Sky type determination using vertical illuminance

Abstract. The modelling of daylight in buildings requires also information about exterior daylight conditions. The regularly measured horizontal and vertical illuminances offer data applicable in daylight research as well as in practical daylight design and energy simulations in buildings. Daylight illuminances are continually changing during days within a year and some of their classification is needed. It seems that new possibilities for determination of daylight conditions based on the measured vertical illuminances exist. This paper presents the concept of the standard sky type determination based on vertical illuminances with orientation to cardinal points and documents its application in case of overcast skies.

Streszczenie. Modelowanie światła dziennego w budynkach wymaga informacji o zewnętrznych dziennych warunkach oświetleniowych. Regularne pomiary poziomego i pionowego natężenia oświetlenia są podstawą do badań oświetlenia zewnętrznego i zastosowania praktycznego w projektowaniu oświetlenia zewnętrznego i symulacji energetycznych w budynkach. Zewnętrzne natężenie oświetlenia nieustannie zmienia się w ciągu dnia i roku, co wymusza potrzebę jego klasyfikowania. Wydaje się, że możliwe staje się nowe opisanie warunków dziennych na podstawie pomiarów pionowego natężenia oświetlenia. W artykule przedstawiono koncepcję określania standardowego nieboskłonu opartą na pionowym natężeniu oświetlenia zorientowanym względem podstawowych stron światłowych i zaprezentowano jej wykorzystanie dla warunków nieboskłonu pokrytego. (Określenie rodzaju nieboskłonu na podstawie pionowego natężenia oświetlenia)

Keywords: Daylight vertical illuminance, solar azimuth, plane orientation, daylight parameters

Introduction

In the daylight theory and measurements were determined exterior daylight conditions especially on the availability of horizontal illuminance levels in various localities and under different cloudiness situations. Now more specific relative sky luminance patterns or sky types were standardised [1, 2] and realistic illuminance on vertical surfaces, such as house windows can be calculated in differently oriented interiors.

This paper tries to coordinate calculated and measured illuminance data within the parameterisation system based on oriented fluxes of sunray and sky luminance influence arbitrary vertical planes. Under clear sky conditions the position between the orientation of the vertical plane and the momentary solar azimuth is of primary importance as evident from measured vertical illuminances and has to be taken into account in calculation programs. Otherwise, outdoor vertical illuminance measured regularly on vertical planes with their orientation to four cardinal points can be used to approximate sky types present during the measurement period [3, 4].

Common used sky type classification method [5, 6] applies the identification ratio of zenith luminance to horizontal diffuse/sky illuminance Lz/Dv. However, if vertical illuminance data are available in several CIE IDMP stations [7], then the sky type differences in four cardinal point directions can be studied and specified.

Derivation of vertical sky illuminance

Usually vertically placed sensors oriented to cardinal point towards North, East, South and West are measuring global illuminances, thus total global values Gz include:
- sunlight, i.e. parallel sunbeam illuminance Pz, in accordance with the momentary sun position and turbidity and/or cloudiness shading,
- skylight, i.e. diffuse illuminance from the sky vault Dv,
- reflected daylight illuminance Rz, from obstructions and the terrain above and/or under the horizon.

To exclude the sunlight influence it is important to identify the presence of sunlight due to the sun position with respect to the orientation of the vertical plane as well as to the sun-shading by clouds. The momentary sunlight effect is easily identified by the difference between the measured horizontal global and diffuse illuminance. The absence of sunlight is also caused by the orientation of the vertical plane in respect of the momentary sun position. Therefore it is necessary to calculate the solar azimuth in the moment of the measurements A, and compare it with the azimuths of each vertical sensor, i.e. A1z, A2z, A3z, and A4z.

Thus can occur following situations:
- The North facing sensor can be reached by direct low sunbeams only during early morning or late afternoon from the spring to autumn equinox days.
- The East facing sensor can be illuminated by direct sunbeams from sunrise hours to noon, i.e. to 12 a.m. true solar time TST.
- The Southern sensor can be reached by sunbeams almost the whole day except the morning hours before 6 a.m. and afternoon hours after 6 p.m.
- The Western sensor can register sunlight from noon until sunset.

Evidently the sunlight component in the global measured value is present only during intervals when the Sun is unshaded by clouds, then Gz = Pz + Dv + Rz. If Sun is shaded then Gz = Dv + Rz is valid and such occasions can be simply selected from the measured data.

During overcast or foggy situations, when sunlight is missing, Lz/Dv is relatively stable within the interval 0.293 - 0.433 or in a more restricted range 0.32 – 0.42, where Lz is the zenith luminance and Dv is the horizontal diffuse illuminance. Under ideal homogeneous atmospheric conditions with dense cloud cover three ISO/CIE sky types can be identified:

A. Sky type 1, ISO/CIE Overcast Sky with luminance gradation 1:3 in the characteristic range of Lz/Dv:

$$Lz / Dv = 0.408 \pm 2.5% = 0.408 \pm 0.025$$

while the zenith luminance can be approximately expressed in kcd/m² as:

$$Lz = (Dv / E_s) [54.65 \sin \gamma_s]$$

where: $$E_s$$ - extraterrestrial horizontal illuminance, $$\gamma_s$$ - the momentary solar altitude.

Because of the uniform azimuth luminance the influence on any vertical plane for all Dv are equal and can be calculated after:

$$Dv = \frac{\pi}{2} \sum_{\varphi=0}^{\varphi=\pi} \left( \frac{Lp \cos \varphi}{Lp \cos \varphi} \right) d\varphi dA_p$$

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where: \( L_\gamma \) - luminance of the sky element, \( \vphi_\gamma \) - elevation of the sky element, \( \eta_\gamma \) - azimuth of the sky element, \( \vphi_0 \) - the incidence angle, i.e. the spherical angle of the sky element to the normal of the vertical surface.

Instead of the tedious integration can be used a numerical summation of elemental sky luminance in solid angles which can yield approximately the same results [8] as:

\[
D_{\nu I} = \sum_{i=1}^{n} \sum_{j=1}^{k} L_{ij} \cos \left( \frac{\pi}{2} - \frac{\vphi_{ij}}{k} \right)
\]

where: \( L_{ij} \) - the luminance of the sky element \( (i, j) \), \( n \) - number of bands in the sky hemisphere, \( k \) - number of elements in each band of the sky hemisphere, \( \eta_{ij} \) - the spherical area of the sky element which is equal to \( \eta_{ij} = \frac{\pi}{2} \cos \frac{\vphi_{ij}}{k} \), while in the integration formula it is expressed as \( dA_{\nu} p_{\nu} \cos \vphi_\nu \).

To increase the accuracy of the numerical integration a division of the sky hemisphere in very small elements is crucial, in [9] is recommended for 145 circular sky patches dimension of diameter 0.2 radians. However, the error of this mathematical operation has to be tested.

If the \( D_{\nu I} \) component is defined by the above calculation, then the reflected components, i.e. \( R_{\nu I}, R_{\nu E}, R_{\nu S} \) and \( R_{\nu W} \) can be derived from the measured \( G_{I\nu} \) illuminance. In case of overall diffuse reflecting surfaces in the downward horizontal plane approximately illuminated as a horizontal plane by \( D_{\nu} \), these reflected components assuming Lambertian diffuse reflection could have the value \( R_{\nu I} = D_{\nu} \rho_{\nu} / \pi \), i.e. the ground reflectance will be \( \rho_{\nu} = R_{\nu I} / D_{\nu} \).

Sometimes the ground reflectance is approximated by the value 0.2, but using the IDMP five year measurements in Bratislava during 1994 - 1998 could be detected also seasonal changes in \( \rho_{\nu I} \), \( \rho_{\nu E} \) and \( \rho_{\nu S} \) and \( \rho_{\nu W} \) with variations during winter snow cover, spring greenery or bare trees in winter with dark ground.

B. Sky type 3, ISO/CIE Overcast Sky with luminance gradation roughly 1:2 is characterized by \( L_{\nu I} / D_{\nu} \) in the range:

\[
L_{\nu I} / D_{\nu} = 0.361 \pm 2.5\% = 0.361 \pm 0.025
\]

with typical zenith luminance in \( \text{kcd/m}^2 \)

\[
L_{\nu I} = \left( D_{\nu} / E_{\nu} \right) \left( 48.3 \sin \gamma_3 \right)
\]

C. Sky type 5, ISO/CIE Overcast Sky with uniform gradation represents the simplest Lambert sky with unity luminance and with the \( L_{\nu I} / D_{\nu} \) characteristic range:

\[
L_{\nu I} / D_{\nu} = 0.318 \pm 2.5\% = 0.318 \pm 0.025
\]

and typical zenith luminance in \( \text{kcd/m}^2 \) will be:

\[
L_{\nu I} = \left( D_{\nu} / E_{\nu} \right) \left( 42.59 \sin \gamma_3 \right)
\]

Under all these three skies the modelled luminance patterns is independent on solar altitude and azimuth angles so these can be used for testing homogeneity of measured real skies. Then the difference in measured four vertical global illuminances should be also similar as well as the ratios \( D_{\nu I} / D_{\nu} \) which should be approximately under the unobstructed ISO/CIE sky type 1 \( D_{\nu I} / D_{\nu} \) = 0.39, under sky type 3 \( D_{\nu I} / D_{\nu} \) = 0.47 and under sky type 5 \( D_{\nu I} / D_{\nu} \) = 0.50.

The value \( D_{\nu I} / D_{\nu} \) is also called the Vertical Daylight Factor \( VDF \) which is used in some light flux methods after [10] divided into sky and ground reflected components as \( VDF = (D_{\nu I} + R_{\nu I}) / D_{\nu} \). It is also to be noted that this ratio corresponds to the \( C \) values in \% i.e. \( C = 100 \times D_{\nu I} / D_{\nu} \).

Similarly in [4] Vertical Sky Components \( VSC \) in \% were derived for the ISO/CIE standard sky types and types 1, 3 and 5 are constant for all scattering angles or solar altitudes under the unobstructed skies.

Even under overcast skies with relatively thinner cloud layers allowing slight brightening towards the sun position (as determined by ISO/CIE sky types 2 and 4) these can cause different illuminance on various vertical planes due to different scattering angle influences as noted also in [4]. It is evident that under these skies the ratio \( D_{\nu I} / D_{\nu} \) will rise in cases when the vertical plane faces the sun position. As the scattering angle on any sky element is dependent on its spherical distance from the momentary sun position, the sky luminance pattern is integrated with respect to the cosine of the incidence angle of each sky element within the half-space of the particular vertical plane. Such an integration is in fact included in the measured vertical illuminance if sunlight is absent. While in presence of sunlight the indicatrix influence is strongest around the solar corona its effects are small on the level of horizontal illuminance in the sun-rising hours under low solar altitudes. Contrary this the level of vertical illuminance is increasing markedly under sky types 2 and 4. Of course, this phenomenon is even more evident under all cloudy and clear sky conditions when the vertical plane is facing the momentary sun position. Such circumstances will occur clearly in the measured values of global vertical illuminance on differently oriented planes \( G_{V}^{m} \) and the exact diffuse component \( D_{\nu I} \).

Then \( D_{\nu I} / D_{\nu} \) is determined respecting all possible components (global, direct and reflected) after:

\[
D_{\nu I} = G_{V}^{m} - R_{\nu I} - R_{\nu I} \ldots \text{or...}
\]

\[
D_{\nu I} / D_{\nu} = G_{V}^{m} / D_{\nu} - R_{\nu I} / D_{\nu} - R_{\nu I} / D_{\nu}.
\]

As in the case of overcast skies the reflected component from the ground or downward space \( R_{\nu} \) is relatively small, thus it can be approximated easier. Considering the diffuse reflectance of the ground illuminated by the global horizontal illuminance \( G_{\nu} \) the reflected component can be:

\[
R_{\nu I} = G_{\nu} \rho_{\nu} / \pi
\]

where roughly \( \rho_{\nu} \) could be either derived form measurements under overcast sky conditions or approximated by its mean value 0.2 or an approximation of reflected component \( R_{\nu} = G_{\nu} / \Delta \rho_{\nu} \) with \( \rho_{\nu} = 0.1 \) can be applied with the so called “ground configuration” of a vertical window is \( \Delta \rho_{\nu} = 0.5 \) (which represents the projected solid angle on a vertical plane).

A computer program Skyfinder evaluating sky types from measured vertical illuminance

Skyfinder is the evaluating software written in C language which consists of two parts with various additional functions. The first part of the program imports raw dataset files containing data measured at the CIE IDMP station ICA SAS located in Bratislava, Slovakia. As a basic input, solar altitude \( \gamma_{2} \) is imported from the data file and solar azimuth \( \delta_{2} \) for a given date and time of measurement is calculated in as:

\[
A_{S, H \leq 12} = \arccos \left( \frac{\cos \delta} { \cos \gamma_{2} \cos \phi \cos \left( 15 \times H \right) } \right)
\]

while for hours \( H > 12 \) of True Solar Time is valid:

\[
A_{S, H > 12} = 360^0 - A_{S, H \leq 12}
\]
The vertical illuminance availability or their ratios to horizontal illuminance were sporadically analysed and published before e.g. in [11-13]. Now, more detail analysis was carried out documenting almost perfect overcast conditions identical with the CIE Overcast Sky [1] or ISO standard sky type 1 [2] from measurements taken in Bratislava during November 11th, 1995 already published in the book [6].

For the sake of comparison and analysis of these Bratislava measurements showing perfectly overcast day changes of $L_{vz}/D_v$ are shown in figure 1. The morning course is very frequent and stable with sky conditions very close to the CIE standard type 1, i.e. $L_{vz}/D_v \approx 0.41$ with the $D_v/E_v$ ratio in the range 0.08 -- 0.2 while the afternoon course is more variable.

It seems that the optimal conditions are under the solar altitude range 18° - 20° (between 9.30 and 10.00 a.m.). The test of dependence of vertical to horizontal diffuse illuminance on solar altitude has slight differences of $G^v_{vz}/D_v$ values with any dependence on the solar altitude. The lowest values were measured at the southern and western orientated sensor and the highest at the northern orientated sensor, figure 2. Both these figures document that illumination levels of sky patches were differed in azimuth directions and real sky conditions can cause various light exposition on vertical windows.

**Analysis of measured vertical illuminances from Bratislava dataset**

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When sky classification parameter $L_{vz}/D_v$ was analysed with associated vertical $G^v_{vz}/D_v$ there were found also small differences in sky type classification. Findings in table 1 confirm results presented in figure 2. The perfectly homogeneous overcast sky type 1 was identified at 9:36, when differences between measured and theoretical parameters were very close to zero. While the sky type 1 was identified in all parts of sky hemisphere using parametrisation of vertical illuminances, only six situations were classified to sky type 2 after the parameter $L_{vz}/D_v$. These cases document higher sensitivity of the $L_{vz}/D_v$ parameterisation to momentary luminance levels in the zenith. The highest classification differences between measured data and theoretical assumptions occur on the eastern and southern sensors.

Similar analysis of data measured on January 28th, 1996 was carried out. This day, the daylight conditions were classified to sky type 5 "Overcast, foggy or cloudy with overall uniformity" when classification parameter $L_{vz}/D_v$ was applied (table 2, column 2). The evaluation of measured and calculated vertical illuminances shows that also can occur azimuthally depended sky luminance distributions classified into several overcast sky categories.

For instance the western orientated sensor documents sky conditions associated with sky type 5, but on the northern side the sky type 3 and on the southern orientation the sky type 2 were dominant while the eastern part of hemisphere looks like the sky type 1.
Table 1 Sky classification after $L_{vz}/D_v$ and $G_{vz}^{m}/D_{vz}$ parameters. Bratislava, November 11, 1995, overcast day, type 1

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Conclusions

Predetermination of representative daylight conditions is crucial for correct design and evaluation of daylighting in buildings. The sky luminance distribution and sun radiation are basic sources of daylight. Their intensities are continually changing, but the reference/typical situations can be classified and applied in practice. The study of sky type classification after parameters $L_{vz}/D_v$ and $G_{vz}^{m}/D_{vz}$ results in the following guidance:
- the $L_{vz}/D_v$ parameter is expressing the simplest method for sky type classification and the overall effect of the sky
pattern on horizontal surfaces, but it requires sky instantaneous luminance measured values very sensitive to cloud changes in the zenith. However, this parameter cannot distinguish influences of various sky luminance distributions on those half hemispheres facing different cardinal points.

- the $c_{f/v}^m / D_{i/f}$ parameter allows to classify sky types in the cases when no sky luminance measurements are available. The azimuth effects of sky luminance distribution irregularities can be identified applying the method Skyfiner, which can study sky standard conditions on the half hemisphere in relation to vertical windows with different orientations. However, various directional sky patterns influence also daylight levels in interiors simulated by standard patterns valid only for particular orientation.

Further studies considering the non-homogeneous distribution of cloudiness and sky luminance distribution have to be elaborated to determine more real daylight conditions.

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**REFERENCES**


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