CIE GENERAL SKY STANDARD DEFINING LUMINANCE DISTRIBUTIONS

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ABSTRACT

Daylighting calculations depend on the luminance distribution of the sky. The new concept of sky luminance distributions is modelling skies under a wide range of occurrences from the overcast sky to cloudless situations without or with sunlight respectively. This concept was proposed for the standardisation of exterior daylight conditions by CIE (Commission Internationale de l'Éclairage) for the world wide application.

In this paper the calculation procedure of the relative sky luminance distribution and sky parametrisation of the fifteen standardised patterns is described. The CIE Standard General Sky is a generalisation of the CIE Clear Sky formula and the presented sky set is expected to be published as CIE standard. It could provide good means for the characterisation of daylight climate in any arbitrary locality or for the calculation of exterior daylight which both define the basic sources of daylight simulations in interiors.

KEYWORDS

sky luminance distribution, standardisation, daylighting simulations.

INTRODUCTION

Natural light has always played a dominant role in human life. It is important for health and comfort thus it predetermines the quality of interiors in buildings. To accomplish energy simulations correctly it is necessary to know daylight conditions during the whole year. There are several methods for defining daylight conditions in different climates and locations. The illuminance availability approach provides a direct view on illuminance changes, their levels and differences (Dumortier et al. 1994). Because illuminance is calculated by the integration of luminance in the window solid angle it is important to define luminance distribution on the sky under different situations. In most simulation programs the models of the CIE overcast and CIE clear sky are applied, e.g. the program SUPERLITE generates the luminance distribution under uniform sky, CIE Overcast Sky, CIE Clear Sky with or without sun (Baker et al. 1993). These sky conditions are also applied in the *gensky* program which is incorporated in the RADIANCE package. Usually in the simulation programs only the CIE Overcast and CIE Clear Sky are included. These extreme sky types are important for window design but for energy simulations these do not represent fully conditions occurring in reality.

The standard methods are needed to harmonise daylight design and daylighting consequences. The recent activities in the CIE were aimed to define typical luminance distributions which can described the sky as a primary vast source of daylight. Three proposals by Nakamura et al. (1985), Igawa et al. (1997), Kittler et al. (1997) or Kittler et al. (1998) were submitted for this standardisation. The solution by Kittler et al. (1998) in a relative version was recommended and adopted by CIE TC 3-15 for application as the CIE standard. After final formalities handled by the CIE Central Bureau this draft standard is expected to be approved in the near future.

PREVIOUS STANDARDISATION OF SKY LUMINANCE DISTRIBUTIONS

The first nonuniform CIE standard for the luminance distribution on the overcast sky was suggested by Moon and Spencer (1942). The changes of luminance from horizon to zenith in ratio 1:3 were described by a trigonometric relation in formula (1)

$$\frac{L\gamma}{Lz} = \frac{1 + 2\sin\gamma}{3} = \frac{1 + 2\cos Z}{3} \tag{1}$$

where $L\gamma$ is luminance of a sky element in cd m^{-2},
Lz is the zenith luminance in cd m^{-2},
γ is the elevation angle of a sky element above the horizon,
Z is the angular distance between a sky element and the zenith, $Z = 90° - \gamma$.

The luminance distribution on the clear sky was derived by Kittler (1967) and together with the CIE

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Overcast Sky published as ISO/CIE standard in 1996 (ISO 1996) using formula (2):

$$\frac{L\gamma\alpha}{Lz} = \frac{\left(1 - e^{-0.32/\sin\gamma}\right)\left(0.91 + 10e^{-3\chi} + 0.45\cos^2\chi\right)}{0.274\left(0.91 + 10e^{-3Zs} + 0.45\cos^2 Zs\right)}$$

where $L\gamma\alpha$ is luminance in any arbitrary sky element,
χ is the angular distance of the sky element from the sun,
Zs is the zenith distance of the sun.

The Perez´s (1991) model was based on the scan measured luminance data at Berkeley but it has been applied in simulation programs using routine irradiance measurements in e.g. RADIANCE or GENELUX.

Japanese authors Nakamura et al. (1985) have classified sky conditions into three groups i.e. overcast, clear and intermediate trying to define the luminance distribution of the intermediate sky. Later Igawa (1997) suggested twenty patterns of luminance distributions based on scan measured luminance data at Tokyo and derived by a statistical method to fill the relative sky luminance distribution gap between two extreme CIE standard skies.

Fifteen sky types of relative luminance distributions in the SSLD model by Kittler et al. (1998) are based on scan measured luminance data at Tokyo, Berkeley and Sydney and were proposed at the same time. Five overcast, five clear and five transitional skies are modelled by the combination of gradation and indicatrix functions. This solution is proposed as a CIE code draft CIE (2001) which is under review by CIE National Committees at present. In contrary to previous solutions the determination of daylighting conditions is more detail (Kittler et al. 1998) and covers the whole occurrence spectrum considering different diffuse scattering by the atmosphere and effects of direct sunlight. Applying additional parametrisation it is possible to calculate illuminance and luminance levels not only in relative but also in absolute physical units.

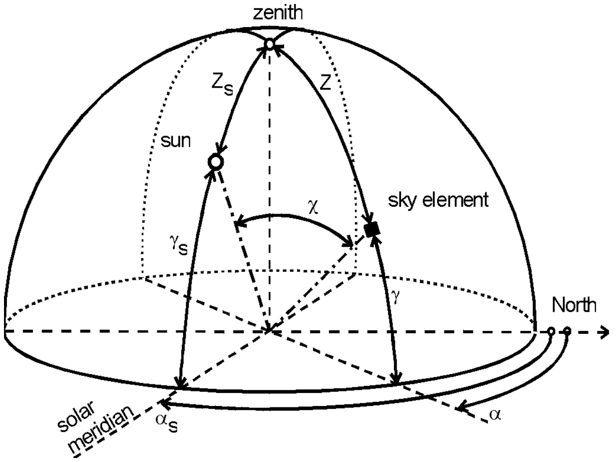

Figure 1. Angles defining the position of the sun and a sky element

CALCULATION OF THE RELATIVE LUMINANCE DISTRIBUTION AFTER THE CIE GENERAL SKY CONCEPT

The position of the sun and of the arbitrary sky element as well as parameters *a, b, c, d, e* which describe atmospheric conditions have to be taken as input calculation quantities. The position of the arbitrary sky element is defined by the zenith angle Z and the azimuth difference Az between the element and the solar meridian Figure 1, then its distance from the sun is defined by equation (3).

$$\chi = \arccos\left(\cos Zs \cos Z + \sin Zs \sin Z \cos Az\right) \tag{3}$$

where $Az = \left|\alpha - \alpha s\right|$.
α and αs are azimuthal angles of the vertical plane of the sky element and sun position respectively.

The ratio of the luminance $L\gamma\alpha$ in an arbitrary sky element to the zenith luminance Lz is expressed in an functional formula following the current CIE Clear Sky Standard:

$$\frac{L\gamma\alpha}{Lz} = \frac{f(\chi)\,\varphi(Z)}{f(Zs)\,\varphi(0°)} \tag{4}$$

The luminance gradation function φ relates the luminance of a sky element to its zenith angle:

$$\varphi(Z) = 1 + a \exp\left(b/\cos Z\right), \tag{5}$$

when $0 \le Z \le \pi/2$
and at the horizon is $\varphi(\pi/2) = 1$

Equation (4) applies also to its value at the zenith:

$$\varphi(0°) = 1 + a \exp b \tag{6}$$

The function f is expressing the scattering indicatrix which relates the relative luminance of a sky element to its angular distance from the sun:

$$f(\chi) = 1 + c\,(\exp(d\,\chi) - \exp(d\,\pi/2)) + e\cos^2\chi \qquad (7)$$

Its value at the zenith is expressed in eq. (8):

$$f(Zs) = 1 + c\,(\exp(d\,Zs) - \exp(d\,\pi/2)) + e\cos^2 Zs$$

STANDARD PARAMETERS

For window design, glare studies, energy analysis, daylight climate classifications and other purposes the parameters a to e in equations (5) - (8) can be selected from Table 1. It lists fifteen standard relative luminance distributions which are based on six groups of a and b values for the gradation function and six groups of c, d and e values for the indicatrix function. The resulting curves are illustrated in Figures 2 and 3.

For a practical simplification not all six by six functions are used because some combinations are very seldom while others are frequent. For instance overcast skies are characterised by declining gradations and more or less even indicatrices while clear skies have rising gradations coupled with toward sun rising indicatrices (Kittler and Darula 2001).

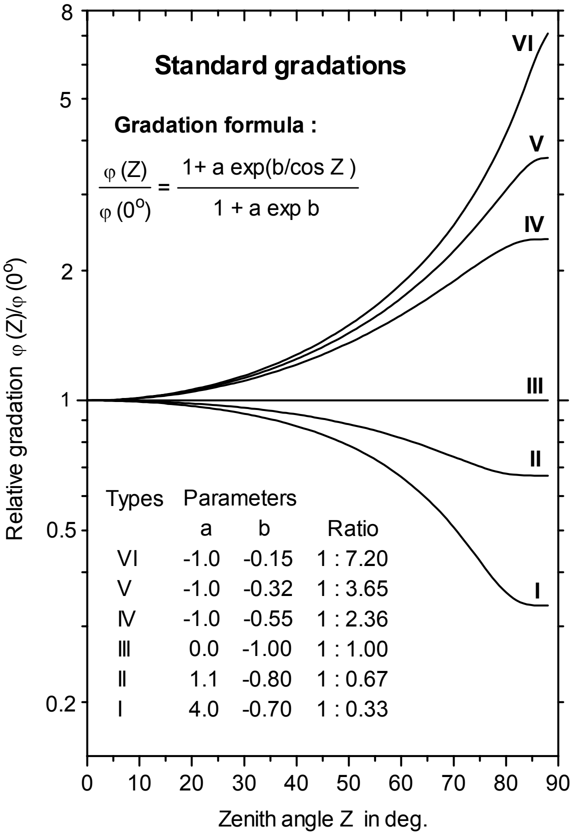

Figure 2. Standard gradations

AN EXAMPLE OF THE LUMINANCE CALCULATION IN THE SKY ELEMENT

To estimate the luminance of the sky element $L\gamma\alpha$ under a white-blue sky (Sky Standard IV.4) in the direction described by azimuth $\alpha = 130°$ from North, vertical elevation is $\gamma = 10°$, while the sun altitude is $\gamma s = 38.02°$ and sun azimuth $\alpha s = 147.67°$. The following procedure is to be used:

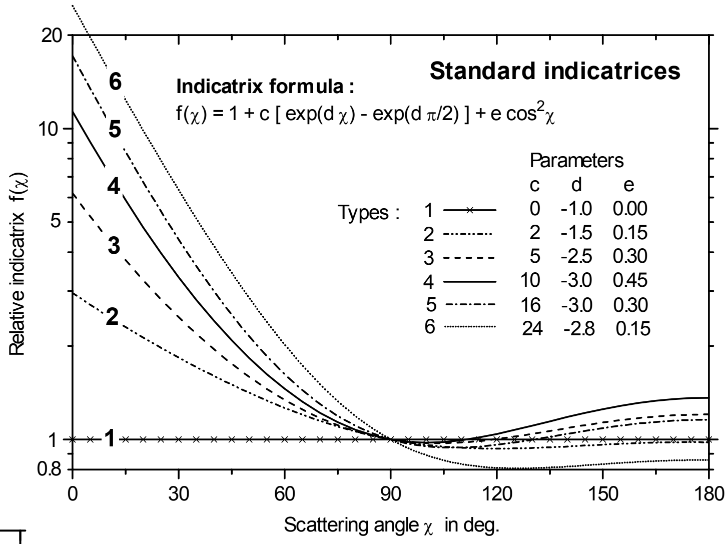

Figure 3. Standard indicatrices

1. The luminance distribution on the sky of type IV.4 is defined by parameters $a = -1.00$, $b = -0.55$, $c = 10.00$, $d = -3.00$ and $e = 0.45$ which are taken from Table. 1.

2. Chosen sky element is defined by angles:

Zenith angle $Z = 90° - \gamma = 90 - 10 = 80°$

The sun zenith angle is

$Zs = 90° - \gamma s = 90 - 38.02 = 51.98° = 0.907$ rad

Sun azimuth from the chosen element

$Az = |\,\alpha s - \alpha\,| = |147.67 - 130| = 17.67°$

Spherical angular distance of sky element from the sun position χ is:

$\cos\chi = \cos Zs\cos Z + \sin Zs\sin Z\cos Az$

$\cos\chi = \cos 51.98\cos 80 + \sin 51.98\sin 80\cos 17.67 = 0.8462$

then $\chi = 32.20° = 0.562$ rad

3. Calculation of gradation and indicatrix functions :

Gradation function for a sky element in view direction:

Table 1. Standard parameters

Type	Gradation	Indikatrix	*a*	*b*	*c*	*d*	*e*	Description of luminance distribution
1	I	1	4.0	-0.70	0	-1.0	0.00	**CIE Standard Overcast Sky, alternative form** Steep luminance gradation towards zenith, azimuthal uniformity
2	I	2	4.0	-0.70	2	-1.5	0.15	Overcast, with steep luminance gradation and slight brightening towards the sun
3	II	1	1.1	-0.8	0	-1.0	0.00	Overcast, moderately graded with azimuthal uniformity
4	II	2	1.1	-0.8	2	-1.5	0.15	Overcast, moderately graded and slight brightening towards the sun
5	III	1	0.0	-1.0	0	-1.0	0.00	**Sky of uniform luminance**
6	III	2	0.0	-1.0	2	-1.5	0.15	Partly cloudy sky, no gradation towards zenith, slight brightening towards the sun
7	III	3	0.0	-1.0	5	-2.5	0.30	Partly cloudy sky, no gradation towards zenith, brighter circumsolar region
8	III	4	0.0	-1.0	10	-3.0	0.45	Partly cloudy sky, no gradation towards zenith, distinct solar corona
9	IV	2	-1.0	-0.55	2	-1.5	0.15	Partly cloudy, with the obscured sun
10	IV	3	-1.0	-0.55	5	-2.5	0.30	Partly cloudy, with brighter circumsolar region
11	IV	4	-1.0	-0.55	10	-3.0	0.45	White-blue sky with distinct solar corona
12	V	4	-1.0	-0.32	10	-3.0	0.45	**CIE Standard Clear Sky, low illuminance turbidity**
13	V	5	-1.0	-0.32	16	-3.0	0.30	**CIE Standard Clear Sky, polluted atmosphere**
14	VI	5	-1.0	-0.15	16	-3.0	0.30	Cloudless turbid sky with broad solar corona
15	VI	6	-1.0	-0.15	24	-2.8	0.15	White-blue turbid sky with broad solar corona

$\varphi(Z) = 1 + a \exp(b/\cos Z)$
$\varphi(Z) = 1 - 1 \exp(-0.55 / \cos 80) = 0.9579$
Gradation function for zenith:
$\varphi(0°) = 1 + a \exp(b/\cos 0°)$
$\varphi(0°) = 1 + a \exp b = 1 - 1 \exp(-0.55) = 0.4231$
Indicatrix function for a sky element in view direction:
$f(\chi) = 1 + c\,[\exp(d\,\chi) - \exp(d\,\pi/2)] + e \cos^2 \chi$
$f(\chi) = 1 + 10\,[\exp(-3 * 0.562) - \exp(-3\,\pi/2)] + 0.45*0.8462^2 = 3.0847$
Indicatrix function for zenith:
$f(Zs) = 1 + c\,[\exp(d\,Zs) - \exp(d\,\pi/2)] + e \cos^2 Zs$
$f(Zs) = 1 + 10\,[\exp(-3 * 0.907) - \exp(-3\,\pi/2)] + 0.45 \cos^2 51.98 = 1.7385$

4. Calculation of relative luminance in the view direction normalised to zenith luminance is:
$L\gamma\alpha / Lz = \varphi(Z) f(\chi) / ((\varphi(0°) f(Zs))$
$L\gamma\alpha / Lz = 0.9579 * 3.0847/(0.4231 * 1.7385) = 4.0175$

5. If zenith luminance is known or measured, e.g. Lvz = 4404 cd/m^2, after statistical analysis of the sky types frequency based on the IDMP Bratislava, then the absolute value of sky luminance in the chosen element is:

$L\gamma\alpha = Lvz\,(L\gamma\alpha / Lz) = 4404 * 4.0175 = 17693$ cd/m^2

In the chosen case the sky luminance is $L\gamma\alpha$ = 17693 cd/m^2 under conditions of sky luminance distribution pattern IV.4. In a similar way it is possible to calculate a set of relative or absolute luminances of any arbitrary sky element and represent whole sky pattern as shown in Figure 4. Then by the integration in the solid angle

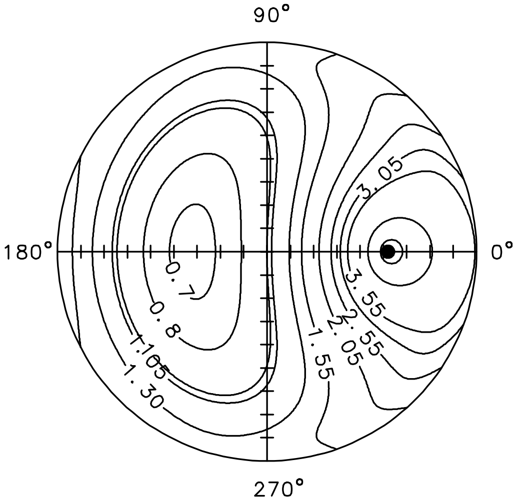

Figure 4 The relative luminance distribution representing IV.4 Sky Standard, when γs = 38,02°

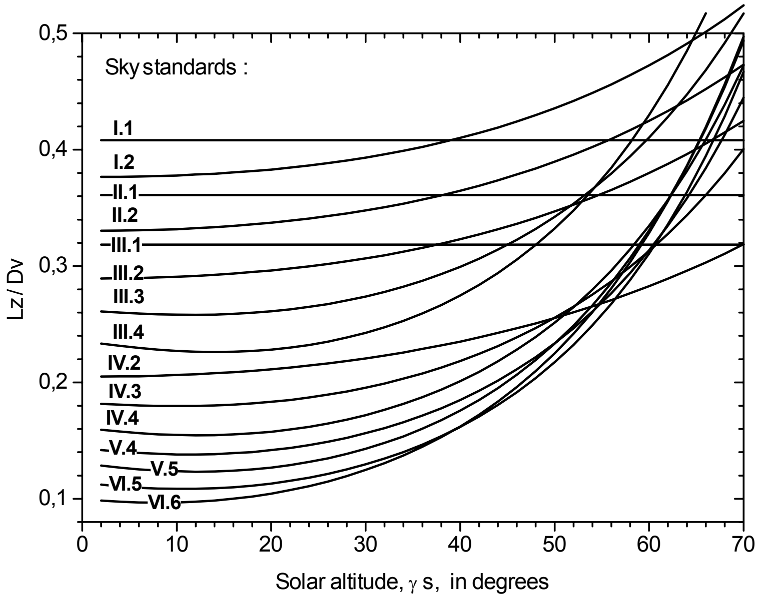

Figure 5. Standard ratio *Lz/Dv* defining every Sky type

of the window the sky illuminance in any point of the interior working plane can be calculated.

DESCRIPTORS OF SKY TYPES

Scattering indicatrix and gradation functions for every sky type in the proposed set define the ratio of zenith luminance *Lz* to diffuse sky illuminance *Dv*:

$$\frac{Lz}{Dv}=\frac{\varphi(0^\circ)\,f(Zs)}{\int_{Z=0}^{\pi/2}\int_{\alpha=0}^{2\pi}\left[\varphi(Z)f(\chi)\sin Z\cos Z\right]dZ\,d\alpha} \qquad (9)$$

So homogeneous sky standards can be defined by a set of *Lz/Dv* curves represented in Figure 5. These curves can be simulated by a very precise best fit approximation formula valid almost to 80° solar altitude:

$$Lz / Dv = [\,B\,(\sin\gamma s)^C/(\cos\gamma s)^D + E\sin\gamma s]\,/Ev \qquad (10)$$

where *Ev* is extraterrestrial horizontal illuminance:

$$Ev = 133.8\sin\gamma s \qquad \text{[klx]} \qquad (11)$$

and *B*, *C*, *D* and *E* are parameters characterising a certain sky standard (see Table 2).

So, to characterise the sun and sky as sunlight and skylight sources in their inter-action including sky luminance patterns at least four parameters are necessary, i.e.:

1. solar altitude γs (or date and time),

2. direct solar horizontal exterior illuminance *Pv* normalised by its extraterrestrial value *Ev*, i.e. *Pv*/*Ev* which defines also the luminous turbidity *Tv*,

3. diffuse/sky horizontal illuminance normalised by *Ev*, i.e. *Dv*/*Ev*. Of course instead of *Pv* very often is measured the global illuminnance *Gv* and then *Pv* = *Gv* - *Dv*. In the regularly measured data at least *Gv* or *Pv*, *Dv* and *Lz* recorded in the same time steps are necessary to identify sky types,

4. the *Lz*/*Dv* ratio just described from which the absolute zenith luminance can be then calculated in kcd/m^2 :

Table 2. Parameters applied for descriptor calculations in absolute units

Sky type	Sky code	Parameter					
		A1	*A2*	*B*	*C*	*D*	*E*
1	I.1	*)		54.63	1.00	0.00	0.00
2	I.2			12.35	3.68	0.59	50.47
3	II.1			48.30	1.00	0.00	0.00
4	II.2			12.23	3.57	0.57	44.27
5	III.1			42.59	1.00	0.00	0.00
6	III.2			11.84	3.53	0.55	38.78
7	III.3	0.957	1.790	21.72	4.52	0.63	34.56
8	III.4	0.830	2.030	29.35	4.94	0.70	30.41
9	IV.2	0.600	1.500	10.34	3.45	0.50	27.47
10	IV.3	0.567	2.610	18.41	4.27	0.63	24.04
11	IV.4	1.440	-0.750	24.41	4.60	0.72	20.76
12	V.4	1.036	0.710	23.00	4.43	0.74	18.52
13	V.5	1.244	-0.840	27.45	4.61	0.76	16.59
14	VI.5	0.881	0.453	25.54	4.40	0.79	14.56
15	VI.6	0.418	1.950	28.08	4.13	0.79	13.00

*) These sky types are associated with no sunlight therefore the formula for these cases is not valid.

$$Lz=\frac{Dv}{Ev}\left[\frac{B\left(\sin\gamma s\right)^{C}}{\left(\cos\gamma s\right)^{D}}+E\sin\gamma s\right] \qquad [\text{kcd/m}^2] \qquad (12)$$

For sunny periods when the sun filter is given by $Tv \leq 12$, then *Lz* in kcd/m^2 can be determined after:

$$Lz = A\sin\gamma s + 0.7\left(Tv+1\right)\frac{\left(\sin\gamma s\right)^{C}}{\left(\cos\gamma s\right)^{D}} + 0.04\,Tv \qquad (13)$$

where $A = (A1\ Tv + A2)$

Tv is the luminous turbidity factor which approximates the number of ideally clean atmospheres representing an actual case. If *Gv* and *Dv* are measured, then $Pv/Ev = Gv/Ev - Dv/Ev$ and the luminous turbidity *T*v can be calculated as

$$Tv = \frac{-\ln Pv / Ev}{av\ m} \tag{14}$$

If *Tv* is greater than 12 the *Pv*/*Ev* is quite small, so the conditions can be taken as sunless. Although there is a continuous reduction possible, sometimes an agreed border, i.e. normal direct irradiance 120 W/m^2 is assumed to measure sunshine duration. In this way the prevailing *Tv* and sunshine duration characteristics can likewise specify the occurrence frequency of different sky types in an actual location (Kittler et. al., 2001).

Simultaneously the *Tv* value, i.e. cloud position in the direction of sun predetermines the parallel beam/direct solar illuminance on a horizontal plane (*Pv*) as:

$$Pv/Ev = \exp(-av\ m\ Tv) \tag{15}$$

where *m* is the air mass penetrated and *av* its ideal luminous extinction, dependent on solar altitude γs in deg., i.e.:

- after Kasten-Young (1989) the optical mass *m* is:

$$m = \frac{1}{\sin \gamma s + 0.50572 \left(\gamma s + 6.07995°\right)^{-1.6364}} \tag{16}$$

- after Clear (1982) and Navvab et. al (1984) *av* is dependent on *m*:

$$av = \frac{1}{9.9 + 0.043\, m} \tag{17}$$

Using these formulae and parameters the diffuse illuminance or *Dv*/*Ev* can be calculated two ways. In presence of sunlight due to a certain *Tv* value *Lz* is given by eq. (13) and inserted to (12) from which *Dv*/*Ev* or *Dv* is determined. If a user-friendly computer program is available *Dv* can be defined by integration from eq. (9).

DESCRIPTORS OF DAYLIGHT CLIMATE

Considering eg. (12) the independence of zenith luminance, sky illuminance and extraterrestrial illuminance is expressed (Kittler and Darula, 1997), but frequently available data are those measured within the world-wide net of meteorological stations usually containing only global irradiance or illuminance. From these can be derived only few informations, i.e. high global levels are linked with clear and partly cloudy skies with sunlight while low global values occur under more extensive cloud covers or overcast skies. In extreme cases due to the dense cloud filter diffuse levels are very low. Thus during rainy and overcast periods, sunless days or months have to be expected with small *Dv/Ev* ratios equal to *Gv/Ev* as *Pv/Ev* is close to zero while *Lz/Dv* ratios under overcast skies are independent on sunheights as after eq. (10)

$$Lz/Dv = (B \sin \gamma s)/(133.8 \sin \gamma s) = B/133{:}8 \tag{18}$$

with *B* for uniform to CIE Overcast Sky standard is roughly in the range 42.6 to 54.63 (Table 2), thus *Lz/Dv* has to be within 0.32 to 0.41.

Additionally due to lower solar altitudes in wintertime all sunless overcast periods have roughly the same character with *Lz/Dv* values over 0.25 while *Gv/Ev* ratios are under 0.25. To document this fact 5-minute data recorded in Bratislava during November 1999 are shown in Figure 6. This month was quite dull with low monthly mean relative sunshine duration *sm* = 0.15, i.e. with few sunny periods or days. Even more imaginative are graphical plots made for a typical day, such as a permanently overcast, a cloudy and a clear one chosen from a larger set (Kittler et al., 2002).

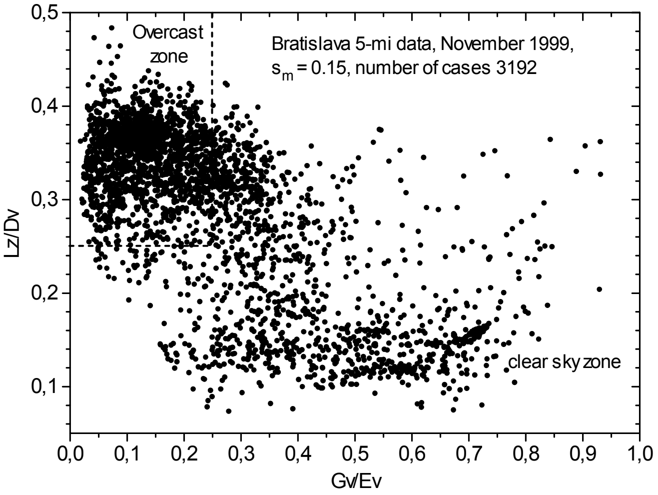

Figure 6. Monthly distribution of sky type descriptors in a dull wintertime season.

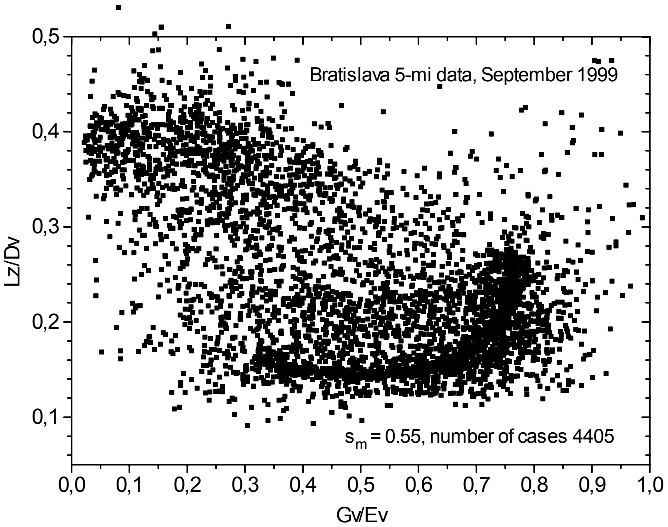

Figure 7. Descriptor distribution in a sunny autumn month.

Although there is in the distribution of *Lz/Dv* a primary dependence on the solar altitude after Figure 5, this is hidden in both Figure 6 and 7, but it is indicated by the level of *Gv/Ev*. The bending and rising clear sky zone in Figure 7 is caused by this implied dependence while the spread of clear sky cases covers also the partly cloudy skies and different turbidities of the real atmospheres (Kittler and Darula, 2000). Of course, the sunshine duration which is in the reverse position to cloudiness (Soler, 2000), is specifying sunny periods and days or months when the utilisation of solar energy and sunlight is effective. Then high Gv/Ev ratios are prevailing and the cumulation of Lz/Dv cases form the rising bend which tends to be higher and higher in summertime due to extreme noon solar altitudes. Studies of occurrence frequency of sky types using long-term data in Athens and Bratislava have shown typical sky conditions characterising local climates (Kittler et al., 2001 and Tregenza, 1999).

HOW TO ESTIMATE DESCRIPTORS IN TYPICAL SITUATIONS

If there are no available informations for simulation purposes, e.g. measured global levels, sunshine durations or cloud covers, there can be taken typical parameters from Table 3. Thus using mentioned formulae (4) and (10) to (14) all necessary descriptors can be estimated including luminance patterns.

Note that in sunless situations the estimated *Dv/Ev* has to be used to calculate *Lz* in absolute values and then luminance distribution is given by eq. (4) using a friendly MODELSKY program (Darula and Kittler 1999, Kocifaj and Darula 2002).

Table 3. Typical values of descriptors linked with various sky types

Sky type	Sky code	Typical parameters		
		Tv	*A*	*Dv/Ev*
1	I.1	over 45	Eq. (13) is not valid	0.10
2	I.2	over 20		0.18
3	II.1	over 45		0.15
4	II.2	over 20		0.22
5	III.1	over 45		0.20
6	III.2	over 20		0.38
7	III.3	12.0	13.27	0.42
8	III.4	10.0	10.33	0.41
9	IV.2	12.0	8.70	0.40
10	IV.3	10.0	8.28	0.36
11	IV.4	4.0	5.01	0.23
12	V.4	2.5	3.30	0.10
13	V.5	4.5	4.76	0.28
14	VI.5	5.0	4.86	0.28
15	VI.6	4.0	3.62	0.30

In case of partly cloudy and clear skies with sunlight the *Tv* value predetermines the *Lz* level and if necessary the appropriate range of *Tv* values can be used (Kittler and Darula, 2000b).

Having *Lz* and luminance patterns also *Dv* and *Gv* levels can be estimated during the whole day either directly from *Lz/Dv* or by integration following the changes of solar altitudes, while *Pv/Ev* ratios can be calculated assuming a constant *Tv* value.

CONCLUSIONS

The set of standard skies represent a realistic method to model daylight which is available for all future energy simulations of buildings and optimalisation studies as well as for determining their environmental and economic consequences. These more objective tools will be world-wide usable to compare daylight climates after the adoption of the draft (CIE 2001) by the CIE. Furthermore, now standardised sky types exist which can enable to work out reference conditions for simulation programs with more realistic daylight and sunlight dynamic changes which model also extremes and absolute levels are taking into account local sunshine duration, turbidity or pollution situations predetermining the prevailing sky patterns.

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