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The simultaneous occurrence and relationship of sunlight and skylight under ISO/CIE standard sky types

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In daylight science the availability of sunlight and skylight at different times has been studied because of the desire to use daylight in both exterior and interior spaces. Exterior skylight illuminances under overcast skies were adopted as a standard for window design in the past. Current ISO/CIE sky types are standardised as relative luminance patterns normalised to the zenith. In this paper, the zenith luminance in candela/square metre and the resulting diffuse illuminance in lux are determined for all sky types. Furthermore, the proportions of sunlight and skylight under different levels of turbidity are found and documented. Efforts to harmonise electric lighting and daylighting standards need to analyse the data on available daylight in physical units in order to ensure energy savings that respect human requirements as well as providing information suitable for computer-aided design.

1. Introduction

During the original research into sky luminance distribution under different homogeneous sky conditions[1] under overcast, cloudy and clear sky patterns, two principal tendencies were found, one characterising the gradation increase or decrease of sky luminance, and a second tendency occurring under sunlight presence which specifies the scattering and filtering effect of the turbidity and cloudiness properties of the atmosphere.[2,3]

The design of older and many current windows has used overcast sky conditions originally assumed, by Lambert,[4] as uniform over the sky vault with unity luminance and later with gradually increasing luminance in the ratio 1:3 from horizon to zenith.[5,6] Still later, a clear sky standard with two luminance patterns was adopted by the Commission Internationale de l'Eclairage (CIE).[7] All of these sky types are currently defined in a set of 15 sky types, standardised by the CIE[8] and the International Standards Organization (ISO),[9] that express the sky luminance patterns in relative terms, i.e. normalised to the zenith luminance. However, the original study[1] also provided the possibility of calculating the relative sunlight and skylight horizontal illuminance ratio normalised by the extraterrestrial horizontal illuminance, in absolute terms, on the ground with an unobstructed horizon. Because these are partially unknown or need a more practical explanation this paper uses graphical tools to try to achieve the necessary understanding of the importance of the proportional relationship of sunlight and skylight outdoors under the homogeneous standardised sky types.

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2. New relationships valid for standard sky types applying absolute luminances and illuminances

2.1. Overcast sky types without any trace of sun position and gradually increasing sky luminance

In the whole set of 15 sky types there are only three sky types (1, 3 and 5) that are valid for homogeneous overcast luminance patterns.

2.1.1. Sky type 1

Sky type 1 or I.1 represents an overcast sky with a steep luminance gradient defined by the gradation function type I resembling the increasing luminance from one-third at the horizon to unity at the zenith and using a scattering function type 1, which means an equal scattering effect in all directions. These two functions determine the same luminance distribution for all azimuths. The dense and diffuse cloud layers produce a thick filter which reduces the horizontal illuminance received at the ground to about one-tenth of the horizontal extraterrestrial illuminance $E_{vo,h}$. Thus, the diffuse skylight illuminance $E_{v,d}$ normalised by $E_{vo,h}$ in a ratio $E_{v,d}/E_{vo,h}$ can reach the proportions 0.1–0.3.[10] Symbols for luminous terms used in this text.[11] If measured outdoors and under an unobstructed horizon the resultant horizontal global illuminance is of course $E_{v,g} = E_{v,d}$ with the zenith luminance $L_{v,z}$ which is in this case related to $E_{v,d}/E_{vo,h}$ as given by

$$L_{v,z} = 54.65 E_{v,d}/E_{vo,h} \sin\gamma_s \left(\text{kcd/m}^2\right) \qquad (1)$$

where γ_s is the solar altitude in degrees.

Using equation (1) and the ISO/CIE sky luminance distribution in relative terms normalised to $L_{v,z}$ the luminance sky pattern can be calculated in kcd/m^2 or cd/m^2, i.e. in absolute physical units. Under the typical ratio $E_{v,d}/E_{vo,h} = 0.1$, $L_{v,z} = 5.465 \sin\gamma_s$ and at the same time is $L_{v,z}/E_{v,d} = 0.4083$, thus

$$E_{v,d} = L_{v,z}/0.4083 = (5.465/0.4083)\sin\gamma_s = 13.385 \sin\gamma_s \text{ (klux)} \qquad (2)$$

which corresponds also with $E_{v,d} = 0.1\, E_{vo,h} = 0.1\, E_{vo} \sin\gamma_s$, where the luminous solar constant[12] E_{vo} taken as yearly average is 133.8 klux. Thus, $E_{v,d}$ would approximately be $E_{v,d} = 0.1 E_{vo,h} = 0.1\ E_{vo} \sin\gamma_s = 13.38 \sin\gamma_s$ in i.e. almost the same as the value found in equation (2).

To document these relations graphically and account for different solar altitudes, several multi-parameter diagrams have already been devised. One nomogram for sky type 1 is shown on the left of Figure 1, which also shows the analysis of the Bratislava IDMP station 1-minute data measured during November 1995 on the right side with an appropriately reduced scale of solar altitudes 0–30°. Note that the occurrence of $E_{v,d}/E_{vo,h}$ ratios as well as absolute zenith luminance is related to solar altitude and occurrence frequency in November, when this sky type 1 was the most frequent.

2.1.2. Sky type 3

Sky type 3 or II.1 represents an overcast sky with a moderate gradient after the ISO/CIE gradation function type II and azimuthal uniformity. The analysis of this sky type[10] showed that $E_{v,d}/E_{vo,h} = 0.15$ most frequently with a mode of 0.114 and a mean of 0.186, while

$$L_{v,z} = 48.3 E_{v,d}/E_{vo,h} \sin\gamma_s \left(\text{kcd/m}^2\right) \qquad (3)$$

As with sky type 1, graphical interpretations of the relationships for sky type 3 can be drawn in a similar nomogram.

2.1.3. Sky type 5

Sky type 5 or III.1 represents Lambert's uniform sky, an overcast sky with an overall

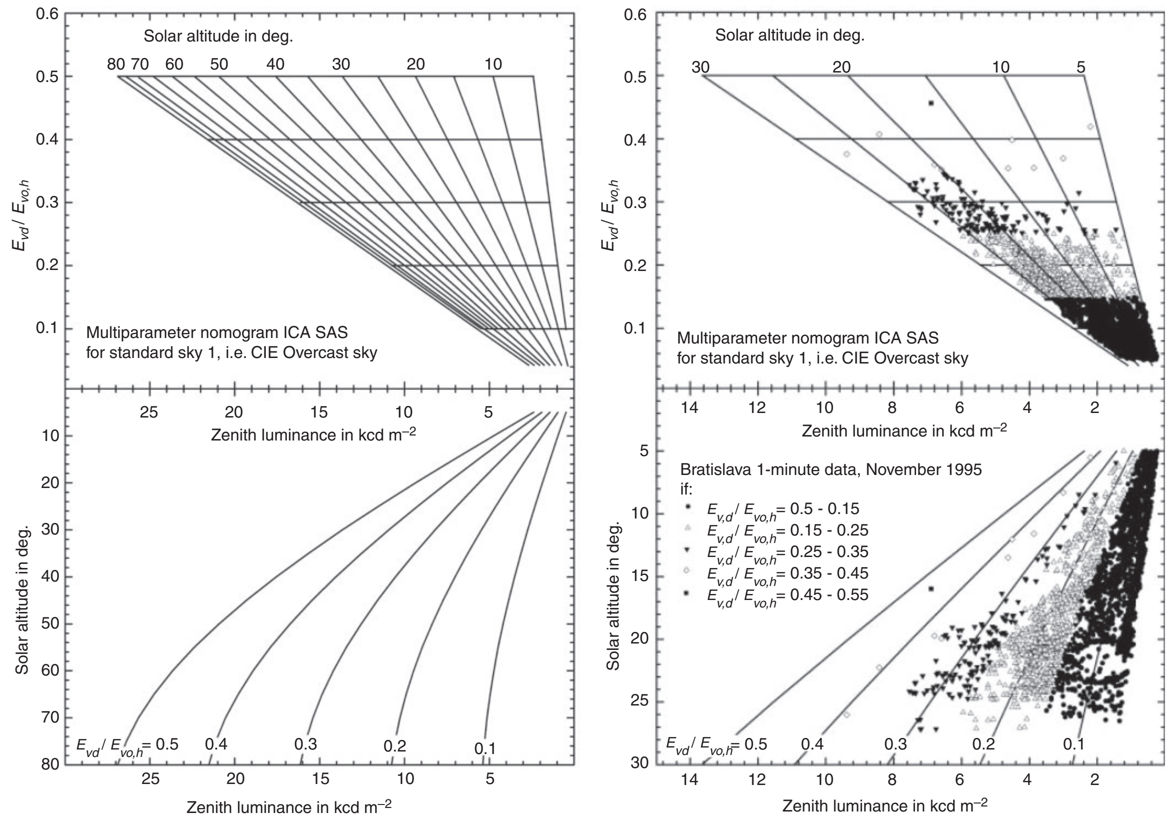

Figure 1 Nomogram for sky type 1 and measured cases in the Bratislava database

uniform unity luminance distribution. A similar analysis of this pattern[10] showed $E_{v,d}/E_{vo,h} = 0.2$ most frequently with a mode of 0.226 and a mean of 0.219. These data were gathered in Bratislava over a 5-year period with the number of cases between these ranges being almost the same. The zenith luminance is related to the solar altitude again, but

$$L_{v,z} = 42.59 E_{v,d}/E_{vo,h} \sin \gamma_s \left(\mathrm{kcd/m^2}\right) \qquad (4)$$

which means for $E_{v,d}/E_{vo,h} = 0.2$ a higher zenith luminance in kcd/m^2 $L_{v,z} = 8.518 \ \sin \gamma_s$ and $L_{v,z}/E_{v,d} = 0.318$. Thus, the outdoor horizontal skylight illuminance is around $E_{v,d} = 0.2 E_{vo,h} = 0.2\, E_{vo} \sin \gamma_s = \ \ 26.760 \sin \gamma_s$ in klux.

In this case, ratios of $E_{v,d}/E_{vo,h}$ can cover a range of 0.1–0.3 as shown in Figure 2. It is interesting to note that although the Lambert sky was considered to occur infrequently the Bratislava data, have shown that during half the days in January sky type 5 was dominant in the 5-year measurement duration 1994–1998[13] and was even more frequent from April to December in the next 5 years 1999–2003.[14]

2.2. Overcast sky types with few traces of sun position and gradually increasing luminance

2.2.1. Sky type 2

Sky type 2 or I.2 has a similar luminance pattern as I.1, but there is a slight influence of the rising indicatrix function 2 towards the sun

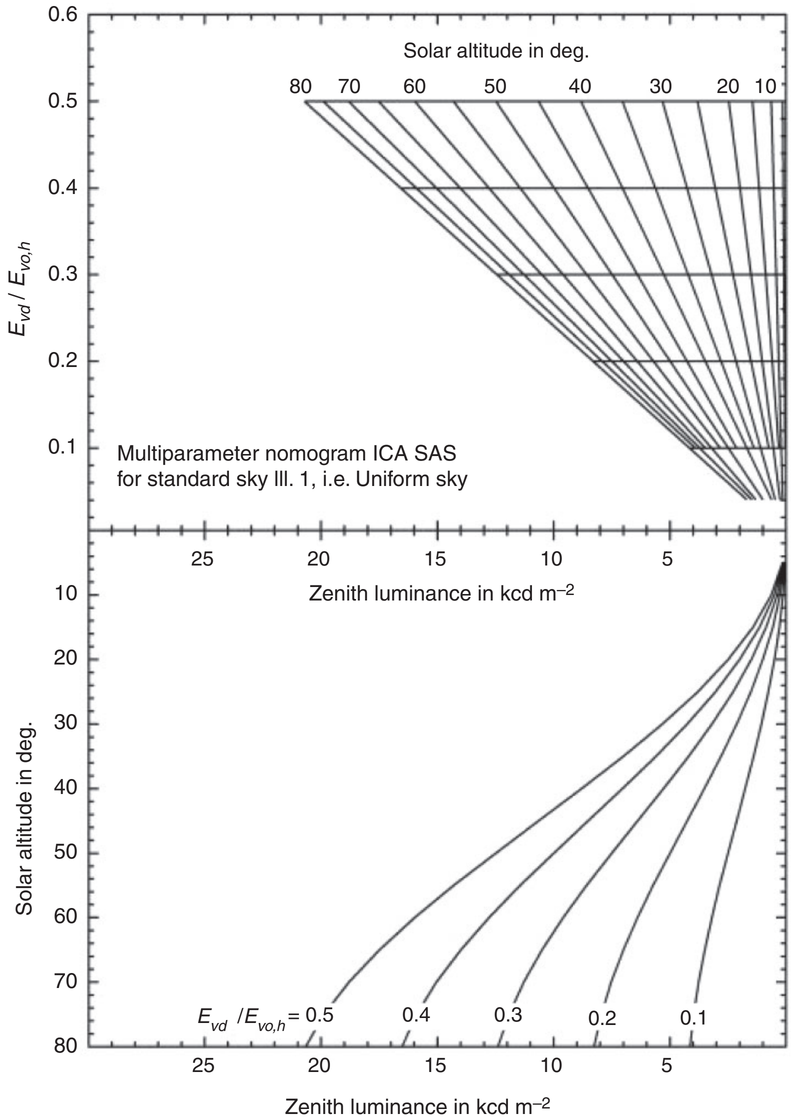

Figure 2 Multi-parametric nomogram for ISO/CIE sky type 5

position although the sun is still covered by the cloud filter, however, a slight brightening around the sun position is evident. In some locations this sky type is not so frequent (e.g. in Athens), but in Central Europe (e.g. in Bratislava) the sky type 2 occurs even more frequently than sky type 1.[15,16] Therefore, the sky type 2 could be important in other geographical locations too. The same calculation procedure is possible using a typical

$E_{v,d}/E_{vo,h} = 0.18$ and its zenith luminance can be calculated using the empirical formula given in equation (5)[16]

$$L_{v,z} = E_{v,d}/E_{vo,h}\left[\frac{B(\sin\gamma_s)^C}{(\cos\gamma_s)^D} + E\sin\gamma_s\right](\text{kcd/m}^2) \tag{5}$$

where $B = 12.35$, $C = 3.68$, $D = 0.59$ and $E = 50.47$ after which a nomogram can be constructed. However, equation (5) is valid only if the solar altitude is under 70°, otherwise integration of the original $L_{v,z}/E_{v,d}$ formula has to be used for the $L_{v,z}$ determination.[16] If $L_{v,z}$ is measured then $E_{v,d}$ can be derived from a modified equation (5).

2.2.2. *Sky type 4*

Sky type 4 or II.2 pattern is similar to I.2; however, the gradient of luminance rises with the sky elements elevation only in the ratio of 1:1.5 from horizon to zenith with a slight influence of the indicatrix function rising towards the sun position. Equation (5) is valid for sky type 4 too, but different parameters are recommended.[10] A typical parameter value found after analysing measurements was $E_{v,d}/E_{vo,h} = 0.22$ and $B = 12.25$, $C = 3.57$, $D = 0.57$ and $E = 44.27$. Following these parameters a specific nomogram can be drawn.

2.2.3. *Sky type 6*

Sky type 6 or III.2 represents an intermediate sky type linking overcast and cloudy sky conditions under rather diffuse cloudiness covering the sun position and is characterised by a turbidity of 15 or even higher. Thus, sunlight is not present. Due to the diffuse and widely spread cloudiness in several layers there is almost no gradation corresponding to function III with unity influence. As in the previous case the typical skylight illuminance is quite high as $E_{v,d}/E_{vo,h} = 0.38$ and the recommended parameters are $B = 11.84$, $C = 3.53$, $D = 0.55$ and $E = 38.78$.

It should be noted that many, even lighting specialists, regard overcast skies as a specific winter event; however, this sky type frequently occurs in spring or autumn and summertime[15] almost in the same frequency.

2.3. Cloudy sky types without or with sunshine under different turbidity and cloudiness

2.3.1. *Sky type 7*

Cloudy sky types beginning with sky type 7 or III.3 are characterised by either a unity or reverse gradient with luminance increasing from zenith to horizon combined with a relatively strong scattering effect so the scattering indicatrix[17] becomes more visible in the sky luminance pattern, as with a solar corona. Also, the $L_{v,z}/E_{v,d}$ curves have steeper trends according to solar altitude[18] and the presence or absence of direct sunlight in turbid conditions produces sunbeams and so has a profound influence on the proportion of sunlight and skylight. Therefore, there is a wide spread of $E_{v,d}/E_{vo,h}$ ratios at all solar altitudes. In the 5-minute data gathered during the years 1994–1998 there are 3769 cases without sunshine which resulted in a mean $E_{v,d}/E_{vo,h}$ value of 0.32 and a mode of 0.38, while there were 1218 cases with sunshine which resulted in a mean $E_{v,d}/E_{vo,h}$ value of 0.38 and a mode of almost 0.4. Again, equation (5) is valid for calculating the respective zenith luminance applying parameters $B = 21.72$, $C = 4.52$, $D = 0.64$ and $E = 34.56$.

2.3.2. *Sky type 8*

Sky type 8 or III.4 characterises similar conditions to sky type 7, but sky type 8 has only 1.65:1 cases without and with sun resulting in a mean $E_{v,d}/E_{vo,h}$ value of 0.336 and a mode of 0.358 under sunless skies and a mean $E_{v,d}/E_{vo,h}$ value of 0.39 and a mode of 0.44 with direct sunlight. Thus, using equation (5) the zenith luminance is obtained from

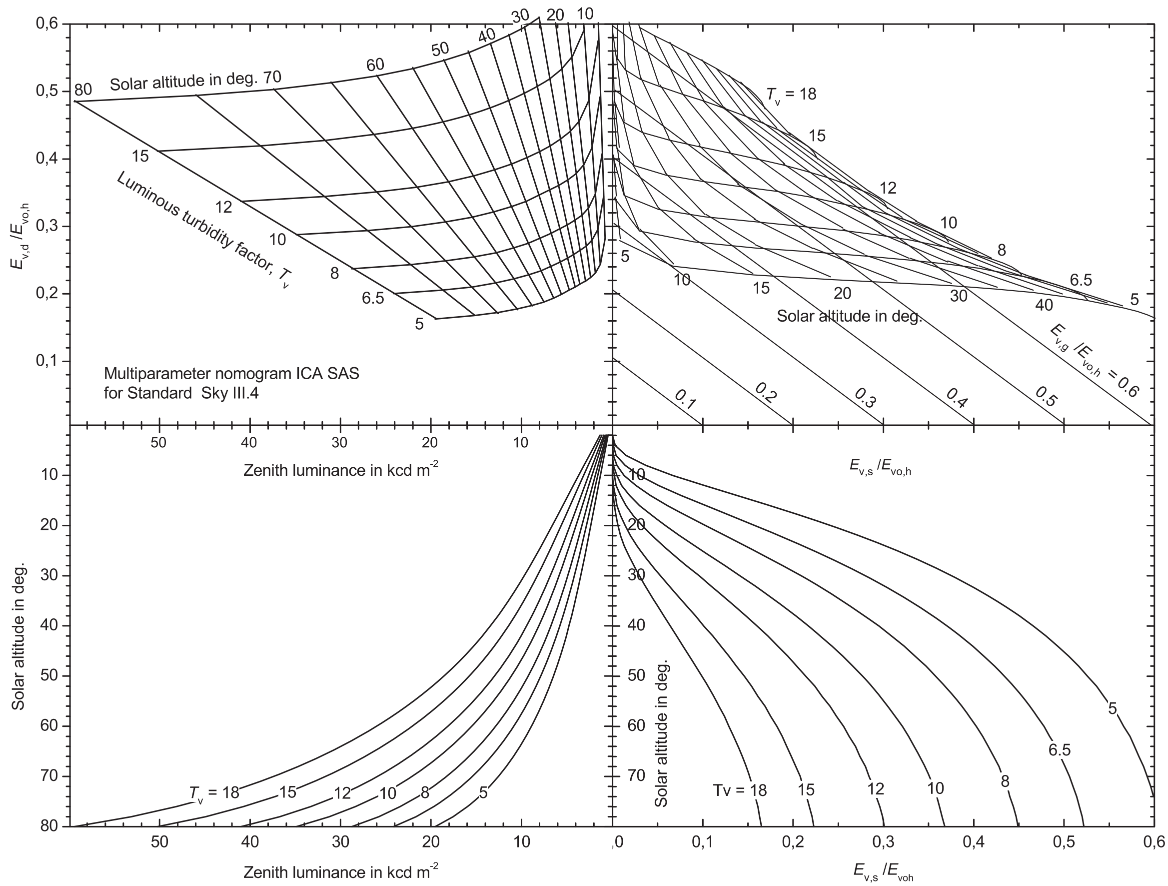

Figure 3 Multi-parameter nomogram for ISO/CIE sky type 8

parameters $B = 29.35$, $C = 4.94$, $D = 0.7$ and $E = 30.41$. From these parameters only zenith luminance without sunshine can be approximately calculated, while in sunshine the additional illuminance from sunbeams can be determined using an empirical formula

$$E_{v,S}/E_{vo,h} = \exp\left(-a_v\, m\, T_v\right) \qquad (6)$$

A nomogram for solar altitudes 0–80° is shown in Figure 3. In Figure 4 a reduced scale of solar altitudes 0–40° and measurements made in Bratislava are shown in 1-minute data gathered in February 1995. Even though at low solar altitudes the $E_{v,d}/E_{vo,h}$ ratios range from 0 to roughly 0.15 these change to higher ratios under dynamic wind-driven clouds and various cloud coverings.

Sky type 8 was chosen by Tregenza[19] as one frequent in maritime regions as well as occurring at any solar altitude under relatively high turbidity, $T_v = 5 - 14$. Therefore, the sunless double field Figure 4 nomogram containing skylight illuminance and zenith luminance is complemented by a double field for sunlight illuminance components $E_{v,S}/E_{vo,h}$ on the right hand side in both Figures 3 and 4 and the participation of sunlight and skylight on global horizontal illuminance is given under various further sky types.

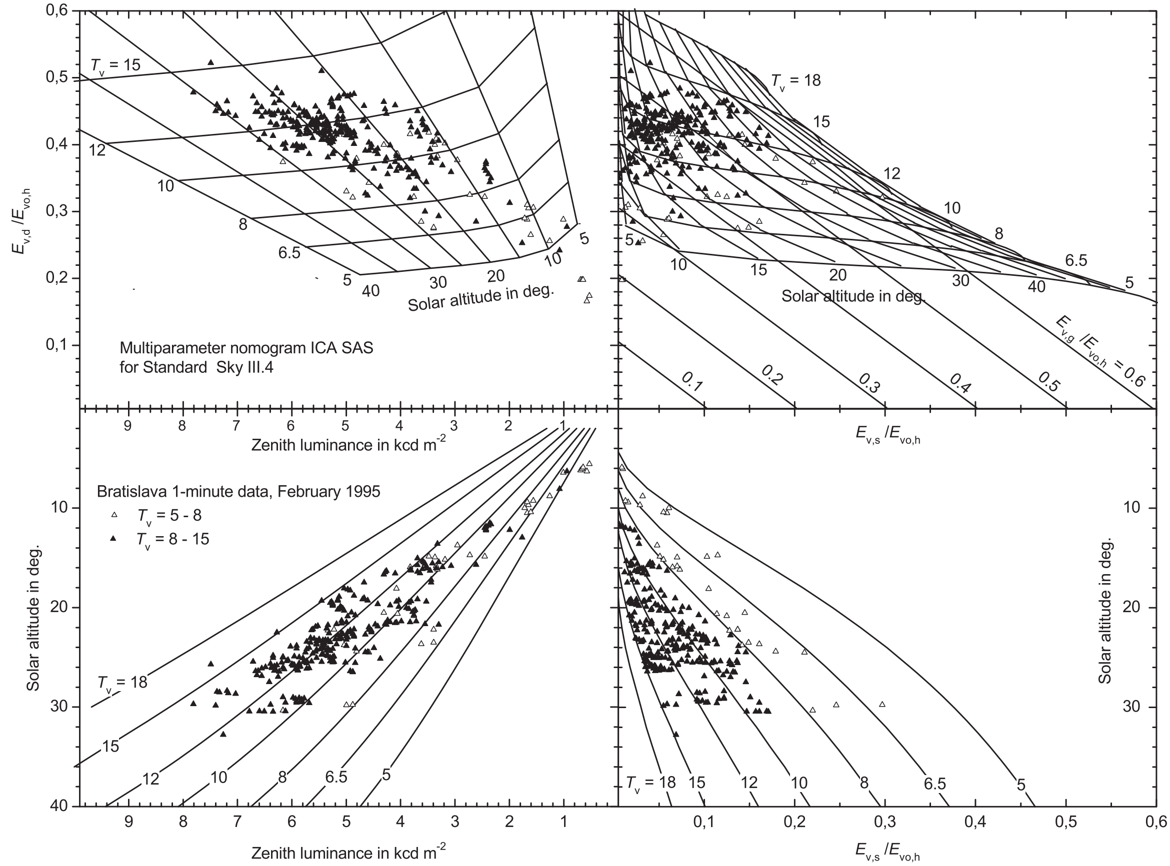

Figure 4 Multi-parameter nomogram for ISO/CIE sky type 8 with inserted measured data

2.3.3. Sky type 9

This sky type specifies partly cloudy skies with an obscured sun position, a low indicatrix function 2 and a gradation function IV, which indicates a luminance increase towards the horizon. Due to high turbidity around $T_v = 12$, $E_{v,d}/E_{vo,h}$ has a mean of 0.33 and a mode of 0.355 with a range of 0.2–0.5 and a maximum occurrence of 0.4.[18] The $L_{v,z}/E_{v,d}$ curve for this sky type used parameters $B = 10.34$, $C = 3.45$, $D = 0.5$ and $E = 27.47$.

2.3.4. Sky type 10

Sky type 10 or IV.3 is characterised by partly cloudy skies with a brighter circumsolar luminance region, with turbidity around $T_v = 10$ and lower $E_{v,d}/E_{vo,h}$ ratios with an almost evenly distributed frequency of 0.15–0.4, with 0.36 considered for sunless periods and 0.25 during sunshine with the $L_{v,z}/E_{v,d}$ fitting curve being based on parameters $B = 18.41$, $C = 4.27$, $D = 0.63$ and $E = 24.04$.

2.4. Sunlight and skylight participation in global illuminance levels under clear sky types with sunshine

2.4.1. Sky type 11

The homogeneous cloudless sky type 11 or IV.4 forms a link between the cloudy and cloudless sky types when the overall turbidity in the direction of sunbeams and all sky elements is very small. However, in this sky type a few clouds can also exist so temporary shading of the sun position on a white-blue sky has to be expected. In the Bratislava, 5-year data[18] the number of 5-minute averages with sun (12, 383 cases) exceeds the number of sunless periods (2168 cases) by 5.7 times and low turbidity conditions $T_v = 3 - 4$ with a mode of 3.4 occur. The $E_{v,d}/E_{vo,h}$ ratio has a range of 0.15–0.4 but 0.23 is recommended. However, the influence of T_v under various $E_{v,d}/E_{vo,h}$ ratios is evident and is approximately given[20] by equation (7)

$$E_{v,d}/E_{vo,h} = \frac{[(A1T_v + A2)\sin\gamma_s + 0.7X(T_v+1) + 0.04T_v]}{BX + E\sin\gamma_S} \quad (7)$$

$$\text{where } X = \frac{(\sin\gamma_s)^C}{(\cos\gamma_s)^D} \quad (8)$$

$$\text{and} \quad L_{v,Z} = (A1T_v + A2)\sin\gamma_s + 0.7X(T_v+1) + 0.04T_v\left(\text{kcd/m}^2\right) \quad (9)$$

For sky type 11, $A1 = 1.44$, $A2 = -0.75$, $B = 24.41$, $C = 4.6$, $D = 0.72$ and $E = 20.76$ are valid. It has to be noted that empirical equations (7) and (9) are restricted to the T_v range 2–7, because at higher turbidities parallel sunbeams are almost totally scattered with no shadow traces visible.

2.4.2. Sky type 12

Sky type 12 or V.4 represents the clear sky already adopted in the previous CIE standard[7] with the so-called Kittler's indicatrix associated with the low luminous turbidity factor value $T_v = 2.5$ applying to the countryside and a higher luminous turbidity factor value $T_v = 4.5$ applying in towns and residential areas. Because of its importance, a convenient multi-parametric nomogram has been drawn in Figure 5, based on equations (6) to (9), using the parameters $A1 = 1.036$, $A2 = 0.71$, $B = 23$, $C = 4.43$, $D = 0.74$, $E = 18.52$. The recommended $E_{v,d}/E_{vo,h} = 0.15$ determines the skylight component while the sunlight participation is expressed by equation (6).

Bratislava data were inserted in Figure 6 to document and verify the proportions of skylight and sunlight. When analysing the overall measured cases in the 5-year database 1994–1998 that have fallen within the classification strip ±2.5% zone[15] along the $L_{v,z}/E_{v,d}$ theoretical curve for sky type 12 there were a few exceptional cases with either very low turbidity around $T_v = 2 - 3$ or quite high turbidity with $T_v = 6 - 7.5$. Driven by curiosity to discover how T_v influences these rare half-day events, an examination of trends was undertaken. On the late winter day of 1st March 1995 very low turbidity was recorded, the Arctic inflow of cold and dry air that occurred around midday having caused the turbidity to drop. The other extreme of high turbidity was found on a cloudless hot summer morning, 7th July 1995 when tropical desert turbidity, almost smoggy air, crossed Central Europe. As seen in Figure 6 even those extremes fit nicely into the nomogram and can be compared with a day having the usual turbidity range of $T_v = 2.5 - 4.5$. This occurred on the afternoon of 15th August 2001 and is also inserted in Figure 6.

2.4.3. Sky type 13

Sky type 13 or V.5 is similar to the previous clear sky type but in the CIE standard[7] with Gusev's indicatrix associated with the high luminous turbidity factor of $T_v = 5.5$, characteristic of polluted areas and industrial regions. Therefore, sunlight is subdued compared to the luminous turbidity factor in the usual range of $T_v = 3 - 7.5$ with the mean value 5 from the Bratislava data. However, the skylight component is relatively higher $E_{v,d}/E_{vo,h} = 0.28$ with $T_v = 3 - 7.5$ and

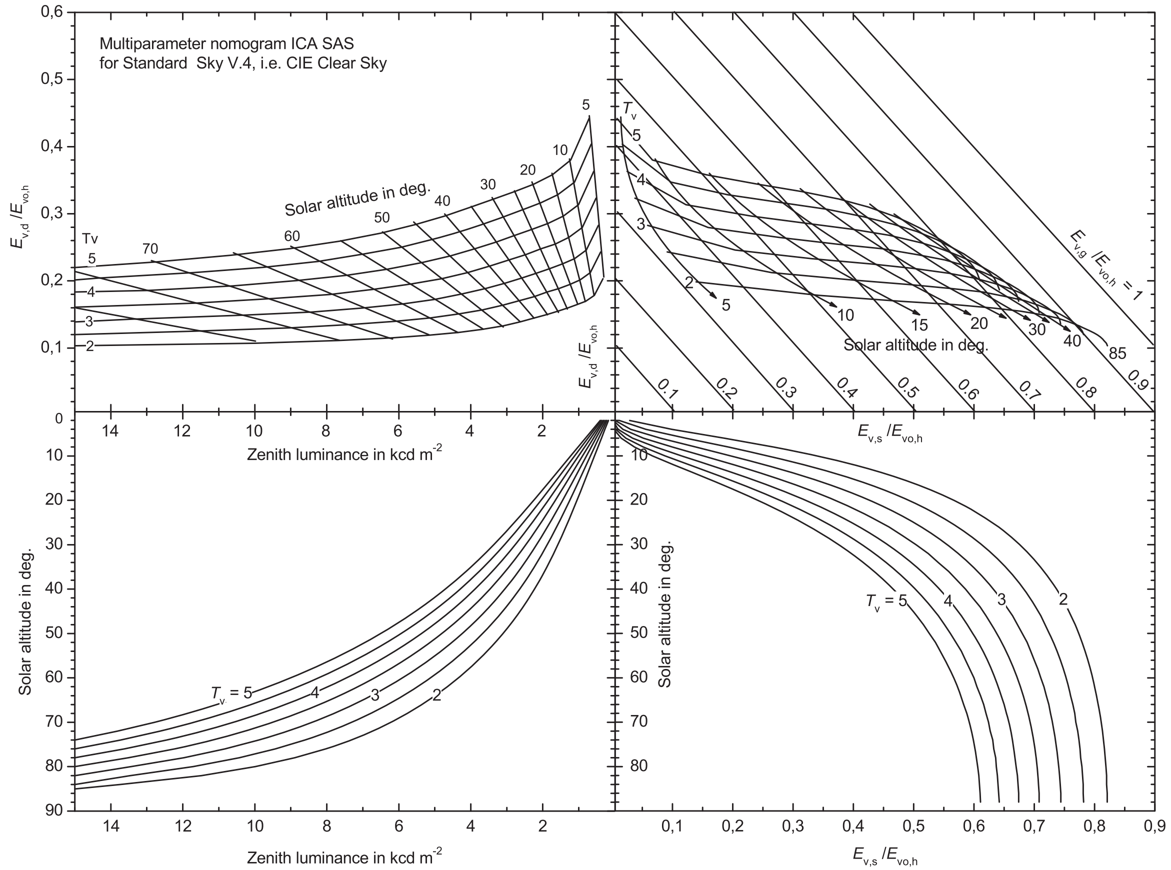

Figure 5 Nomogram for a clear ISO/CIE sky type 12 showing the interrelation between skylight and sunlight

$E_{v,d}/E_{vo,h} = 0.15 - 0.45$. The appropriate parameters for this sky type are $A1 = 1.244$, $A2 = -0.84$, $B = 27.45$, $C = 4.61$, $D = 0.76$ and $E = 16.59$.

2.4.4. Sky type 14

This is the cloudless turbid sky VI.5, i.e. with a broader solar corona with an indicatrix of 5 and a steeper luminance gradient from zenith as it approaches the horizon in relation to the previous sky type 13. Sky types 14 and 15 were the least frequent types in Bratislava, but in Mediterranean Athens these were even more frequent than all overcast and cloudy skies[15,16] so they are probably also important in subtropical and tropical regions. From the Bratislava 5-year data, approximately the same typical $E_{v,d}/E_{vo,h} = 0.28$ is recommended with the range of turbidity being very broad between $T_v = 3 - 10$ with a mean value of 5.53 and a mode of 4.17, the most frequent being in the range $T_v = 3 - 5$. The $L_{v,Z}/E_{v,d}$ curve was produced using the parameters $A1 = 0.881$, $A2 = 0.453$, $B = 25.54$, $C = 4.4$, $D = 0.79$ and $E = 14.56$.

2.4.5. Sky type 15

This sky type characterises the white-blue turbid sky, sometimes with a thin, veiling cloud layer partly covering the sky vault, thus with a broad solar corona region specified by indicatrix 6 and gradation VI. This is the

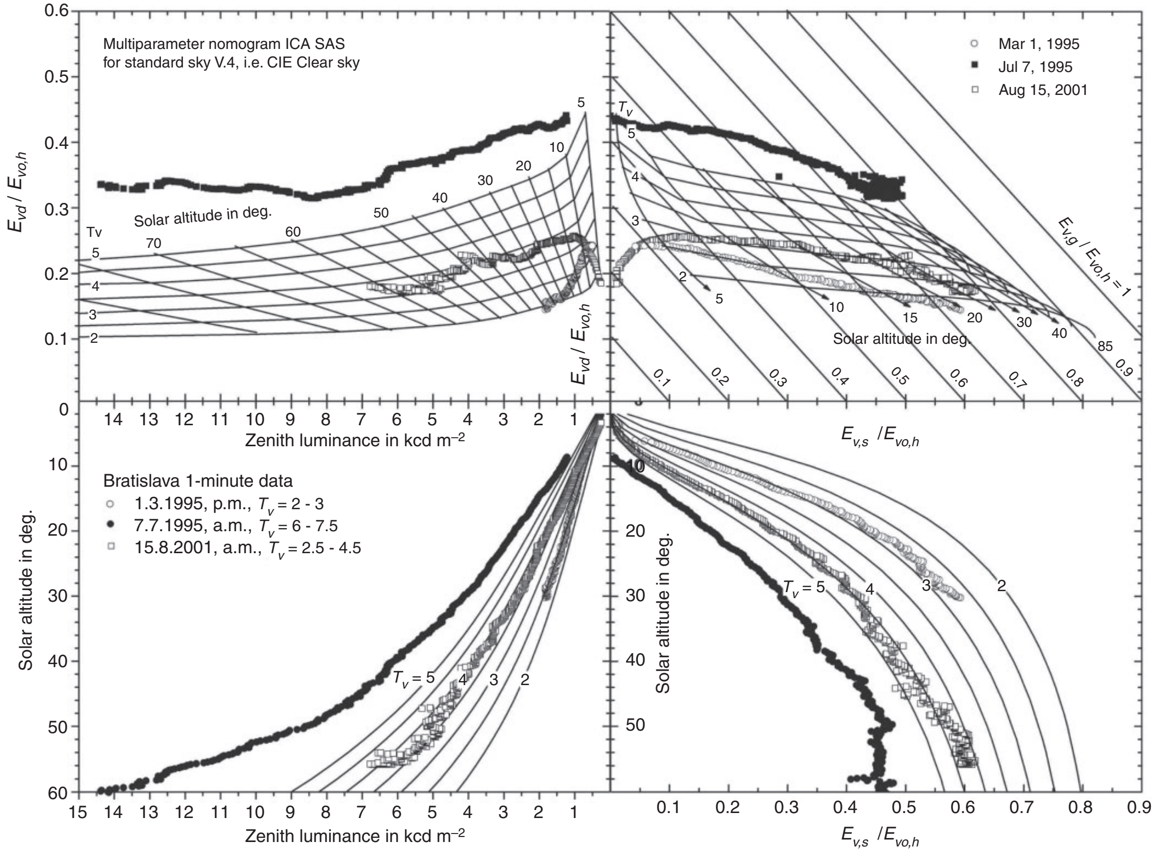

Figure 6 Inserted measured data show the possibility of sky type 12 occurring with different turbidity conditions

extremely turbid clear sky with sunlight reduced to $T_v = 3 - 8$ and $E_{v,d}/E_{vo,h} = 0.15 - 0.4$, respectively. The multi-parametric nomogram is shown in Figure 7.

3. Predetermination of absolute sunlight and skylight illuminances outdoors

3.1. Absolute skylight horizontal illuminance under overcast sky types

3.1.1. Overcast sky types with azimuthal uniformity

The assumption of cloudiness and turbidity homogeneity means there is an equal luminous turbidity factor T_v in the direction of sunbeams as well as in all directions towards sky vault elements. So, there is an unique possibility to express all ISO/CIE sky types in a proportional relationship of skylight and sunlight and also in absolute physical units as the scattering indicatrix is related to the turbidity of cloud layers[2] which is exact in the case of dense overcast skies, thus parameters $C = 1$, $D = E = 0$.

Under three overcast skies, i.e. ISO/CIE sky types 1, 3 and 5 resembling dense turbid media, the sunlight scattering causes an equal spread in all directions which is represented

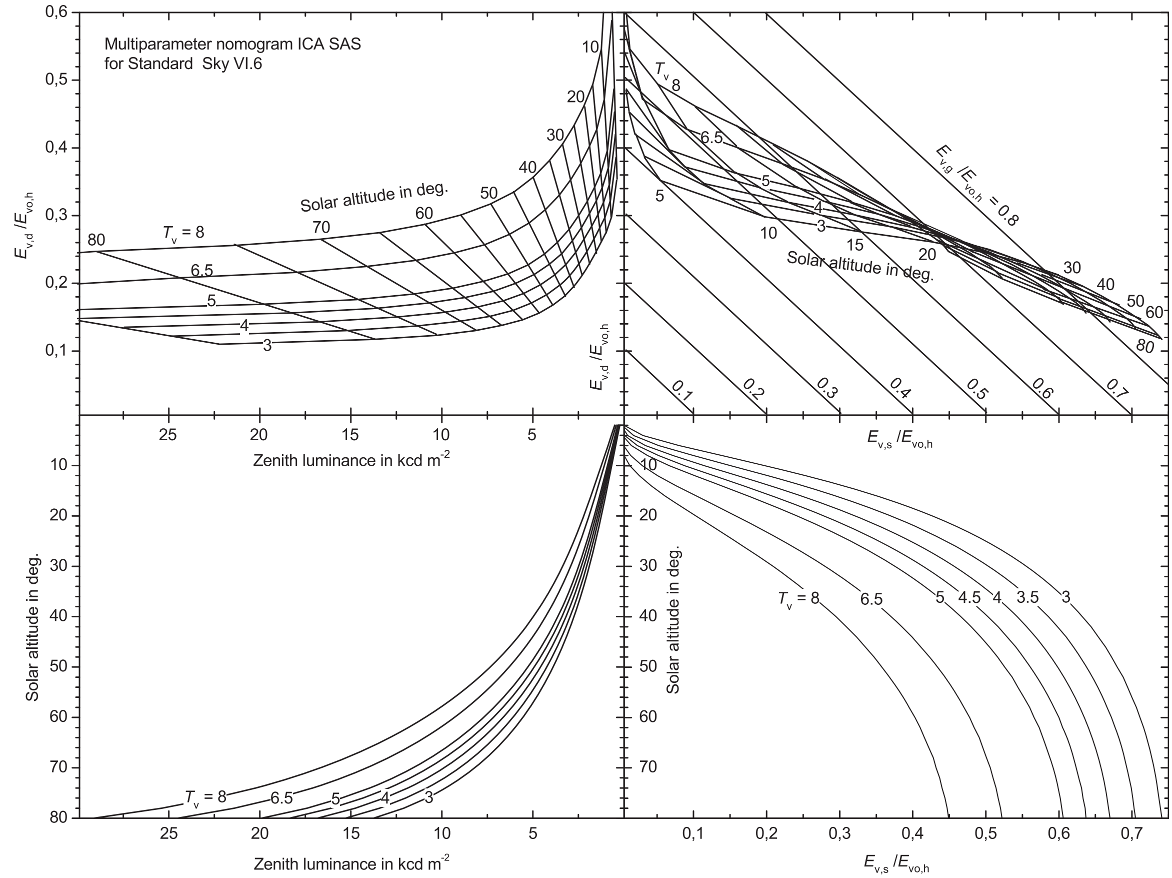

Figure 7 Nomogram for ISO/CI sky type 15 representing a very turbid clear sky

by a relative scattering function equal to 1 and very high values of T_v (over 20). This means:

- The very low transmittance of the multiple cloud layers reduces the $E_{v,d}/E_{vo,h}$ ratio to extremely low values, e.g. 0.05 or typically 0.1.
- The dense filter in the direction of parallel sunbeams causes an absolute shading of the sun position so that the direct solar component is practically zero as shown in case of $T_v = 20$ applied to equation (6)

$$E_{v,S}/E_{vo,h} = \exp\left(-a_v m T_v\right) = \exp(-20\, a_v m) \cong 0$$

- The ratio of zenith luminance to horizontal illuminance $L_{v,z}/E_{v,d}$ is constant and dependent on sky type gradation[10], i.e.:
  - for sky type 1, $L_{v,z}/E_{v,d} = 0.4083 = B/\left(E_{v,o}\varepsilon\right)$, which enables determination of the parameter B, assuming the ellipticity factor $\varepsilon = 1$, i.e. for the average luminous solar constant $E_{v,o} = 133.8$ klux, $B = 0.4083(133.8) = 54.63$ klux;
  - for sky type 3, $L_{v,z}/E_{v,d} = 0.361$ and $B = 0.361(133.8) = 48.3$ klux;
  - for sky type 5, $L_{v,z}/E_{v,d} = 0.3183 = 1/\pi$ and $B = 0.3183$, thus for the average luminous solar constant of 133.8 klux, $B = 42.59$ klux.

Sky type 1 absolute skylight illuminances can be found on the left of Figure 8 where the possible ranges of yearly changes are indicated in the luminous solar constant value due to the ellipticity of the Earth's orbit, i.e. applying an ellipticity correction ε due to date. In this respect the yearly change is approximately ±3.3% from the average 133.8 klux value, which is exactly valid on the 3rd April and 5th October, but is at its maximum in wintertime. On the 3rd January it is 138.35 klux, while in summer, on the 4th July, the minimum value of the solar constant is 129.25 klux. These extremes are indicated in Figure 8 on both sides by dashed lines.

Similarly to sky type 1, sky type 3 can be drawn graphically in terms of absolute skylight illuminance outdoors in klux. It is to be noted that the absolute skylight illuminance in klux can be derived in two ways, i.e. after equation (3) if $\varepsilon = 1$ and $E_{v,d}/E_{vo,h} = 0.15$, the zenith luminance in cd/m^2 for sky type 3 is $L_{v,z} = 7245 \ \sin\gamma_s$ and $L_{v,z}/E_{v,d} = 0.361$, so in lux $E_{v,d} = L_{v,z}/0.361 = (7245/0.361)\sin\gamma_s = 20069 \sin\gamma_s$ which quite nicely corresponds to the simple calculation based on ratio $E_{v,d}/E_{vo,h}$ when $E_{v,d} = 0.15 E_{vo,h} = 0.15\, E_{vo}\sin\gamma_s = 20070 \sin\gamma_s$ in lux.

Furthermore, for all these sky types when $E_{v,d}/E_{vo,h}$ is known, then zenith luminance can also be determined by the equation

$$L_{v,Z} = B\sin\gamma_s\left(E_{v,d}/E_{vo,h}\right) = E_{v,d}B/133.8\left(\mathrm{kcd/m^2}\right) \qquad (10)$$

For sky type 5 a similar diagram is shown on the right side of Figure 8 to predict diffuse skylight illuminance outdoors.

3.1.2. *Overcast sky types with slight brightness patches*

Both sky type 2 or I.2 and 4 or II.2 are overcast skies with thinner overall diffusing cloud layers causing some diminishing of sunlight but with imperfect filtering of the sun position that results in brighter luminance patches in its vicinity. As in these sky types an

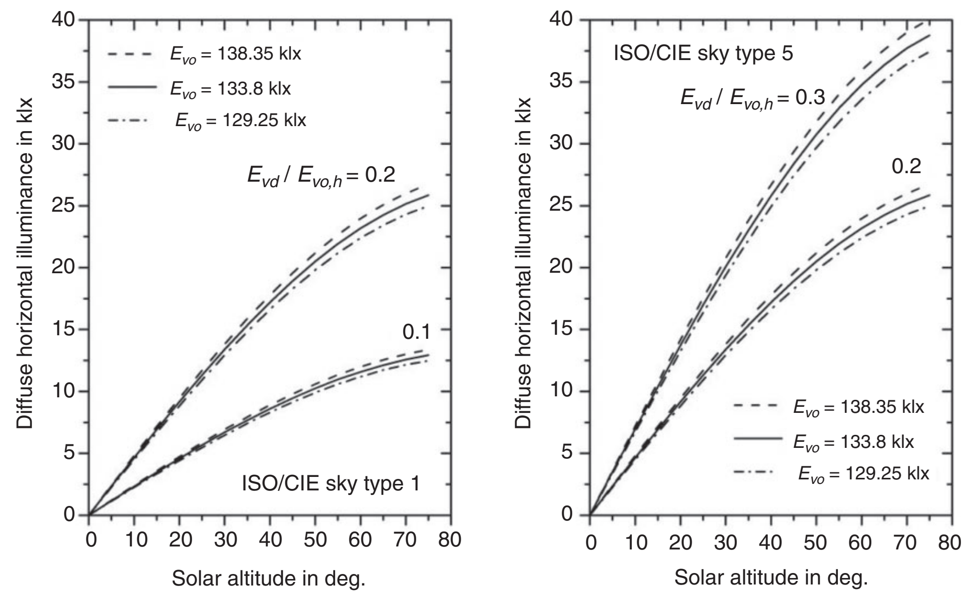

Figure 8 Diagrams for overcast sky types 1 and 5 with typical ratios of $E_{v,d}/E_{vo,h}$

indicatrix function 2 is to be taken, equation (5) is valid with *B, C, D* and *E* parameters as given in Sections 2.2.1 and 2.2.2.

3.1.3. Partly cloudy and clear sky types with sunlight participation

Using equation (7) both zenith luminance and skylight horizontal illuminance can be determined

$$L_{v,z} = \left(E_{v,d}/E_{vo,h}\right)(BX + E\sin\gamma_s)\left(\mathrm{kcd/m^2}\right) \tag{11}$$

and

$$E_{v,d} = \frac{L_{vz}}{(BX + E\sin\gamma_s)} = \frac{L_{vz}}{(BX + E\sin\gamma_s)}(\mathrm{klux}) \tag{12}$$

These two formulae use the interdependence $L_{v,Z}/E_{v,d}$ which generally defines the relationship between the sky pattern and horizontal sky illuminance. In fact under clear sky types with T_v homogeneity the sunbeam horizontal illuminance $E_{v,S}/E_{vo,h}$ from equation (6) and $E_{v,d}/E_{vo,h}$ are also interrelated depending on T_v values which generally express the transmission as well as the scattering property of the atmosphere and are associated with the luminance sky pattern defined in the ISO/CIE relative distribution. Equations (11) and (12) as well as equations (7) and (9) should provide approximately the same absolute zenith luminance and skylight diffuse illuminances.

The relationship of $E_{v,d}/E_{vo,h}$ for a particular sky type depends on the solar altitude and turbidity factor T_v as documented by the Bratislava 5-minute data as shown in Darula and Kittler[20] (measured data are used in Figures 1, 4, 6 and 10). These multi-parametric interrelations were studied[21] and were used to draw the diagrams shown in Figures 9 to 13 of reference 21. Therefore, only skylight

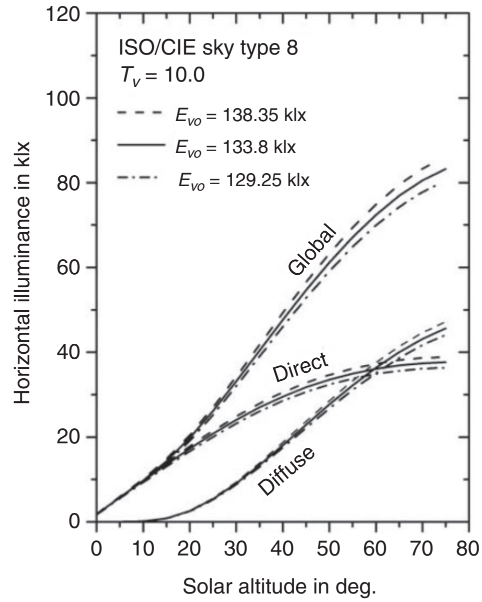

Figure 9 Diagram of horizontal illuminances under ISO/CIE sky type 8

illuminance diagrams with their dependence on solar altitude showing absolute illuminances outdoors $E_{v,d}$ and $E_{v,S}$ are shown here (Sky type 8 is shown for example in Figure 9). In the case of the clear sky type 12 on the left side in Figure 10 a value of $T_v = 2.5$ is applied for countryside localities and on the right side $T_v = 4.5$ is applied for townships. Selected data measured in Bratislava on the afternoon of the 15th August 2001 in the range $T_v = 4 - 5$ are also shown.

Generally, *A1, A2, B, C. D* and *E* parameters for any other sky type with typical T_v values can be used to calculate and draw similar diagrams for any sky type, if needed.

4. Conclusions

Sunlight from the Sun falls in the form of parallel beams on the outer borders of the Earth's atmosphere. Extraterrestrial sunlight reaches the ground level either filtered or scattered by the contents of the atmosphere,

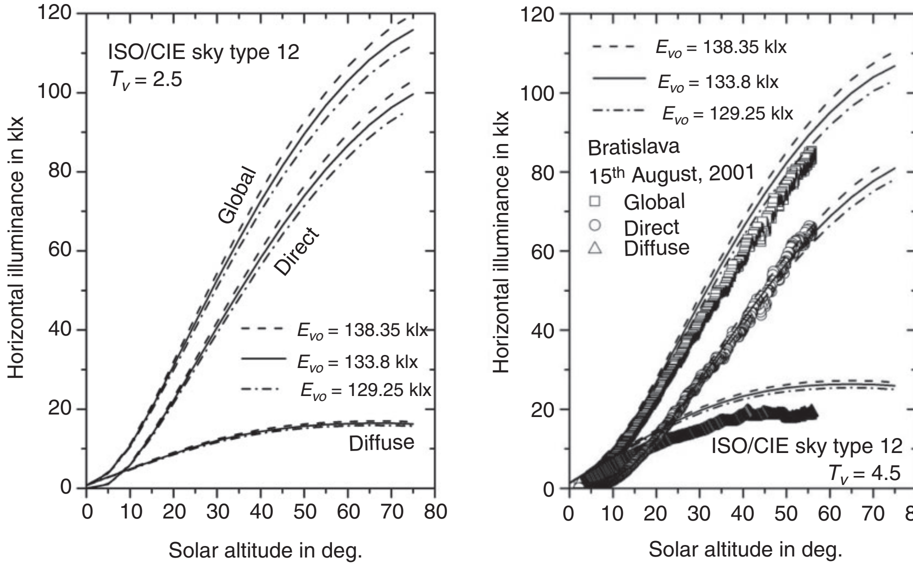

Figure 10 Diagram of horizontal illuminances under ISO/CIE sky type 12 with selected measured data recorded during a summer morning

thus forming the luminance distribution of the sky vault resulting in diffuse skylight. Even under densely overcast skies the overall skylight level is dependent on the extraterrestrial horizontal illuminance as well as on the solar altitude and the transmittance or thickness and turbidity of the diffusing cloud layers. There are specific links between the atmospheric transmittance and the ratio of horizontal illuminance to its extraterrestrial level together with a relationship between zenith luminance and the resulting horizontal illuminance especially under the homogeneous ISO/CIE standard sky types. These relationships are coupled with the solar altitude and so also with the local true solar time. Analysis of relative homogeneous ISO/CIE standard sky patterns normalised by their zenith luminance $L_{v,z}$ and their resultant diffuse horizontal illuminance $E_{v,d}$ forms a ratio that can be taken as a sky type classification. Thus, by measuring $L_{v,z}/E_{v,d}$ parameters under a momentary solar altitude a certain ISO/CIE standard sky type can be identified along a narrow $L_{v,z}/E_{v,d}$ zone.[22] At the same time, due to zenith luminance, any relative standard sky luminance pattern can also be defined in absolute physical units for practical use.

Under homogeneous turbidity conditions a proportional link between sunlight and skylight is influenced by the specific scattering effects under particular ISO/CIE sky types. These proportions characterise local daylight changes as shown in multi-parametric nomograms and the resulting horizontal outdoor illuminances documented in diagrams for some example standard sky types. The advantage of the graphical visual display demonstrates also the possibility of drawing intermediate sky types using given parametric constants $A - E$ for specific sky types. As the nomograms and diagrams are based on solar altitude these are valid for any location worldwide. However, simple general calculations based on the empirical formulae can facilitate further simulations in computer-aided design, in special cases to test mutual interconnections in local evaluations of primary influential parameters or in physical or numerical modelling of daylight conditions. Furthermore, using specified luminance and illuminance relationships can enable their modelling under artificial skies.

It should be noted that the physical attributes of illuminance, in lux, or luminance, in cd/m^2, when measured in absolute referenced quantities can be evaluated in relation to their known incidence. However, these physical quantities Φ, e.g. luminance and luminance ratio, can also be converted to perceived magnitudes Ψ through psychophysics. Their perception over the vast luminance range from vision threshold to direct sunlight follows a series of power relationships after Steven's law[23] $\Psi = k\Phi^{\alpha}$. However, for visual perception under adequate viewing daylight $\alpha = 1$ and k is the appropriate continuum constant for brightness or glare evaluations.[16] Fortunately, as with spectral quantity and quality, these broad-band physical and psychophysical measures are amenable to independent study, with psychophysics being an endpoint translator of quality once the quantities are known. However, an important prerequisite to determine window glare is the absolute sky/window luminance which can either facilitate good or bad daylighting design and must be physically controlled through window configuration, orientation and shading devices.

Therefore, it follows that there is an urgent need to understand the physics and the incidence of sunlight to skylight proportions to address and refine these physical influences for energy economy in daylight utilisation strategies and simulations. Thus, ISO/CIE standard sky types predetermine physically measured absolute daylight outdoor illuminances and ultimately quantity as well as the quality criteria of interior daylighting.

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