facto design standard. The original Lambertian sky [Lambert 1760] with uniform and unity luminance used first in calculations; then the Lambertian unity luminance and luminous distribution were replaced by the densely overcast sky standard with the luminance gradation 1:3 from horizon to zenith [CIE 1955]. Later, the standard of a cloudless sky with two atmospheric turbidity possibilities was added [CIE 1973]. Then within the Slovak–U.S. cooperation grant [Kittler and others 1997], a set of 15 homogeneous sky types was proposed for standardization and subsequently adopted by the CIE [2003] and the ISO [2004]. Of course, the simplest daylight conditions occur under the dense fully ISO/CIE overcast sky types 1, 3, and 5 in relative terms when any sunlight is absent and the scattering indicatrix function is of unity value. If value L_{vZ} is known, the sky luminance distribution can be calculated in physical units in kilocandelas per square meter as shown in Figs. 1a–1c.

The classifying ratio of zenith luminance L_{vZ} to sky/diffuse horizontal illuminance $E_{v,d}$, $L_{vZ}/E_{v,d}$, is not dependent on solar altitude and the relative standard sky luminance patterns can be integrated and yield:

$$\text{for the sky type 1: } L_{vZ}/E_{v,d} = 0.4083 \tag{6}$$

$$\text{for the sky type 3: } L_{vZ}/E_{v,d} = 0.361 \tag{7}$$

$$\text{for the sky type 5: } L_{vZ}/E_{v,d} = 0.3183/ \tag{8}$$

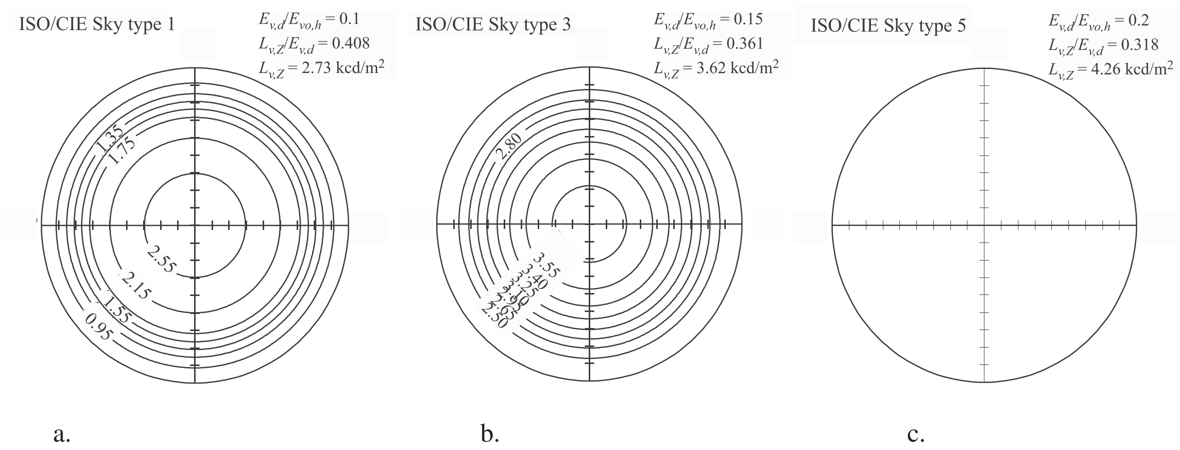


Fig. 1 **Sky luminance distribution in kilocandelas per square meter on overcast skies: (a) sky pattern with luminance gradation 1:3; (b) sky type 3 with higher luminance levels; and (c) Lambertian uniform sky with overall luminance equal to zenith luminance.**

The latter corresponds with the Lambertian sky as $L_{vZ}/E_{v,d} = 1/\pi$.

After the integration of these sky luminance patterns, an empirical formula was derived for all ISO/CIE sky types after the fitting procedure that simulated exactly the integration results by a simpler empirical equation (9) valid for solar altitudes lower than 70° and for sunless homogeneous skies:

$$L_{vZ}/E_{v,d} = \frac{B\left(\sin\gamma_s\right)^C/\left(\cos\gamma_s\right)^D + E\,\sin\gamma_s}{E_{vo}\,\sin\gamma_s} = \frac{Y}{E_{vo}\sin\gamma_s}. \tag{9}$$

Equation (9) can be reduced in case of sky types 1, 3, and 5 to

$$L_{vZ}/E_{v,d} = \frac{B\,\sin\gamma_s}{E_{vo}\,\sin\gamma_s} \approx \frac{B}{133.8} \tag{10}$$

In case of ISO/CIE sky types 2, 4, and 6, (9) has to be applied due to a small relative indicatrix rise depending on the solar altitude. If $E_{v,d}/E_{vo,h}$ is statistically determined as a prevailingly recurring ratio in a certain location, then

$$L_{vZ} = \frac{E_{v,d}Y}{E_{vo}\sin\gamma_s} = \frac{E_{v,d}Y}{E_{vo,h}} \quad \left[\mathrm{kcd/m^2}\right] \tag{11}$$

and

$$E_{v,d} = \frac{L_{vZ}E_{vo}\sin\gamma_s}{Y} \quad [\mathrm{klx}]. \tag{12}$$

Formulae (9), (11), and (12) are valid also for all sky types 7–15 when the sunlight is absent, whether during a full eclipse or shaded totally by a single cloud, but appropriate Y parameters have to be calculated after B, C, D, and E auxiliary values [Kittler and others 2012]. However, daylight conditions when occasionally due to cloud movements certain periods are without sunshine the skylight illuminance is permanently present according to these relations.

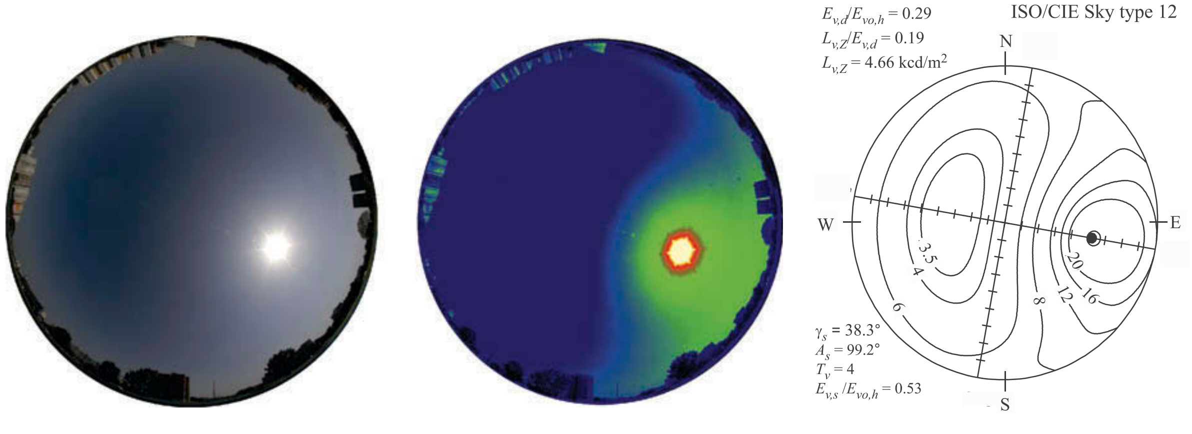
During sunny periods under cloudy or clear skies, $E_{v,d}/E_{vo,h}$ and $E_{v,s}/E_{vo,h}$ ratios are dependent on the value of the luminous turbidity factor T_v. An empirical formula to fit all sunny conditions under ISO/CIE sky types under various $E_{v,d}/E_{vo,h}$ ratios was tested [Darula and Kittler 2005] that expresses a general relation of $E_{v,d}/E_{vo,h}$ with zenith luminance and the luminous turbidity factor value T_v:

$$E_{v,d}/E_{vo,h} = \frac{\left[(A1\,T_v + A2)\sin\gamma_s + 0.7\,X(T_v+1) + 0.04\,T_v\right]}{BX + E\,\sin\gamma_s}, \tag{13}$$

$$\text{where } X = \frac{(\sin\gamma_s)^C}{(\cos\gamma_s)^D}, \tag{14}$$

$$\text{and } L_{vZ} = (A1\,T_v + A2)\,\sin\gamma_s + 0.7X\,(T_v+1) + 0.04\,T_v \quad [\mathrm{kcd/m^2}]. \tag{15}$$

Under a specific solar altitude and using the appropriate auxiliary of $A1$, $A2$, B, C, D, and E values for different sky types as well as typical or measured T_v and $E_{v,d}/E_{vo,h}$ after



a. b. c.

Fig. 2 **Almost the same reproduction of a clear sky luminance image in the plan equidistance projection of the sky hemisphere: (a) photographed by a fisheye lens; (b) luminance map analyzed from the fisheye photo; (c) calculated pattern after ISO/CIE sky type 12.**

(13) and L_{vZ} after (15) in kilocandelas per square meter can be calculated. However, the absolute diffuse illuminance $E_{v,d}$ and $E_{v,s}$ in kilolux or lux is of equal importance to the design of an artificial sky's illumination system. The measuring platform's elevation, location, and dimensions critically affect the absolute diffuse illuminance $E_{v,d}$ and $E_{v,s}$ in kilolux or lux to define the scale for modeling luminance patterns and additional sunlight [Darula 2014]. Further, during sunny periods when the relative luminous turbidity factor is less than $T_v = 7$, if parallel sunbeams form visible direct shades, the direct solar illuminance on a horizontal plane can be calculated after (5). The typical $T_v = 2.5 - 3.5$ is in the mountainous or countryside locations, $T_v = 3 - 4.5$ in towns, and $T_v = 4 - 6$ is usually characteristic for urban regions with industrial pollution.

It is important to note that after the absolute zenith luminance value, any ISO/CIE sky standard in relative terms can be expressed in kilocandelas per square meter. For example, a horizontal projection on the fisheye photo in Fig. 2a is shown and after its luminance map in Fig. 2b, it is compared to calculated luminance pattern with isolines in kilocandelas per square meter for the clear sky type 12 in Fig. 2c.

4. DESIGNING ARTIFICIAL ISO/CIE SKY TYPES WITH AN ARTIFICIAL SUN

Due to the enormous space size of the sky vault representing the Earth's atmosphere, a fictitious virtual hemisphere is imagined on which ISO/CIE luminance patterns in elementally small solid angles are simulated. It is important to model standard sky types in their homogeneous or quasihomogeneous nature as in their mathematically defined set as proposed for daylight calculation purposes and as a basis for computer-aided design and evaluation tools. Therefore, the simulation of the 15 ISO/CIE luminance patterns in an artificial sky has to follow certain basic requirements regarding items:

1. The genuine smoothness, evenness, and fluent luminance sky distribution on all the homogeneous 15 ISO/CIE sky types have to be reproduced in a certain model scale in a fictitious hemisphere. Because real luminance in absolute units cannot be achieved on the artificial sky dome, the currently valid 15 ISO/CIE sky types are specified in relative sky patterns normalized to zenith luminance. However, when the artificial sky has to simulate luminance patterns and illuminance levels in absolute physical units expressed in a scale ratio to reality, the artificial sky design will respect real skylight conditions [Kittler and Darula 2014].
2. In the same scale, illuminance levels have to be simulated on the measuring model table where architectural model buildings or rooms with windows would be placed.
3. Due to the required precision of model measurements, a hemispherical sky dome of at least 7.5 m in diameter is needed to accommodate 1/10 scale models and to provide reflections from simulated ground. The highly diffuse reflective inner surface with reflectance coefficient of at least 0.9 is recommended to illuminate a model table representing an outdoor horizontal plane of at least 2 × 2 m for placing the architectural model room.

4. If the artificial sky is also to be equipped with an artificial sun producing parallel light beams, then its size has to be a compromise between its distance from the model table, which is close to a small solid angle of the sun disc, and a contrary requirement to cover all model windows with parallel sunbeams. Furthermore, the interdependence of the sky dome luminance pattern with the intensity of sunbeams under different cloudy and clear sky types with a typical atmospheric turbidity T_v is to be simulated most likely by dimming, which requires special attention while conducting scale and calibration tests.
5. In addition to the size of the artificial sun disc, another problem must be solved; that is, to imitate the larger and intensive solar corona luminance surround that must be moved with the sun position and is crucial under clear sky luminance patterns.
6. When modeling the clear sky color by LED sources it could be possible to use some additional bluish or blue light for higher sky dome luminance opposite the sun position, which could be another realistic feature of new sky domes facilitated by LED technology.
7. In daylight research and model experiments, the scales of all models used in the artificial sky must respect the scaling limitations of the sky simulator and the size of building models.

When designing a new artificial sky, any designer has to decide first the simulation sky shape, dimensions, and placement of the electric lighting system. As the dome dimensions increase, or the assessment model size is decreased, the horizon scale error, which cannot be avoided, is also decreased. Before building an artificial sky, the following have to be considered: the utility and feasibility of the desired simulation sky shape; the necessary dimensions and position of the light delivery system and its controls; and the data gathering instrumentation and luminance sensors, all with respect to the accuracy required and its impact on space and cost constraints.

Due to competing cost and space constraints, which are driven by external factors (political incentives and knowledge), small sky models or only sky panels were used [Kittler 1959]. Since Pleijel used a high mirror box sky [Pleijel 1949] and a less expensive and shorter BRS (Building Research Startion, U.K.) box sky [Hopkinson and Longmore 1954], many architectural faculties own a box-type artificial sky simulating the former CIE overcast sky standard, which are shown to undergraduate students. These facilities can explain some daylighting problems of the curriculum but partly distort the principal role of sun and sky influence in architectural design. Vitruvius [13 BC], in his seminal textbook for architects, stressed the daily sun path image as basic for designing the orientation of urban and building spaces with regard to the well-being and daylighting of interiors.

Today when the overcast conditions and daylight factor criteria seem to be less important and, at least in tropical and subtropical regions, already obsolete, architectural students have to be instructed on the whole complexity of a much forgotten daylight science [Kittler and others 2012].

All artificial skies with sun designed for experimental research in Table 1 were built on the concept of a hemisphere or its partial lunes. Traditional hemispheric reflective domes for the first time included an additional artificial sun from outside in the Russian uniform sky luminance with a diameter $d = 9$ m [Gusev and Lugovskoy 1950], followed by the Slovak 8-m artificial sky with an interior 0.9-m sun modeling the CIE clear sky [Kittler 1974], the Berkeley, California, sky [Navvab 1981], and the Ann Arbor, Michigan, sky [Navvab 1991]. However, Tregenza [1989] introduced a new concept for architectural model measurements by simulating the sky luminance only on its single meridian arc with 30 close-packed lamps on a virtual 3.4-m hemisphere. The model, placed on a rotating table, could be turned in 800 azimuth steps to simulate a sky subdivided into 184 zones without a sun. That was a tempting and cheap concept to fill in the hemisphere by a number of circular sources placed either in its lune or on its whole surface, like that proposed by Michel and others [1995] or for the dome in Cardiff [Anonymous 2014a].

5. DISCUSSION OF POSSIBLE ERRORS

With regard to items in Section 4, the following notes can be mentioned and discussed.

Note to item 1. In reflective artificial sky domes [Kittler 1959, 1974; Selkowitz 1982], depending on the light sources placed under the dome horizon there are also some problems to be solved:

- How to avoid direct light from primary sources catching the ceiling areas in model rooms and eliminate the parallax effect by the placement of the model.
- How to cope with the parallax error caused with the finite distance between the model placement and inner surface of the dome. In comparison to reality, the scale model windows receive a different quantity of skylight

TABLE 1 List of artificial skies with sun as measuring facilities for daylight research

Type of sky	Institution and location	Specification		Details in references
		Sky	Sun	
Reflective hemispherical domes	CNIPS–Central Research Institute of Industrial Buildings, Perovo, Moscow, Russia	$d = 9$ m, 16 lamps (500 W), uniform luminance	$d = 0.9$ m, parabolic mirror outside sky, solar altitudes 0–90°	Gusev and Lugovskoy [1950], Kittler [1959] Now dismantled
	Institute of Construction and Architecture, Slovak Academy of Sciences, Bratislava, Slovakia	$d = 8$ m, overcast, uniform and clear sky patterns	$d = 0.9$ m, parabolic mirror inside sky with solar altitudes 0–70°	Kittler [1974]
	Lawrence Berkeley Laboratory, Berkeley, CA, USA	$d = 7.32$ m	$d = 1.5$ m, stand alone area source of collimated beams	Navvab [1981] Selkowitz [1982]
	The University of Michigan, Ann Arbor, MI, USA	$d = 9.2$ m, overcast, uniform and clear sky patterns	$d = 1.5$ m, parabolic disc, 1,000 W quartz lamp	Navvab [1991, 1996]
Translucent hemispherical domes	Sekisui House Institute of Building Science, Nara, Japan	$d = 5$ m, 853 circa 0.3/0.2 m cassette luminaires	$d = 0.8$ m, parabolic mirror inside sky with solar altitudes 0–90°	Okado and others [1997]
	Bartenbach Ltd., Aldrans, Austria	$d = 6.5$ m, 393 lamps with diffuse shading	$d = 1.2$ m, any position of the sun as a added heliodon	Anonymous [2014b]
Hemispherical sky simulators	NIISF–Research Institute of Building Physics, Moscow, Silver Pines, Russia	$d = 16.8$ m, 2,000 spots of individual luminaires	Five parabolic stable sun reflectors with fixed altitudes	Bolenok and others [1986] Lioutsko and Spiridonov [1992]
	Welsh School of Architecture, Cardiff, UK	$d = 8$ m, 640 spots of individual luminaires	Artificial sun as an added heliodon	Anonymous [2014a]
	Danube University, Krems, Austria	$d = 6$ m, 230 spots of individual luminaires	$d = 1.2$ m	Anonymous [2014c]
	Bartlett Faculty of the Built Environment, University College, London, UK	$d = 5.2$ m, 270 lamps, 11W	$d = 0.8$ m, parabolic reflector, 16 mercury lamps	Anonymous [2014d]

and sunlight from different sky areas due to different positions with respect to the artificial sky center. This error is quite low under overcast skies but can be significant in clear sky simulation with the sun position and reduced by a larger size of artificial skies [Mardaljevic 2002].

- The horizon scale problem can be reduced, as mentioned earlier, by using smaller scale models and sensors. Basically, the modeled window facade should be located in the center of the dome to keep it as close as possible to the point from which the sky luminance distribution was measured. This means sliding the scale model and artificial ground together over the sky's central measurement table as explained by Navvab [1989].
- How to distribute the luminaire output on the sky dome white surface in such a way that it will fluently approximate the luminance patterns of every specific sky type.
- Special attention should be given to the white diffuse plastic grain-free water-based paint on the inner surface

of the reflective sky dome, which has to respect its sucking plaster. Note, that the standardized white paint for the Ulbricht sphere integrators applicable on metal surfaces cannot be used.

A special group of artificial skies are those with a translucent dome [Croghan 1964] where there is a need to achieve a perfect diffusivity of a translucent layer to decrease the luminance unevenness caused by lightbulbs or tubular sources placed behind it. Photo ultraviolet degrading of the Perspex transilluminator must be avoided, though it probably was not in the Cambridge sky.

Many of the artificial skies designed recently ignore the first requirement of luminance evenness and smoothness of a fluent natural luminance distribution due to construction ribs supporting the glass or Plexiglas panels illuminated from behind, thus forming the translucent sky dome; for example, in the Japanese 5-m-diameter sky with a 0.8-m sun in Nara [Okado and others 1997] or in Ann Arbor [Navvab 1989] domes. However, even more erroneous are sky domes simulating luminance patterns by either hemispheric arrays of reflectors; for example, in the dome with a 16.8 m diameter with five fixed-position parabolic artificial suns at the Scientific Research Institute of Building Physics (NIISF) in Serebryanye Bory, Moscow [Bolenok and others 1986; Lioutsko and Spiridonov 1992], Cardiff [Anonymous 2014a], or Betanit, so-called complete domes.

The sky simulators with only reflectors in their lune arrangements are even more suspect, such as in Lausanne forming the 5-m sky by six lunes [Michel and others 1995] or in Torino [Filippi and others 2000] as well as the so-called Kiwi prototypes [Anonymous 2014e]. It is evident that such solutions introduce luminance peaks and dark or black patches without fluent gradations and evenly distributed scattering effects (Fig. 3).

The main problem of the artificial sky simulators with the uneven luminance distribution modeling the sky with series of evenly spaced point or tubular light sources was dealt with by Zijl [1951], who compared such solutions with regard to skylight and large artificial windows or ceiling panels. Their luminance distribution is inadequate and horizontal illuminance can be designed to prescribed levels. However, an error is also caused by the area cover of the sky hemisphere. For instance, the area of the whole hemisphere is $2\pi R^2$, where R is the artificial sky radius, and the solid angles of a number of round sources cover a smaller area. Even closely placed circular sources, due to their solid angles, will cover the whole hemisphere only in a percentage of the whole hemisphere area as documented in Kómar and Kocifaj [2014]. Nevertheless, Tregenza's [1987] subdivision scanning system of 145 circular solid angles cannot be misused to imitate the sky lunes by spot circular reflectors because the whole luminance sky pattern is reproduced only to 60%–70%.

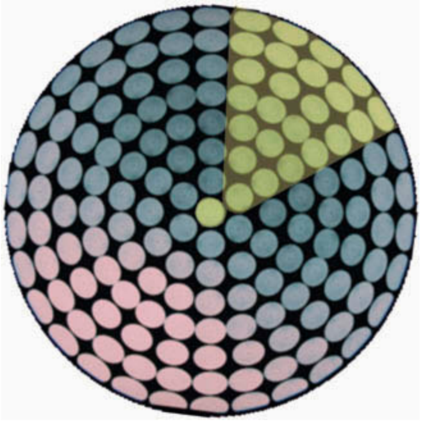


Fig. 3 **Modeling of the sky lune by a 60° segment used in sky simulators.**

Calibration tests must determine the accuracy of simulating the luminance patterns from the dome center as well as the calibration of illuminance distributions on the whole plane of the model measuring table and its elevation limits.

The currently valid 15 ISO/CIE sky types are specified in relative sky patterns normalized to zenith luminance, but when the artificial sky also has to simulate luminance and illuminance levels in absolute physical units expressed in a scale ratio to reality, its design has to respect real skylight and sunlight relations [Kittler and Darula 2014]. Because very often exquisite and original architectural designs are to be tested, using their scale models under an artificial sky, a perfect modeling of sky luminance patterns in the widest window solid angles (for example, from the aperture center) is needed because interreflection conditions within the model rooms are dependent on skylight illuminance of their differently sloped and oriented surfaces.

Note to item 2. To calibrate the sky luminance patterns and their zenith luminance in an appropriate scale to reality, it is recommended that the same ratio for sky luminance distributions be used. Such calibrations are usually either not measured or not published in protocols for the majority of artificial skies in use. It is evident that when no calibration of the sky dome luminance pattern is made, any calibrated illuminance on the measuring model table does not represent a proof of simulating ISO/CIE luminance patterns because the same illuminance levels exist under different sky standards.

Note to items 3 and 4. It is assumed that artificial skies with an artificial sun have a hemispherical shape and the sun position can be moved to different solar altitudes along the sun meridian. The size of the sky dome and the appropriate size of the artificial sun diameter are problematic, but the larger the dome, the more realistic the modeling of the sun disc or the band of parallel sunbeams reaching the architectural model.

The 8-m-diameter Bratislava sky with its artificial sun disc with 0.9 m diameter after 40 years service is now being prepared for refurbishing and installation of a novel illuminating electronically controlled LED lighting system. The scale of a model in the sky dome is dependent on the daylight experiment proposed. In the case of only overcast and sunless conditions, experience has shown that an appropriate scale of 1:20 is usually satisfactory, but under cloudy or clear conditions, due to possible luminaire developments, alternative possibilities to simulate sunbeams at higher solar altitudes scales 1:100 to 1:250 could produce satisfactory results.

Note to item 5. In the first NIISF reflective 9-m dome in Perovo, Moscow [Kittler 1959], the artificial sunbeams were simulated by a parabolic mirror reflector placed outside the dome. This design needed to open a wide gap along the sun meridian that had to be covered by inserting white panels in the gap, and the solar corona higher luminance had to be realized by additional illumination sources from the dome floor.

In the Bratislava hemispherical simulator [Kittler 1974], the parabolic mirror was placed inside the dome suspended on an outer trolley wheel support through a 10-cm gap, which also enabled adjustment to any solar height in the range 0–70°, as well as using the mirror rim to place an additional row of incandescent lamps to illuminate the solar corona helped by additional reflectors placed under the dome horizon.

Note to item 6. Luminous flux from incandescent or other white–yellow fluorescent sources reflected from the original sky dome white surface simulate mostly overcast and cloudy skies with or without sunlight presence. Using LED sources enables the use of some additional bluish or blue light for the lower sky dome luminance opposite the sun position, an added realistic feature of new or refurbished sky domes.

Note to item 7. Several facts and interrelations influence the scale choice in modeling daylight situations:

- Architectural models use the space/dimension scale and reduce real dimensions of buildings accordingly. Rooms and daylight apertures with or without frames in appropriate reduction scale—for example 1:5, 1:10, 1:20, et cetera—assume that the solid angles and proportional space/dimension ratios are equal and proportionate to reality.
- Modeling of material properties in such architectural models has to be simulated by their real unreduced property coefficients in a 1:1 scale—that is, introducing real transmittance of glazing, reflectance and color of surfaces, et cetera—but, for example, glass size in model window frames has to be reduced in the scale although the thickness of the glass has to be in real dimension.
- Real luminance and illuminance levels outdoors, due to their extremely high intensities, can be simulated in a sky dome and artificial sun only in a reduced scale but with regard to their interdependence on physical units and should be in the same scale ratio—for example 1:20, 1:100, 1:200, et cetera—resembling the introduction of an appropriate neutral filter similar to atmospheric turbidity or transmittance.
- To reduce measurement errors in models, the sensitivity range and size of spectrally and cosine corrected sensors should be appropriately reduced to fit to model scales used [MacGowan 1965]. Basically the largest accurate sky simulator coupled with the smallest practical building scale model and the smallest accurate luminance sensors is best for physical measurement accuracy.
- To resemble natural conditions and also to suit model experiments, the size and shape of the artificial sun should be carefully decided by the designer of the artificial sky.

6. RECOMMENDATIONS FOR THE CALIBRATION OF SKY LUMINANCE PATTERNS IN THE SKY DOME

6.1. Requirements Concerning the Calibration of Instruments

When the artificial sky with sun is designed as multipurpose laboratory equipment to research and test daylighting in architectural scale models, it is important to calibrate the accuracy of the sky luminance simulation patterns as well as the distribution of illuminance levels on the horizontal measuring table. At least some of the most important ISO/CIE sky types should be modeled and calibrated in a reduced scale luminance distribution on the hemispherical sky surface, because these primarily affect the skylight and sunlight distribution within model interiors, resulting in the sky component and interreflection component illuminance levels.

For sky luminance pattern calibration the following protocol can be recommended:

- Calibrate and use luminance meters with a narrow acceptance angle (in the ranges 0.3–3.3°) to calibrate the luminance gradation and scattering indicatrix function in relative terms normalized to the zenith or in absolute units respecting the desired scale [Kittler and others 2012].
- Calibrate luminance meters to measure sky type luminance in the points of a hemispherical mask.
- Calibrated fisheye camera with the additional computer evaluation of the sky luminance pattern image.
- Calibrated image luminance measuring devices or videophotometers can be used to measure sky element/pixel luminances as well as luminance distribution.

Of course, these methods of calibration can be applied with the possibility to compare resulting tests when all luminance sensors are spectrally (that is, $V(\lambda)$ and illuminance sensors both $V(\lambda)$) and cosine corrected and the fisheye projection system is known. In the calibration process, any irregularities in modeling the sky patterns have to be adjusted by adopting the installed illumination system in a step-by-step correction.

Sky luminance patterns can be calibrated using a portable luminance meter on a tripod with a rotatable head adjustment to follow:

- Various elevation angles of the sun meridian and horizontally defined azimuth angles on the solar or sky almucantars.
- A more sophisticated system is to measure and determine directly the scattering indicatrix $f(\chi)$ as well as to detect the luminance gradation function and both should agree with those compared to the appropriate ISO/CIE sky type to be simulated [Kittler and others 2012]. The scattering indicatrix could be measured on the sun as well as on sky almucantars where the point of $f(90°)$ has to be found and measured. Then in 5° or 10° azimuth steps along any almucantars the course of the $f(\chi)$ can be determined. The gradation function $\varphi(Z)$ following its increasing or decreasing trend can be measured from the zenith with a constant angle Z_s on a circular section of the hemisphere passing the horizon.
- The luminance pattern can be measured by a sky scanner or other scanning luminance meter if available.

For the calibration of illuminance levels, all calibrated illuminance meters with sensors spectrally and cosine corrected have to be used:

- Measuring either in the center or over the plane of the measuring table to test outdoor levels.
- With sensors placed inside a reference model with black matte interior surfaces, the actual results can be compared to calculated and measured sky factor distribution under a simple outdoor overcast sky pattern.

After the calibration, all relevant adjustments and inaccurate solutions have to be written in a protocol document with statements of special model scales used for various sky type simulations.

6.2. Basic Simulation Requirements for Adjusting the Artificial Lighting System of the Reflective Artificial Sky with Sun

Understanding the principal relations of the ISO/CIE homogeneous sky patterns expressed in the basic luminance distribution formula in relative terms

$$\frac{L_{\chi Z}}{L_{v,Z}} = \frac{f(\chi)\,\varphi(Z)}{f(Z_S)\,\varphi(0°)}, \tag{16}$$

it is obvious that two separate influences determining any sky luminance pattern can be also modeled separately:

- The gradation drop or increase given by $\frac{\varphi(Z)}{\varphi(0°)}$, which is normalized to a unity zenith function for the zenith angle Z, where $\varphi(0°)$ is very important under overcast sky types 1, 3, and 5 when the indicatrix influence is absent as $\frac{f(\chi)}{f(Z_S)} = 1$. In homogeneous overcast skies, no differences around sky azimuths is expected and it seems that at least two dimmable groups of light sources regularly placed under the artificial sky horizon can be used. The first group could simulate a gradation increase from horizon to zenith under overcast sky types from 1:3 to 1:1, whereas the second group will serve for cloudy and clear sky opposite gradations roughly 2.5:1, 4:1, and 8:1 to simulate quite high luminances around the horizon. In addition to the gradation ratio adjustments, the calibration protocol has to provide the measured ratios as well as $E_{v,d}/E_{vo,h}$ ratios for the modeled sky type without sunlight and $E_{v,s}/E_{vo,h}$ ratio when the artificial sun is turned on.

- The influences of the indicatrix function are present in sky types 2 and 4 and 6–15 together with the appropriate gradation influences and are linked with the sun position and the scattering angle χ, which defines the distance of any sky element from the sun. As the highest luminances are centered around the sun position, it seems that a ring of dimmable artificial sources could simulate this solar corona pattern and be made movable with the sun altitude.

7. CONCLUSIONS

Modeling of sky luminance patterns in artificial skies as laboratory facilities is worth the relatively high cost only if serious daylight research is to follow; any educational or advertising services are an additional advantage. Research projects using measurement results under real skies are usually lacking stability conditions in time and sky luminance distribution due to moving clouds and sun path changes. Current computer simulation programs cannot take into account all circumstances in case of unique architectural solutions in the local urban obstruction scene, such as unusual arbitrary apertures in size, shape, and placement or interreflexion conditions due to complex exterior and interior, arbitrarily sloped surfaces, et cetera. Furthermore, any new or improved computer programs have to be based on theory and measurements principally verified under artificial skies in stable laboratory means.

Generally, the accuracy of simulated results strongly depends on the algorithm applied in the individual computer program.

Therefore, the advantage of artificial skies using architectural models is in the possibility to simulate and measure any alternative solutions in the stage of designing their luminous environmental resulting from their apertures, glazing and shading materials, and color and reflexion of surfaces or interior furniture. Therefore, artificial skies for such testing should be designed as special laboratory experimental instruments capable of simulating all relevant daylight conditions worldwide with stable sun and skylight reference conditions uniquely linked to extraterrestrial and atmospherically determined luminance. These cause the resulting illuminance on flat terrain, vertical house fronts with arbitrary orientation, as well as in interiors via their aperture solid angles. It should be noted that novel glazing means that, due to their transmission, reflexion, scattering or color properties, shading constructions, shelves, jalousies, light tubes, or ceiling anidolic cavities and others have to be tested. These are also the reasons why artificial skies have to serve as extraordinary laboratory instruments calibrated for experimental purposes and testing needs. The usefulness of artificial skies can be documented by several experiments or tests in some recent papers; for example, by Navvab [1996], who tested the Rock Museum model design; by Aghemo and others [2007], who experimentally studied different shading systems; or by Lo Verso and others [2011], who measured the efficiency of daylight guidance systems.

The design of an artificial sky has to follow the daytime sky image of the largest daylight diffuse source with the ever changing luminance patterns powered by the mighty solar parallel beams filtered and scattered by the complex content of the atmospheric environment.

The ISO/CIE standard sky luminance patterns, whether in relative terms or in absolute luminances, predetermine the basic characteristic homogeneous distribution on the whole sky vault. Their uniformity of structure and mutually similar fluent image characteristics are dependent on angular changes expressed by an even luminance distribution caused by sunbeam scattering and density of atmospheric layers. The basic requirement in artificial sky design due to the enormous size of the natural virtual sky vault is to simulate sky luminance in elemental solid angles equivalent in scale to reality and equal in image to ISO/CIE standard sky patterns. If more than simple overcast skies are to be used in modeling, then box-type artificial skies are out of question. Reflective hemispherical sky domes are recommended to simulate ISO/CIE sky types with the addition of a movable artificial sun, which can closely model fluent luminance changes over the sky dome surface in sunless and sunny situations.

Abrupt illuminance changes in outdoor ground illuminance levels are caused by moving clouds sometimes blocking direct sunbeams from reaching the ground. When background skylight corresponds to the particular sky type, simply switching on and off the artificial sun can simulate cloudy daylight conditions under the so-called dynamic daily courses. Under cloudless conditions, the proportional sun to sky influences are dependent on the relative turbidity, which can be expected and averaged or measured.

Any ISO/CIE luminance pattern chosen to be simulated in the artificial sky dome also has to be calibrated and documented before its experimental use. Then this laboratory equipment is ready for experimental research, proving the luminance and illuminance appropriate precision of simulation and accurate illuminance results on the model measuring table as well as inside and around the architectural model tested.

It is evident that the electric system of the artificial sky has to cover two major tendencies when simulating the ISO/CIE sky types:

- The gradation rise of horizon to zenith luminance from 1/3 to 1 under overcast sky conditions and a further rise from 1 to 8 under intermediate to clear sky types. A logical regular placement of light sources around the artificial sky horizon is expected with either turnable reflectors or a fixed double-row system controlling its output to achieve the gradually dimming of both rows.
- The sunbeam scattering influence has a rising tendency from 1 to 20 toward the sun position in accordance with the turbidity layers diffusing the sun beams; that is, the relative indicatrix in all sky elements displaced from the sun is unity and the solar corona light sources have to be turned off under overcast skies, whereas under clearer sky types a higher solar corona luminance is expected. These requirements are best met by a circular ring of sources or a bended tube source hidden behind the artificial sun. This arrangement was enabled by the "solar" parabolic mirror placed inside the sky dome as first used in the Bratislava sky.

Of course, an artificial sky with models of all ISO/CIE sky types would be very welcome. However, nobody has documented yet that possibility to realize a task so complex, especially when clear sky types at higher solar altitudes are losing practical accuracy. Therefore, even partial success in modeling several relevant sky types or locally typical ones should be favored.

In the calibration protocol of the artificial sky and sun, a list of all simulated sky types has to be verified with prescribed conditions, restrictions, and scales compared to measured, recorded reality. Specific or typical cases of atmospheric turbidity or cloudiness linked to solar altitude ranges under different sky types with or without the presence of the sun have to be related to a valid scale.

The related investment costs to build the artificial sky dome with an artificial sun are justified when such laboratory equipment will serve as true and precise equipment for daylight research and a verified testing tool for expensive architectural designs.

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