# DERIVING ILLUMINANCE FOR MODEL MEASUREMENTS UNDER ARTIFICIAL SKIES

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## Abstract

Simulation of real sky luminance patterns with resulting illuminance levels is to be respected when designing a new or refurbished sky dome with a smooth luminance distribution and the artificial sun producing parallel beams as in nature. The homogeneous sky luminance is to follow the ISO/CIE standard in relative terms which offers the whole range from overcast to cloudless skies. To measure illuminance distribution on the working plane inside a model room under an artificial sky have to be achieved by artificial sources with proportions of sky and sun components corresponding to gradation and indicatrix scattering functions specific for any ISO/CIE sky type.

In this study are applied mathematically defined equations for computer calculations to predetermine maximal exterior zenith luminance and horizontal illuminance with the aim to find the scale reduction for their possible representation under an artificial sky and sun. The actual high intensities of sunlight and skylight occurring in Bratislava after regular minute local data cannot be realised by any artificial sources therefore the scaling and calibration requirements have to be set for the construction or an artificial sky or its refurbishment.

*Keywords*: Artificial sky and sun, Zenith luminance, Exterior illuminance, Scaling sunlight and skylight

## 1 Introduction

To simulate sophisticated outdoor sunlight and skylight conditions in the older mirror box type artificial skies (Kittler, 1959) is not more possible, therefore only reflecting dome sky simulators with the artificial sun facility have to be designed and built (Kittler, 1974, Navvab 1996, Darula, Kittler, 2014). Currently available new technological inventions like LED sources (Macha, 2013) enable to simulate many relevant daylight conditions but for their installation and placement of the new electric system as well as for the model scale and calibration have to be predetermined relevant real luminance and illuminance levels proposed for modelling.

Therefore the first task is to document those real typical or extreme sky types and situations in absolute physical units (Kittler, Darula, 2014) that could be simulated with respect to sensor size, their reliable measurement precision and other restrictions that stem from the construction, form and size of the dome construction newly built or from older already available domes to be refurbished. Questionable is also the source of parallel sunbeam installed in the artificial sun which has to simulate a relative wide stream falling on the model window apertures in an adequate intensity or reduced influenced by typical dimmable turbidity, filtering and scattering while coupled together to the appropriate sky type component.

## 2 Basic interrelations defining ISO/CIE sky types

### 2.1 Luminance distributions on the general homogeneous ISO/CIE skies

Sky luminance $L_{v,\chi z}$ distributed over the whole sky hemisphere normalised to zenith luminance $L_{v,Z}$ serves as a relative ratio to standardise the luminance ISO/CIE (2004/2003) sky types with a particular pattern defined by their gradation $\varphi(z)$ and scattering indicatrix $f(\chi)$ functions, as:

$$\frac{L_{v,\chi z}}{L_{v,Z}} = \frac{f(\chi)\varphi(Z)}{f(Z_s)\varphi(0°)} \tag{1}$$

where

$\chi$ is the angular distance from the sun position to an infinitive element of the sky hemisphere;

$Z$ is the zenith distance of this infinitive small sky element;

$Z_s$ is solar zenith angle.

Note: Any further explanations can be found in (Kittler, Darula, Perez, 1997 or Kittler, Kocifaj, Darula, 2012, pp.127-136). However, when sky luminance and resulting exterior horizontal illuminance have to be in absolute physical units (i.e. kcd.m$^{-2}$, klx) their basic source is the extraterrestrial flux of parallel sunbeams reaching the outer border the atmosphere, i.e. linked to the Luminous Solar Constant.

### 2.2 Maximal extraterrestrial sunlight as the basic prerequisite source of daylight

The extraterrestrial solar radiation in its widest spectrum was recently defined and in its visible part could be evaluated with respect to human luminous efficiency function $V(\lambda)$ in an integration leading to the average value of the Luminous Solar Constant $E_{vo}$ = 133,8 ± 3,3% klx (CIE 1994, Darula, Kittler, Gueymard, 2005). As the highest average flux is assumed to pass or fall on a fictitious plane in the normal directions of sun beams a more representative for a horizontal plane in any place on the globe surface is the horizontal extraterrestrial illuminance $E_{vo,h}$ = $E_{vo} \sin\gamma_s$ which is comparable to horizontal illuminances measured at ground level, i.e. to solar/direct horizontal illuminance $E_{v,s}$ sky/diffuse illuminance $E_{v,d}$ or their summation called global illuminance $E_{v,g} = E_{v,s} + E_{v,d}$, where $\gamma_s$ is solar altitude.

Note: If the regular year-round outdoor measurements are available then due to actual day number within the year $J$ the daily solar distance of the Earth to Sun can be applied to calculate the daily value of the Luminous Solar Constant varying from the average 133,8 klx on the 3$^{rd}$ April and 15$^{th}$ October to approximately the maximum value 138,35 klx on the 3$^{rd}$ January in the winter season and symmetrically decreasing in the summer season gradually to its minimum 129,25 klx reached on the 4$^{th}$ July. Thus fluent gradual variations during a year are within the range 133,8 ± 4,55 klx with daily average values $E_{voJ}$ respecting any actual day number within the year $J$ after Kittler, Kocifaj, Darula, 2012, Equation (3.11) on p. 53:

$$E_{voJ} = E_{vo}\left[1 + 0{,}034\cos\left(0{,}9863°(J-2)\right)\right]. \tag{2}$$

### 2.3 Horizontal sunlight illuminance by parallel beams reaching the ground

Since Bouguer´s and later studies the atmospheric attenuation of sunlight was determined and expressed for the horizontal surface as:

$$E_{v,s} = E_{vo,h} \exp(-a_v\, m\, T_v) \tag{3}$$

where

$a_v$ is the luminous extinction coefficient of an absolutely clear and clean atmosphere after Clear´s (1982) formula;

$$a_v = \frac{1}{10{,}1 + 0{,}045\, m} \tag{4}$$

$m$ is the relative air mass usually determined by the Kasten, Young (1989) formula;

$$m = \frac{1}{\sin \gamma_s + 0{,}050572\left(\gamma_s + 6{,}07995°\right)^{-1{,}6364}} \tag{5}$$

$\gamma_s$ is the solar altitude in deg. changing in time within the daily sun path that is mathematically determined by different formulae (e.g. Kittler, Mikler, 1986, Tregenza, Wilson, 2011) and recommended by Kittler, Kocifaj, Darula (2012, p 55, Equations (3.13a and b));

$T_v$ is the luminous turbidity factor in the direction of sun beams that should be determined either after the measured $E_{v,s}$ illuminance or derived from global and diffuse components, i.e. $E_{v,s} = E_{v,g} - E_{v,d}$;

$$T_v = \frac{-\ln\left(E_{v,s} / E_{vo,h}\right)}{a_v\, m} = \frac{-\ln\left[\left(E_{v,g} - E_{v,d}\right) / E_{vo,h}\right]}{a_v\, m}. \tag{6}$$

If all these interrelated parameters are mathematically defined in any moment and in any location on globe the direct horizontal solar beam illuminance can be calculated using a computer.

## 2.4 Horizontal skylight illuminance reaching the ground from the whole sky vault

To express the diffuse skylight illuminance on the horizontal plane at ground level in klx means to find the ratio of zenith luminance to the integrated diffuse illuminance caused by the sky luminance pattern of the particular ISO/CIE sky type both based on gradation $\varphi(Z)$ and scattering indicatrix $f(\chi)$ functions as:

$$\frac{L_{vZ}}{E_{v,d}} = \frac{f(Z_s)\,\varphi(0°)}{\int\limits_{z=0}^{\pi/2} \int\limits_{A_z=0}^{2\pi} \left[f(\chi)\,\varphi(Z) \sin Z \cos Z\right] dZ\, dA_z}. \tag{7}$$

It is possible to achieve the $L_{vZ} / E_{v,d}$ ratios for any ISO/CIE sky type with its dependence on solar altitudes occurring in a particular location using a special computer integration, but a simpler approximation with a very precise fit was found within the Slovak-U.S.A. grant project (Kittler, Darula, Perez, 1998) for solar altitudes 0 - 70°:

$$\frac{L_{vZ}}{E_{v,d}} = \frac{Y}{E_{vo} \sin \gamma_S} \tag{8}$$

while

$$Y = B\,X + E \sin \gamma_S \qquad \text{and} \qquad X = \frac{\left(\sin \gamma_s\right)^C}{\left(\cos \gamma_s\right)^D} \tag{9}$$

and all these parameters $B$, $C$, $D$ and $E$ were defined for any ISO/CIE sky type in Table 1 for overcast sky types 1 - 6 and in Table 2 for cloudless sky types after (Kittler, Darula, Perez, 1998).

The restriction to the solar altitude 70° is in the case of the Bratislava artificial sky fully valid because the maximum solar altitude here at noon on the summer solstice day is $\gamma_s$ = 180° - 90° - 48,17° + 23,45 = 65,28°, which is under 70°. In locations in the tropics the original integration has to be used for solar altitudes over 70° (Darula, Kittler, Wittkopf, 2006).

Due to the design of the artificial sky are relevant extreme overcast and cloudless ISO/CIE sky types 1 – 6 and 11 – 15 presented on Figure 1. All overcast sky types are without any sunlight present, either with no indicatrix influence when characterised by the horizontal lines of sky types 1, 3 and 5 or with some brightening around the hidden sun position (sky types 2, 4 and 6 respectively). It is evident that for all sky types the classifying ratio $L_{vZ} / E_{v,d}$ after the fitted Equations (8) and (9) marked with crosses exactly follows the curves derived by integration

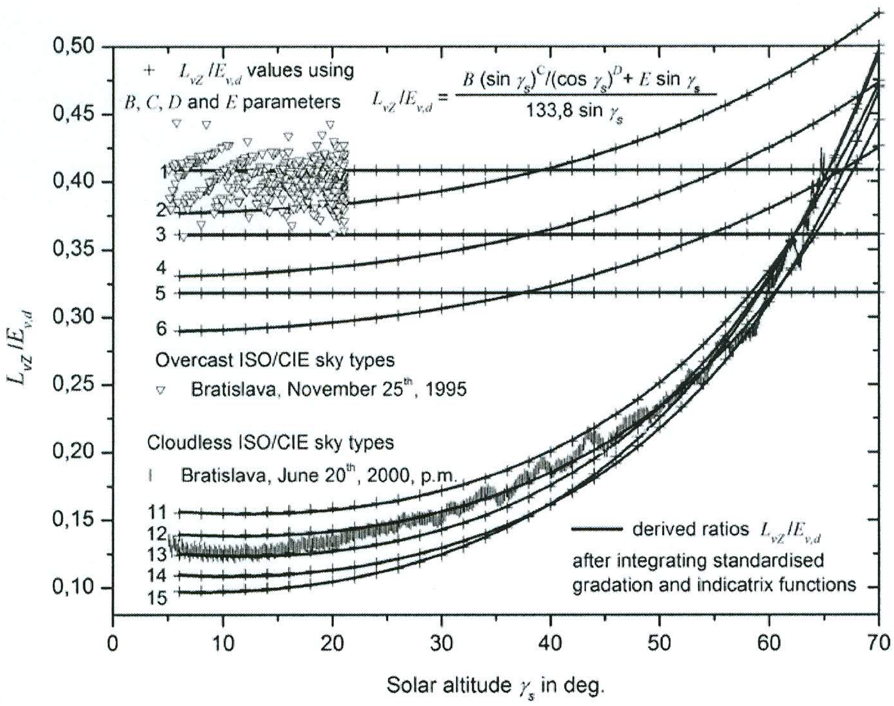


**Figure 1 – Classifying $L_{vZ} / E_{v,d}$ ratio for ISO/CIE overcast and cloudless sky types**

after Equation (7). These theoretical tendencies are compared with two extreme measurements from the Bratislava IDMP data collected since 1994, namely gathered during an absolutely fully overcast day on November 25th, 1995 and a cloudless clear afternoon on June 20th, 2000. In reality some deviations from standard homogeneous sky types are occurring in both cases due to either variations in ratios $E_{v,d} / E_{vo,h}$ or turbidity changes $T_v$ during sunny periods (Figure 2).

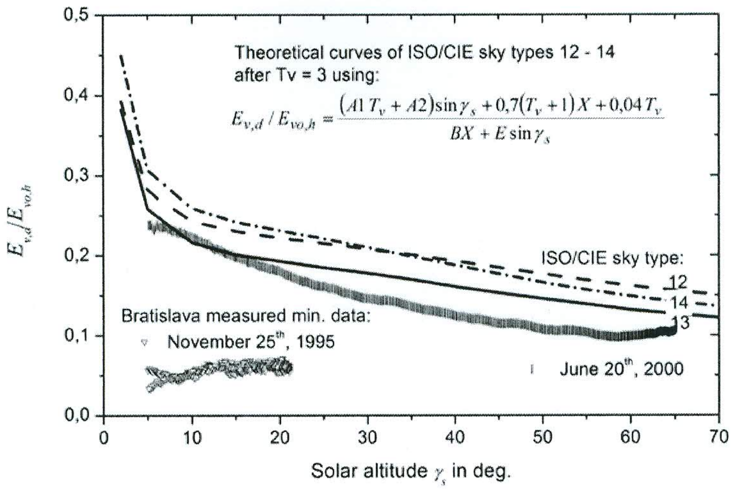


**Figure 2 – Turbidity influence on $E_{v,d} / E_{vo,h}$ ratio**

The variations during the overcast day are at the minimum values around $E_{v,d} / E_{vo,h}$=0,05 while the $E_{v,d} / E_{vo,h}$ ratios during a sunny day are dependent on the sky type and changing $T_v$ measured according to

$$E_{v,d} / E_{vo,h} = \frac{(A1\,T_v + A2)\sin\gamma_s + 0{,}7(T_v + 1)X + 0{,}04\,T_v}{BX + E\sin\gamma_s}. \quad (10)$$

Under clear type standards 11 - 13 the relatively stable $T_v$ values during some days are expected as documented for the June 20th, 2000 in Figure 3. There is also shown the unstable morning rise from $T_v$ = 2,5 to 3 due to the evaporation and temperature increase. Then a certain saturation was reached at noontime thus $T_v$ value around 3 lasted the whole afternoon indicating a stable quasi-homogeneous state of the atmosphere.

**Table 1 – Parameters *B, C, D, E* for the prediction of zenith luminance and horizontal illuminance on six standard overcast skies**

| Sky type | Gradation type | Indicatrix type | Description of luminance distribution | Auxiliary parameters | | | |
|---|---|---|---|---|---|---|---|
| | | | | *B* | *C* | *D* | *E* |
| **1** | **I** | **1** | **CIE Standard Overcast sky** Steep gradation towards zenith, azimuthal uniformity | 54,63 | 1,00 | 0,00 | 0,00 |
| **2** | **I** | **2** | Overcast, with steep gradation and slight brightening towards the sun | 12,35 | 3.68 | 0,59 | 50,47 |
| **3** | **II** | **1** | Overcast, moderately graded with azimuthal uniformity | 48,30 | 1.00 | 0,00 | 0,00 |
| **4** | **II** | **2** | Overcast, moderately graded and slight brightening towards the sun | 12,23 | 3.57 | 0,57 | 44,27 |
| **5** | **III** | **1** | **Sky of uniform luminance** Overcast or cloudy with overall unity luminance | 42,59 | 1.00 | 0,00 | 0,00 |
| **6** | **III** | **2** | Cloudy sky, no gradation toward zenith, slight brightening towards the sun | 11,84 | 3.53 | 0,55 | 38,78 |

**Table 2 – Auxiliary parameters *A1, A2, B, C, D* and *E* for the prediction of absolute zenith luminance and horizontal illuminance on five standard cloudless skies**

| Sky type | Gradation type | Indicatrix type | Description of luminance distribution | Auxiliary parameters | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | *A1* | *A2* | *B* | *C* | *D* | *E* |
| **11** | **IV** | **4** | White – blue sky with distinct solar corona | 1,440 | -0,750 | 24,41 | 4,60 | 0,72 | 20,76 |
| **12** | **V** | **4** | **CIE Standard Clear Sky** with low luminous turbidity | 1,036 | 0,710 | 23,00 | 4,43 | 0,74 | 18,52 |
| **13** | **V** | **5** | Cloudless sky with polluted atmosphere | 1,244 | -0,840 | 27,45 | 4,61 | 0,76 | 16,59 |
| **14** | **VI** | **5** | Cloudless turbid sky with broad solar corona | 0,881 | 0,453 | 25,54 | 4,40 | 0,79 | 14,56 |
| **15** | **VI** | **6** | White – blue turbid sky with broad solar corona | 0,418 | 1,950 | 28,08 | 4,13 | 0,79 | 13,00 |

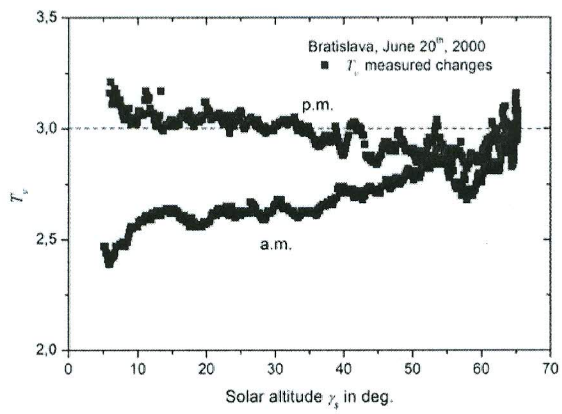


**Figure 3 – Daily changes of measured luminous turbidity factor $T_v$**

## 3 Simplifying conditions under ISO/CIE overcast sky types

### 3.1 Extreme overcast sky types with a unity scattering indicatrix

Under the three overcast skies when sunshine is absolutely shaded with relatively dense diffuse layers of Stratus clouds the relative scattering indicatrix has a unity value in all directions due to overall turbidity thus there are no effects with regard to the sun position on the sky vault. The filter effect of the sky is determined by the ratio $E_{v,d} / E_{vo,h}$ thus

$$L_{vZ} = Y\left(E_{v,d} / E_{vo,h}\right) \tag{11}$$

while from Equation (10) and Table 1 is resulting $Y = B \sin\gamma_S$ and $X = \sin\gamma_S$ while the absolute diffuse horizontal sky illuminance on the ground is

$$E_{v,d} = \frac{L_{vZ}}{Y}\left(E_{vo,h}\right). \tag{12}$$

As in case of sky types 1, 3 and 5 is $Y = B \sin\gamma_S$ and $E$ = 0, in consequence the $L_{vZ} / E_{v,d}$ ratios for all these sky types is independent on the solar altitude and forms a horizontal straight line equal to the ratio $B / E_{vo}$. Therefore the $L_{vZ} / E_{v,d}$ ratios level for any solar altitude for sky type 1 is 0,4083, for sky type 3 is 0,361 and for sky type 5 is 0,3183 respectively, as are these ratios graphically documented in Figure 1.

After five year long Bratislava measurements during 1994 – 1998 (Darula, Kittler, 2004a) the most frequent "filter ratio" for sky type 1 is $E_{v,d} / E_{vo,h}$ = 0,1, for sky type 3 is $E_{v,d} / E_{vo,h}$ = 0,15 and for "Lambert's" sky type 5 is $E_{v,d} / E_{vo,h}$ = 0,22 respectively (see Table 3).

## 3.2 Overcast sky types with a low scattering indicatrix

Of course, for overcast sky type 2, 4 and 6 appropriate Y parameters have to be calculated after $B$, $C$, $D$ and $E$ auxiliary values (Kittler, Darula, Perez, 1998) given in Table 3. In accordance with recommended $E_{v,d} / E_{vo,h}$ the values of relevant sky/diffuse illuminance courses $E_{v,d}$ for sky types 1 - 6 y, compared with the minimum daily data measured on November 25$^{th}$, 1995 in Bratislava are presented in Figure 4. This dim dark day fully overcast with minimal illuminance levels selected from the five year data 1994 – 1998 was found having probably the lowest $E_{v,d} / E_{vo,h}$ at around 0,05 as shown in Figure 4. Of course sky type 1 – 3 are seldom occurring when solar altitudes are over 30° – 40°.

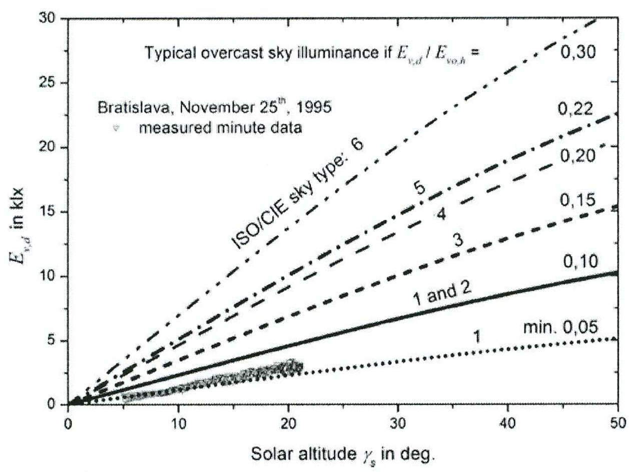


**Figure 4 – Sky/diffuse illuminance levels for six overcast ISO/CIE sky types**

Even under the simplest overcast skies due to different $E_{v,d} / E_{vo,h}$ occurrence possibilities as documented by Bratislava long term data 1994 – 1998 happen either in a wider range, frequent or recommended as typical summarised in Table 3.

**Table 3 – The sky type occurrence range of $E_{v,d} / E_{vo,h}$ with mean and mode values as well as with typical and recommended values**

| Sky type | Relative range | Mean value | Mode value | Recommended typical |
|---|---|---|---|---|
| 1 | 0,05 – 0,25 | 0,154 | 0,094 | 0,10 |
| 2 | 0,05 – 0,25 | 0,158 | 0,092 | 0,10 |
| 3 | 0,05 – 0,30 | 0,186 | 0,114 | 0,15 |
| 4 | 0,05 – 0,35 | 0,216 | 0,190 | 0,20 |
| 5 | 0,10 – 0,40 | 0,219 | 0,226 | 0,22 |
| 6 | 0,15 – 0,45 | 0,275 | 0,215 | 0,25 |

Although in the whole data package the sky type 2 was the most prevailing it is advisable to simulate in the artificial sky the basic types 1, 3 and 5 due to their perfect homogeneity and also with regard to their stable ratio $L_{vZ} / E_{v,d}$ without any dependence on solar altitude.

However, in spite of the sunlight absence the absolute horizontal illuminance $E_{v,d}$ during an overcast day will increase to reach its maximum at midday and decrease to sunset. This daily course is linked via solar altitude to true solar time and also to local clock time when regular illuminance and luminance measurements are recorded, e.g. in 1-minute or 5-minute steps. So diagrams representing daily momentarily measured horizontal illuminances $E_{v,d}$ courses usually divert from fluent curves drawn after above mentioned standard formulae due to slightly changes of $E_{v,d} / E_{vo,h}$ influenced by variable atmospheric conditions.

## 4 Extreme clear sky luminance patterns and extreme illuminances with sunlight present

Generally under relatively stable turbidity conditions during sunny days under any sky type 10 – 15 when the $L_{vZ} / E_{v,d}$ ratios as well as illuminance levels can be calculated following basic Equations (1) – (9) that are easily programmable on computer programs. Such a procedure was applied to document outdoor luminance and resulting illuminance levels to be modelled in an artificial sky. Extreme cloudless and clear skies are expected under sky type 12 – 14 dependent on the reduction of sunlight due to rising atmospheric turbidity, while the zenith luminance can be calculated after a best fit relation (Kittler, Darula, Perez, 1998)

$$L_{vZ} = 0{,}7(T_v + 1)X + (A1\,T_v + A2)\sin\gamma_s + 0{,}04\,T_v\,. \qquad [\text{kcd.m}^{-2}] \qquad (13)$$

If $L_{vZ}$ is determined after Equation (13) then the sky luminance pattern can be drawn using Equation (1) and also the horizontal outdoor sky/diffuse illuminance can be calculated for any ISO/CIE sky type 11 – 15 as

$$E_{v,d} = \frac{L_{vZ}\,E_{vo}\sin\gamma_s}{BX + E\,\sin\gamma_s}\,. \qquad [\text{klx}] \qquad (14)$$

Due to present sunlight illuminance $E_{v,s}$ also this has to be added after Equation (3) considering actual $m$, $a_v$ and $T_v$ parameters dependent on the momentary solar altitude. Thus extreme outdoor horizontal illuminance under a clear sky can be documented in Figure 5.

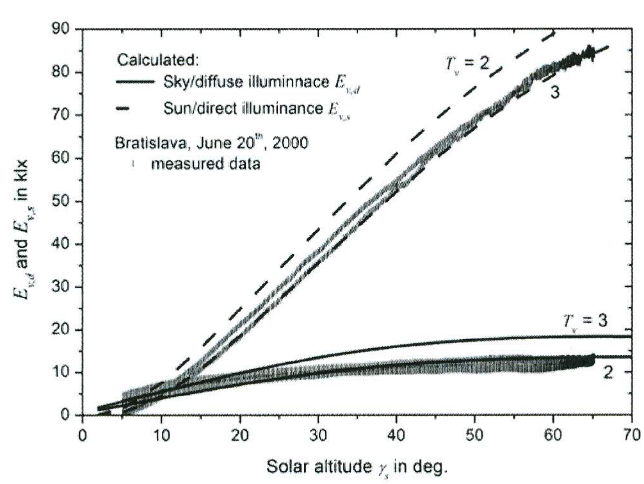


**Figure 5 – Sun and sky illuminances under ISO/CIE sky type 12**

It is evident that very high illuminance levels over 2 klx cannot be modelled on the measuring table of the artificial sky especially with sunlight. Therefore, considering the extreme sky type situations shown in Figures 4 and 5 which will determine the overall reduction of the intensity scale.

## 5 The choice of illuminance scale suitable to reduce daylight levels in the artificial sky

Due to extremely high sunlight illuminance range in comparison to skylight levels there might be a possibility to choose one mutual scale 1:20 which when applied would lead to levels shown in Figure 6. However, for the overcast sky types with very low illuminance levels often under winter low solar altitudes the scale 1:20 could mean an exaggerated reduction especially in the Northern countries resulting in incorrect interior measured values. Thus in such cases the scale 1:10 would be quite attractive to use.

Note, that introducing a certain scale for luminance and illuminance reductions in an artificial sky is associated with the intensity levels in absolute physical units as well as with the luminance patterns of ISO/CIE sky standards especially under clear skies with sunshine present. Thus in fact is introduced an "intensity scale" (ISC).

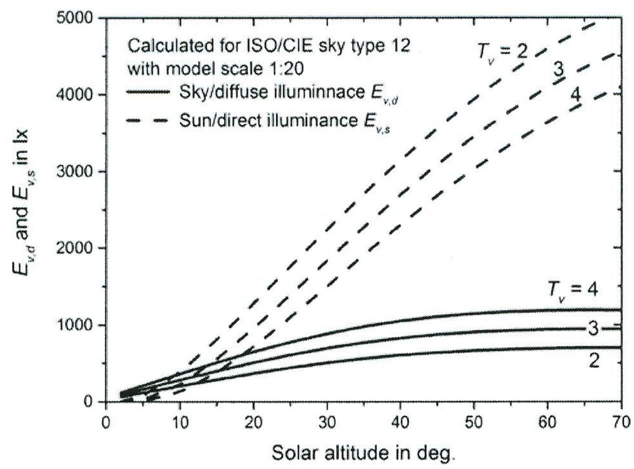


**Figure 6 – Same outdoor illuminance levels reduced for the artificial sky by ISC 1:20**

On this basis in history until the first half of the 20th Century were derived mathematical formulae and calculation nomograms for the criterion of the so called Sky or Daylight Factor that could be applied for the ISO/CIE sky type 5 (Lambertian diffuse sky). Approximately also sky types 1 and 3 after the adoption of skies with increasing/gradual sky luminances which have the same unvaried luminances around the horizon and all horizontal/almucantar sky circles. Such assumption is in fact using a "reference or relative scale" (RSC) comparing indoor illuminance $E_{v,i}$ levels to the simultaneous outdoor $E_{vo,h}$. Originally RSC is based on the Lambertian overcast sky with unity uniform luminance over the whole sky vault assuming that $E_{v,i} / E_{vo,h}$ is not influenced by the sky luminance, thus $E_{v,i} / E_{vo,h} = \frac{\omega_p}{\pi}$, i.e. interior illuminance is equal to the projection of the window solid angle onto the horizontal working plane indoors, while $\pi$ is the projection of the whole sky hemisphere with unity radius onto the unobstructed horizon plane outdoors. However, RSC cannot be used in case of clear skies when the sky luminance pattern is following the sun path changes dependent on indicatrix functions. Thus the basic assumption is untrue and invalid because luminance time and orientation changes within the window solid angle have to be taken into account.

The third type of scaling is used in reducing dimensions of architectural models where a "dimension scale" (DSC) is used for rooms placed inside the artificial sky. The assumption of reducing room and window dimensions in a certain scale is generally applied in maps, models, design documentation with comparison to real dimensions. When DSC is applied in architectural models under an artificial sky the basic requirement is that the solid angle reduction is in scale proportionality.

A calibration procedure and actual measurements on the artificial sky platform or inside a model room have to be tested under both extreme daylight situations under realistic proportionality between sun and sky illuminance levels (Darula, Kittler 2014) respecting important calibration means to test also luminance patterns in relative terms according to ISO/CIE standard as well as absolute luminance distributions on the sky dome. Respected and calibrated should be also the appropriate zenith luminance of the simulated ISO/CIE sky types in the chosen scale of modelling which has to be stated in the calibration protocol (Kittler, Darula, 2014). This requires to allow measurements of zenith luminance avoiding any shading of the special construction for the adjustment of artificial sun positions.

## 6 Conclusions

A step forward in the progress from relative to absolute daylight illuminance criteria seem to be taken place respecting the fifteen ISO/CIE standard sky luminance patterns. Thus could be characterised several yearly daylight climates worldwide for energy efficiency calculations on local basis as well as the future adjustment of interior illuminance criteria for national standards in accordance with the evaluation of coordinated reasons of daylight and artificial illumination participation. As shown in this contribution the sunlight and skylight illuminances outdoors, indoors and their intensity scales for an artificial sky can be defined. Fundamentally the simulation of homogeneous ISO/CIE sky types in photometric units are specified respecting local yearly sun-paths as well as the states and turbidity of the atmosphere.

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