



International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

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TECHNICAL REPORT

CIE Standard General Sky Guide

CIE 215:2014

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Descriptor: Daylighting of interiors
Light from celestial bodies and the sky

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The International Commission on Illumination (CIE) is an organization devoted to international co-operation and exchange of information among its member countries on all matters relating to the art and science of lighting. Its membership consists of the National Committees in about 40 countries.

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Die Internationale Beleuchtungskommission (CIE) ist eine Organisation, die sich der internationalen Zusammenarbeit und dem Austausch von Informationen zwischen ihren Mitgliedsländern bezüglich der Kunst und Wissenschaft der Lichttechnik widmet. Die Mitgliedschaft besteht aus den Nationalen Komitees in rund 40 Ländern.

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3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
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5. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

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Alle vier Jahre findet eine Session statt, in der die Arbeiten der Divisionen berichtet und überprüft werden, sowie neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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This Technical Report has been prepared by CIE Technical Committee 3-51 of Division 3 "Interior Environment and Lighting Design" and has been approved by the Board of Administration as well as by Division 3 of the Commission Internationale de l'Eclairage. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory.

Ce rapport technique a été élaboré par le Comité Technique CIE 3-51 de la Division 3 "Environnement intérieur et étude de l'éclairage" et a été approuvé par le Bureau et Division 3 de la Commission Internationale de l'Eclairage. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tous les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire.

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CIE STANDARD GENERAL SKY GUIDE

Summary

This report collects information for the application of the CIE Standard General Sky for general users and designers. The guide provides an explanation of the CIE Standard General Sky concept, which is described in ISO 15469:2004/CIE S 011:2003, and of its simplified use by practitioners. The document includes an extensive list of references on the subject and gives recommendations for prediction methods, tools and computer programs.

GUIDE DU CIEL GÉNÉRAL NORMALISÉ CIE

Résumé

Ce rapport résume les informations sur l'utilisation du ciel général normalisé CIE pour les utilisateurs en général et les concepteurs. Le guide fournit une explication du concept du ciel général normalisé CIE, défini dans ISO 15469:2004/CIE S 011:2003, et de son utilisation simplifiée par les professionnels. Le document contient une liste détaillée de références sur le sujet et donne des recommandations sur les méthodes de prédiction, les outils et les programmes informatiques.

LEITFADEN FÜR DEN "CIE STANDARD GENERAL SKY"

Zusammenfassung

Dieser Bericht fasst Informationen zur Anwendung des "CIE Standard General Sky" für gewöhnliche Nutzer und Planer zusammen. Der Leitfaden stellt eine Erläuterung des Konzepts des "CIE Standard General Sky", welches in ISO 15469:2004/CIE S 011:2003 beschrieben wird, und dessen vereinfachte Anwendung durch Fachleute bereit. Das Dokument beinhaltet eine ausführliche Liste von Referenzen zum Thema und gibt Empfehlungen für Vorhersagemethoden, Hilfsmittel und Computerprogramme.

1 Introduction

The Joint ISO/CIE Standard ISO 15469:2004/CIE S 011/E:2003 “Spatial Distribution of Daylight – CIE Standard General Sky” (subsequently referred to as the “ISO/CIE Standard”) lists a set of sky luminance distributions for a wide range of atmospheric conditions. It provides a universal basis for the classification of measured sky luminance distributions and a method of calculating sky luminance distributions for daylight prediction and daylighting design procedures.

The purpose of this guide is to assist the user in the application of the ISO/CIE Standard in accordance with CIE recommendations for the application of Standard Sky Luminance Distributions (SSLD). It should be read as an adjunct to the ISO/CIE Standard because reference is made from time to time to formulae and diagrams to be found in that document.

Daylight design predictions and window system evaluations have traditionally been based on the worst-case winter weather conditions in Europe, namely the standard overcast sky, with relative values expressed as daylight factors on an interior working plane. However, this assumption ignores variable daylight conditions, especially in clear sky climates. It also fails to account for modern daylighting design approaches that seek to minimize glare and balance interior light distributions with electrical illumination.

The need and ability to predict and simulate skylight in different daylight climates, connected with energy conservation, solar energy use and air-conditioning of interiors, initiated regular one-minute measurements at the International Daylight Measurement Programme (IDMP) stations and introduced new criteria respecting the classification of sky luminance patterns (CIE, 1994). These activities in turn fostered the development of methods for expressing sun and sky luminance distributions in absolute units, a requirement for interior lighting design that integrates daylight with electric lighting design and lighting controls.

In the last decade, several advances and improvements have been achieved in:

- 1) the definition of luminance and illuminance characteristics of the sun and sky as primary radiation and light sources, with their standardization for world-wide application (e.g. definition of the standard solar constant and luminous solar constant, the CIE Standard General Sky, ratio parameterization etc.);
- 2) the regular recording of sun and skylight variations in daylight annual profiles in one-minute steps at many stations of the IDMP network, enabling the study and expression of long-term interrelations and the parameterization of their effects (e.g. in standard Daylight Reference Years);
- 3) the development of computer programs as professional tools for the simulation of building performance, including daylighting design, with simulations based on the CIE Standard General Sky and physically realistic radiative flux transfer algorithms.

These challenges continue to stimulate lighting research, and are forming an innovative chapter in daylight theory by introducing progressive methods, models, criteria, and simulation systems. To be useful to lighting designers and researchers alike, they need to be based on a common internationally-agreed and applicable system of daylight measurement and simulation respecting the ISO and CIE standards.

2 Scope

This Guide provides the following:

- 1) An explanation of the CIE Standard General Sky concept and its simplified use by general practitioners, together with an appropriate list of generally available references.
- 2) A recommended procedure for the classification and frequency analysis of skies usable for various design or energy use purposes, with a recommended procedure to derive absolute values from the values expressed in relative units of the ISO/CIE Standard, i.e. luminance in $\text{cd}\cdot\text{m}^{-2}$ and illuminance in lx, when necessary for supplementary electric lighting or any control purposes.

- 3) Examples of production of CIE sky type frequencies around the world as annual daylight profiles (Daylight Reference Years) using the application of all or several standard skies.
- 4) The possibilities to simulate sky luminance distributions in artificial sky facilities.

This Guide is intended to be used by both, users of sky models (for daylight estimation and lighting simulation purposes) as well as the developers of computer software that use the models to estimate the availability of daylight in their simulation models.

Users are those who

- 1) are interested in the range of sky luminance patterns that can be modelled by the SSLD models presented in the ISO/CIE Standard, and
- 2) must choose a particular model or series of models, for use in a computation of daylight availability or a lighting simulation to match their locale.

Developers are those who

- 1) are developing building simulation software systems that implement the SSLD model equations, and
- 2) must ensure that their implementations are correct.

For practical use additional computations are required, for example:

- 1) The sun position must be determined from the local latitude, longitude, date and time, using a suitable Equation of Time, and
- 2) the zenith luminance can be determined by local measurements or estimated in relation to known local diffuse horizontal illuminance.

3 Terms and Definitions

For the purposes of this document, the terms and definitions given in CIE S 017/E:2011, partly reproduced here, and the following apply.

3.1

CIE standard clear sky

cloudless sky for which the relative luminance distribution is as described in ISO 15469:2004/CIE S 011:2003 Spatial distribution of daylight – CIE standard general sky

[SOURCE: CIE S 017/E:2011 ILV, term 17-164]

3.2

CIE standard overcast sky

completely overcast sky for which the ratio of its luminance, L_γ , in the direction at an angle, γ , above the horizon to its luminance, L_z , at the zenith is given by the relation:

$$L_\gamma = \frac{L_z(1 + 2 \sin \gamma)}{3}$$

[SOURCE: CIE S 017/E:2011 ILV, term 17-169]

Note 1 to entry: This formula is used in ISO 15469:2004/CIE S 011:2003 for definition of the traditional CIE standard overcast sky, which is referred to as 'Sky Type 16',

Note 2 to entry: This is equivalent to the overcast Sky Type 1 in ISO 15469:2004/CIE S 011:2003, which is defined by an exponential function.

3.3

clear sky

cloudless sky

3.4

daylight

part of global solar radiation capable of causing a visual sensation

[SOURCE: CIE S 017/E:2011 ILV, term 17-278]

3.5**diffuse horizontal illuminance** (from the sky) E_{vd}

illuminance produced by skylight on a horizontal surface on the Earth

Unit: lx = lm·m⁻²

[SOURCE: CIE S 017/E:2011 ILV, term 17-302]

3.6**direct solar illuminance** E_{vs}

illuminance produced by direct sunlight on a horizontal surface on the Earth

Unit: lx = lm·m⁻²

[SOURCE: CIE S 017/E:2011 ILV, term 17-321]

3.7**global horizontal illuminance** E_{vg}

illuminance produced by daylight on a horizontal surface on the Earth

Unit: lx = lm·m⁻²

[SOURCE: CIE S 017/E:2011 ILV, term 17-495]

3.8**gradation function** $\phi(Z)$ function which describes the changes of the luminance along the sky meridian from horizon to zenith from horizon to zenith, where Z is the zenith angle of the sky element**3.9****homogeneous sky**

sky for which the luminance distribution is similar in kind, structure or composition throughout the whole sky vault

3.10**horizontal extraterrestrial illuminance** E_{voh} illuminance on a horizontal plane at the outside border of the atmosphere considering the local reduction due to the real solar altitude, γ_s , i.e. $E_{voh} = E_{vo} \sin \gamma_s$, where E_{vo} is the luminous solar constant**3.11****indicatrix function** $f(\chi)$

function which expresses the diffusion of sunbeams within the atmosphere dependent on the angular direction

3.12**luminous extinction coefficient** (of the atmosphere) a_v

measure that expresses the attenuation of the direct illuminance when the sun rays cross vertically the pure and dry atmosphere (Rayleigh atmosphere)

Unit: 1

[SOURCE: CIE S 017/E:2011 ILV, term 17-737, note omitted]

3.13**luminous solar constant** E_{vo}

illuminance produced by the extraterrestrial solar radiation on a surface at the outer border of the atmosphere perpendicular to the Sun's rays at mean Sun-Earth distance

Unit: lx = lm·m⁻²

[SOURCE: CIE S 017/E:2011 ILV, term 17-741, modified by adding the phrase “at the outer border of the atmosphere”]

3.14

luminous turbidity factor

T_v

ratio of the vertical optical thickness of a real turbid atmosphere to the vertical optical thickness of the pure and dry atmosphere (Rayleigh atmosphere), related to the visible part of the solar spectrum

Unit: 1

[SOURCE: CIE S 017/E:2011 ILV, term 17-743, note omitted]

3.15

overcast sky

sky completely covered with diffuse and dense cloud layers without direct sunlight

3.16

relative optical air mass

m

ratio of the optical thickness of the atmosphere at angle ε to the vertical, $\delta(\varepsilon)$, to the vertical optical thickness, $\delta(0^\circ)$, of the atmosphere

$$m = \frac{\delta(\varepsilon)}{\delta(0^\circ)}$$

Unit: 1

[SOURCE: CIE S 017/E:2011 ILV, term 17-1082, notes omitted]

3.17

sky luminance

L_v

luminance of a sky element

Unit: $\text{cd} \cdot \text{m}^{-2}$

[SOURCE: CIE S 017/E:2011 ILV, term 17-1193, note omitted]

3.18

sky luminance distribution

pattern of luminance on the sky vault

3.29

skylight

part of sky radiation capable of causing a visual sensation

[SOURCE: CIE S 017/E:2011 ILV, term 17-1194, definition 1]

3.20

sunlight

part of direct solar radiation capable of causing a visual sensation

[SOURCE: CIE S 017/E:2011 ILV, term 17-1281]

3.21

uniform sky

sky for which the luminance distribution is uniform over the whole sky hemisphere

[SOURCE: CIE S 017/E:2011 ILV, term 17-1371]

Note 1 to entry: This Lambertian luminance sky distribution is represented in ISO 15469:2004/CIE S 011:2003 by Sky Type 5.

3.22

zenith luminance

L_{vz}

luminance of the zenith sky element

4 Sky Standard Basis

The set of fifteen SSLDs defined by the ISO/CIE Standard covers the whole range of normally- and frequently-occurring typical sky patterns under quasi-homogeneous atmospheric conditions.

An SSLD is analytically defined at any point on the sky dome (a “sky element”) in relative rather than absolute terms (i.e. normalized to zenith luminance), assuming that

- 1) the resulting sky patterns are symmetrical about the solar meridian (i.e. the vertical plane of the momentary sun position);
- 2) the solar altitude and azimuth on any day and in true solar or local time per hour is known;
- 3) except for homogeneous turbidity or cloudiness, the uneven cloud types and distributions can be neglected;
- 4) sunshine with overcast sky types is completely absent; sunshine is present with clear skies, but real sunshine duration can be respected under dynamic, cloudy or partly cloudy skies which might occur either with or without sunshine;
- 5) SSLDs are not expressed in absolute units of the SI system (i.e. neither in $\text{kcd}\cdot\text{m}^{-2}$ nor in $\text{cd}\cdot\text{m}^{-2}$);
- 6) the ISO/CIE Standard does not state any parameter (such as $L_{\text{vz}}/E_{\text{vd}}$ and others as listed in 4.4) for the classification of sky scans or measured distributions related to the fifteen SSLDs.

The SSLD models are intended to represent a wide range of sky conditions based on two gradation parameters (a and b) and three indicatrix parameters (c , d and e). In its basic form, the model provides estimates for the relative luminance, normalized to a zenith luminance, at any point on the sky dome for a given sun position.

The relative sky luminance distribution equations and their parameters are documented in Clauses 4 and 5 of the ISO/CIE Standard. The equations are needed in order to implement the SSLD models in e.g. computer programs for building performance simulations. For the lighting designer who uses these programs however, a more intuitive description is needed in order to better understand their operation.

4.1 Average Sky Conditions

The SSLD models represent average sky conditions, i.e. they do not consider the effect of clouds except on an average basis taken over the entire sky dome.

The SSLD models further do not consider the perceived chromaticity (colour) or spectral power distribution of sky elements. There are physically-based mathematical models that have been developed for computer graphics applications, but this topic is beyond the scope of the ISO/CIE Standard. In practice, the sky colour varies with the sky element position, and also with atmospheric conditions.

4.2 The Standard General Sky and Previous Sky Standards

4.2.1 Uniform Sky

For an extended, uniform, diffusely radiating source irradiating a plane surface, the relationship between the luminance of the source, L , and the irradiance on the surface, E , is given by:

$$E = \pi L \Omega_0,$$

where

$$\Omega_0 = 1 \text{ sr.}$$

This same relationship can be applied for a uniform sky model; in other words, the outdoor illuminance on the horizontal plane, E_{vd} , from the whole diffusely radiating hemisphere representing the uniform sky, is given by the relationship:

$$E_{vd} = \pi L_{vz} \Omega_0 \quad \text{or} \quad L_{vz} = E_{vd} / (\pi \Omega_0) \quad (1)$$

where

L_{vz} is the zenith luminance.

It is often convenient to consider the zenith luminance in terms of its relationship to the normal extra-terrestrial illuminance, E_{vo} . In this case a standardizing parameter, B , can be introduced such that, for the uniform sky condition:

$$L_{vz} = \frac{B \cdot E_{vd}}{E_{vo}} \quad (2)$$

where

E_{vo} is the luminous solar constant, i.e. normal extra-terrestrial illuminance $E_{vo} = 133,8 \text{ klx}$ (CIE 1994),

B is, for the case of the uniform sky, determined according to Eq. 3 below and expressed in $\text{kcd} \cdot \text{m}^{-2}$:

$$B = \frac{133,8 \text{ klx}}{\pi \Omega_0} = 42,59 \text{ kcd} \cdot \text{m}^{-2} \quad (3)$$

Under the CIE Standard General Sky model, the uniform sky condition is represented by CIE Sky Type 5 (gradation group III, indicatrix group 1)¹, with the unity gradation function and unity relative indicatrix function. Using this model and the parameters for Sky Type 5 (III.1) listed in Annex C, Table C.1, the general formula for calculating absolute zenith luminance given in 4.7 (Eq. 7) is identical to the relationship 2 above, with B for this uniform sky condition having the value given in Eq. 3.

4.2.2 Overcast Skies

Sky Types 3 (II.1) and 1 (I.1) representing overcast skies are characterized by a steeper luminance rise from horizon to zenith while azimuthal evenness is stable. Such luminance gradations are specific for very densely overcast skies in Europe as measured first by Kähler (1908) and under snow cover by Petherbridge (1955). Later Moon and Spencer (1942) introduced the CIE standard overcast sky with vertically gradual luminous distribution, the so-called Moon-Spencer sky.

The previous overcast standard sky used only the gradation function expressed by a sine or cosine approximation specified in Clause 6 and in Equation (9) of the ISO/CIE Standard which was adopted from CIE (1955). This is now replaced by the exponential approximation in the gradation type one for Sky Type 1 (I.1).

4.2.3 Clear Skies

The exponential gradation function is compatible with the two previous clear standard skies adopted by CIE (1973). In the present ISO/CIE Standard the previous two clear standard skies are represented by Sky Types 12 (V.4) and 13 (V.5) with the indicatrix function as introduced in CIE (1973).

¹ In the following standard sky types according to ISO 15469:2004/CIE S 011/E:2003 will be referred to as "Sky Type" followed by their number and, if appropriate, by the associated gradation group and indicatrix group in brackets, e.g. "Sky Type 5 (III.1)".

4.3 Current Daylight Modelling Practices

4.3.1 The Daylight Factor

The daylight factor method is still the most commonly used approach to determine a quantitative measure of daylight in buildings. The daylight factor approach is of course founded on the CIE standard overcast sky. The limitations of the daylight factor are manifest. Nevertheless it persists as the dominant approach largely because of its familiarity and simplicity rather than as a reliable measure of daylight provision. A critical review of the daylight factor use was published by Mardaljevic (2006).

It is possible to convert a daylight factor value (i.e. a relative measure of illumination under a static sky condition) into an estimation of the annual provision of daylight using cumulative diffuse illuminance availability curves. Applying a simple technique, cumulative internal illuminance availability can be calculated from daylight factor values and charts of cumulative diffuse sky illuminance (Hunt, 1979). This gives a first order approximation to annual daylighting provision from which supplementary lighting requirements can be estimated.

For example, suppose that the minimum required internal illuminance, E_i , at a point in an office is 500 lx, and that an evaluation using the CIE standard overcast sky (equation, scale-model or simulation) predicts a daylight factor value of $D = 3,3 \%$. Then the minimum diffuse horizontal illuminance, E_{vd} , which provides an internal illuminance of 500 lx, is:

$$E_{vd} = \frac{E_i}{D} = \frac{500 \text{ lx}}{0,033} \approx 15\,000 \text{ lx} \quad (4)$$

Figure 1 shows that a diffuse sky illuminance of 15 000 lx is exceeded during about 55 % of the normal working time in Kew, United Kingdom (UK).

The CIE standard overcast sky is likely to be a reasonable approximation to some of the duller skies in the cumulative distribution. However, only about 40 % of the skies in the Kew Test Reference Year (TRY) (see also 6.6) for the UK can be considered as heavily overcast (Mardaljevic, 2000). For locales sunnier than the UK, the percentage of overcast skies throughout the year will of course be lower.

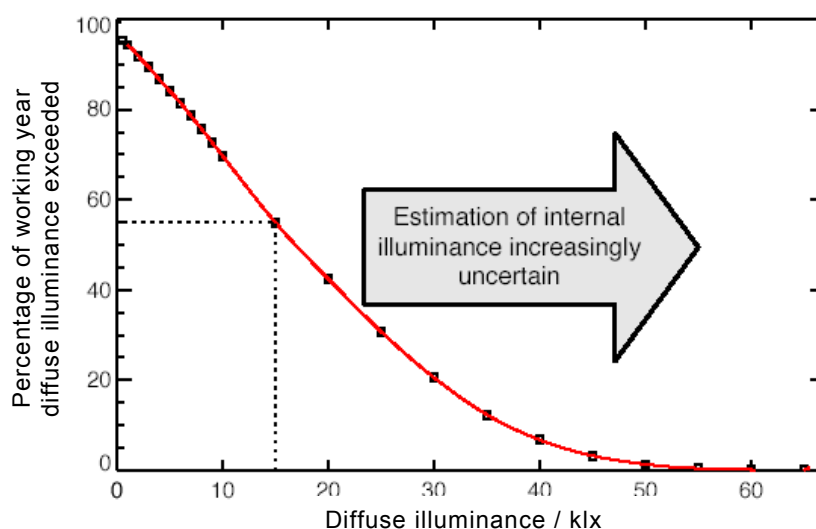


Figure 1 — Cumulative diffuse illuminance availability, Kew, UK

The principal weakness of this approach is that it tries to extend the daylight factor modelling paradigm (i.e. relative illumination under standard overcast sky conditions) to include non-overcast skies. Since real non-overcast skies diverge enormously from overcast sky

luminance patterns, the estimations of illuminance from the non-overcast skies in the distribution will be greatly in error. Additionally, the method cannot of course account for the illuminance contribution of the sun – either directly or from reflection. Thus the divergence between estimation and reality increases as higher illuminances in the cumulative distribution are considered (Figure 1). Needless to say, this approach is highly inappropriate for building designs where the redistribution of direct beam radiation to provide diffuse illuminance is a significant feature of the daylighting system.

Despite the limitations, the cumulative illumination approach must be considered to be an advance on the daylight factor alone because the results, however flawed, do at least depend on absolute measures of the climate for the locale. In other words, the results for St. Petersburg will be different to those for Cairo. The effect of building orientation on internal illuminance (i.e. the difference between North and South facing glazing) can be roughly estimated by applying so-called orientation factors (BRE, 1985).

Even though cumulative diffuse illuminance availability can be readily derived from standard climate files (Mardaljevic, 2000), it should be noted that this is rarely carried out in practice. Thus, for most practitioners, quantitative daylight evaluation begins and ends with the daylight factor – little attempt is made to determine absolute values for illuminance. Based on anecdotal evidence, this is largely due to ready acceptance by practitioners of the daylight factor alone as an indicator of illuminance rather than an appreciation of the limitations of the cumulative approach.

4.3.2 Use of Selected Non-Overcast Skies

The research literature contains examples of studies where daylight evaluation under non-overcast skies has been described (BRE, 1985). These are invariably “snapshot” studies for particular times of the day/year, e.g. the summer solstice. For example, clear sky conditions with sun are selected from the simulation program options, and point illuminance values and/or images are generated for various times of the selected day. Whilst these studies do attempt to predict daylight levels under non-overcast conditions, the generated results are inevitably a very small sample of the possibly occurring conditions. As such, the findings must be considered incomplete. They may even be highly misleading if the user relies on the simulation program alone to generate absolute values for the sun and sky conditions (e.g. diffuse horizontal illuminance and direct normal illuminance) rather than basing them on actually occurring values from a suitable climate file. This is because the simulation program is likely to use a simple latitude dependant algorithm to generate absolute values (when not supplied by the user) – the generated values may be greater than any which can be derived from a climate file for that locale. Regardless of the plausibility, or otherwise, of the sky and sun conditions selected, a “snapshot” study considers only a very small number of possible climatic conditions – all the other possible conditions are ignored. This type of evaluation attempts to go beyond the confines of one founded on a single overcast sky (i.e. the daylight factor). However, it offers a handful of solutions for daylight illumination from all of those that can occur.

The parameters governing the availability of daylight do not lend themselves to any form of averaging. Whilst it can be informative to determine, say, a monthly average for a scalar quantity such as temperature, illumination is strongly dependant on the directional character of the incident light. Illumination parameters are generally not suited to manipulations such as averaging.

Rather than simple selection, partial-sampling of the meteorological dataset (e.g. taking only the first or 15th day of each month) is sometimes employed. This action however will inevitably introduce biases because equally valid – but most likely quite different sky and sun conditions/positions – would be excluded.

4.4 Need for New Standardized Universal Sky Models

For climate-based daylight modelling, the purpose of the sky model is to reproduce the pattern of luminance on the sky vault that prevailed during the time of measurement for each unique data entry in the climate file, e.g. for every hour or less.

The greatest uncertainty in the modelling process is perhaps in the selection of a suitable sky model description at each time-step of the simulation. Recall that the relevant data supplied in the climate file are usually direct normal and diffuse horizontal irradiance and/or illuminance. Direct normal will need to be derived if the supplied values are global and diffuse. From these values, together with solar position determined from the time-stamp, the prevailing sky luminance conditions – and thus the most appropriate sky model type – must be inferred.

Further discussion of how to select the most appropriate sky model is provided in 4.5 of this guide. It is clear, however, that the range of sky models that can be represented by the ISO/CIE sky standard is far greater than could be represented by the previously limited set of standard skies.

5 Fundamental Concept

The world-wide standardization of skies is based on an assumption that under the same atmospheric conditions the same distribution of sky luminance will occur in any location. This assumption is valid especially for homogeneous situations which represent overcast as well as cloudless skies with various turbidities. Penetration of light through the atmosphere is influenced by its momentary absorbing and scattering properties which can be specified by the gradation and indicatrix function.

5.1 Gradation and Indicatrix Functions

5.1.1 Sky Luminance Gradation

Each SSLD model assumes that the sky dome has a luminance gradation component that varies with the altitude of the sky element. This luminance gradation is therefore symmetric about the sky meridians. There are six gradation groups, labelled I through VI. The gradation is due to direct sunlight that is diffusely scattered by air molecules and suspended particulates, and reflected by moisture vapour and clouds. The gradation is mathematically described by the gradation function, formula (5) in the ISO/CIE Standard, and documented in Table A.1 in Annex A.

5.1.2 Scattering Indicatrix

Each SSLD model further assumes that direct sunlight is scattered by air molecules and suspended particulates to form a luminance distribution that is symmetric about the solar position. There are six indicatrix groups, labelled 1 through 6. The scattering of sunlight in the atmosphere is mathematically described by the indicatrix function - see Equation (7) in ISO/CIE Standard and Table A.1 in Annex A.

5.2 Relative Standard Sky Luminance Distributions

The standard skies are described in the ISO/CIE Standard based on the SSLD model. The specification of the relative sky luminance of every standard sky is described in Clause 4 of the ISO/CIE Standard, i.e. normalized to unity zenith luminance.

Figure 2 demonstrates a series of measured and photographed real sky luminance distributions. These are compared with each of the 15 types of SSLD, illustrating the full range of occurring sky conditions that are modelled by the ISO/CIE standard skies.

5.3 Overview of Standard Sky Luminance Distributions

Figure 2 shows examples of luminance distributions and photographs for each of the SSLD models. The first column shows the relative luminance distributions on the solar meridian. The corresponding relative luminance distributions in equidistant projection are plotted in the second column. Every case corresponds to the situation taken on the fish-eye photos in the third column. These photos are of real skies fitting each of the different sky types, for sun positions that match the preceding relative distributions. Pictures of Sky Types 1 to 14 were taken at the Ecole Nationale des Travaux Publics de l'Etat in Vaulx-en-Velin near Lyon, France, geographical latitude $\varphi = 45^\circ 47' \text{ N}$ and geographical longitude $\lambda_{10} = 4^\circ 56' \text{ E}$ (luminance distribution diagrams were made by the program SkyModeller (see 6.2) and fisheye images were supplied by Dumortier and Kobav), while Sky Type 15 at the University

of Santa Catarina in Florianópolis, Brazil, $\varphi = 27^\circ 32' \text{ S}$ and $\lambda_{10} = 48^\circ 43'$ (Scarazzato and Souza, 2011).

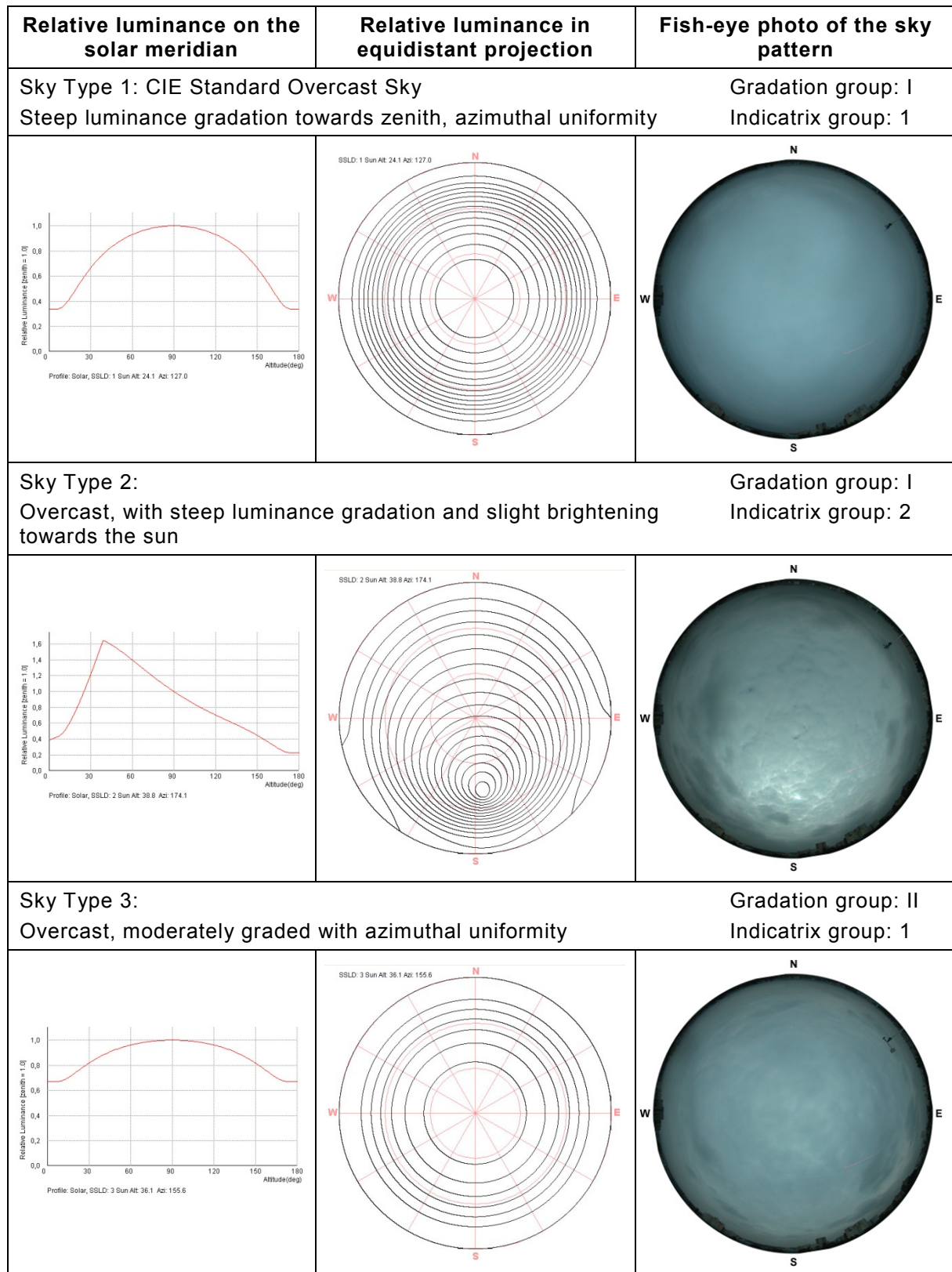


Figure 2 — Luminance Distributions for SSLD Models

Relative luminance on the solar meridian	Relative luminance in equidistant projection	Fish-eye photo of the sky pattern
Sky Type 4: Overcast, moderately graded and slight brightening towards the sun		
		Gradation group: II Indicatrix group: 2
Profile: Solar, SSLD: 4 Sun Alt: 39.0 Azi: -179.5	SSLD: 4 Sun Alt: 39.0 Azi: -179.5	
Sky Type 5: Sky of uniform luminance		
		Gradation group: III Indicatrix group: 1
Profile: Solar, SSLD: 5 Sun Alt: 32.6 Azi: 144.3	SSLD: 5 Sun Alt: 32.6 Azi: 144.3	
Sky Type 6: Partly cloudy sky, no gradation towards zenith, slight brightening towards the sun		
		Gradation group: III Indicatrix group: 2
Profile: Solar, SSLD: 6 Sun Alt: 49.8 Azi: 177.0	SSLD: 6 Sun Alt: 49.8 Azi: 177.0	

Figure 2 — (Continued)

Relative luminance on the solar meridian	Relative luminance in equidistant projection	Fish-eye photo of the sky pattern
Sky Type 7: Partly cloudy sky, no gradation towards zenith, brighter circumsolar region		
Gradation group: III Indicatrix group: 3		
Sky Type 8: Partly cloudy sky, no gradation towards zenith, distinct solar corona		
Gradation group: III Indicatrix group: 4		
Sky Type 9: Partly cloudy sky, with the obscured sun		
Gradation group: IV Indicatrix group: 2		

Figure 2 — (Continued)

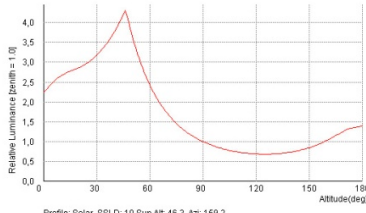
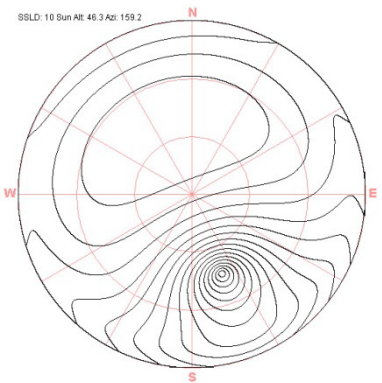
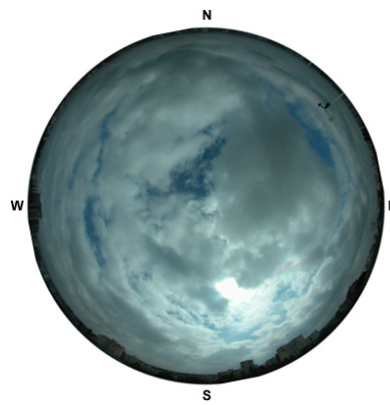
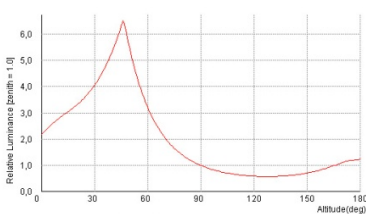
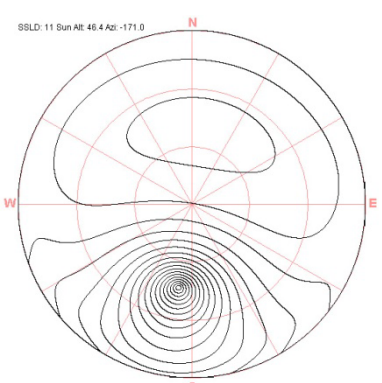
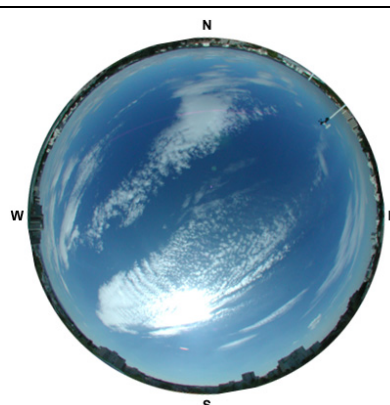
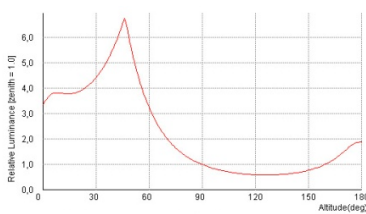
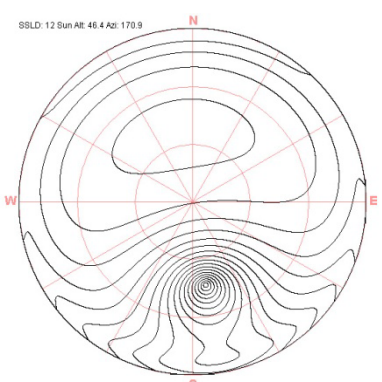
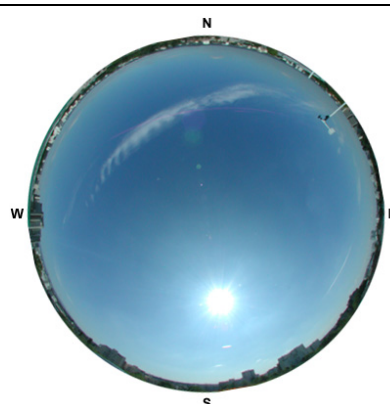
Relative luminance on the solar meridian	Relative luminance in equidistant projection	Fish-eye photo of the sky pattern
Sky Type 10: Partly cloudy, with brighter circumsolar region		
		Gradation group: IV Indicatrix group: 3
		
Sky Type 11: White-blue sky with distinct solar corona		
		Gradation group: IV Indicatrix group: 4
		
Sky Type 12: CIE Standard Clear Sky, low luminous turbidity		
		Gradation group: V Indicatrix group: 4
		

Figure 2 — (Continued)

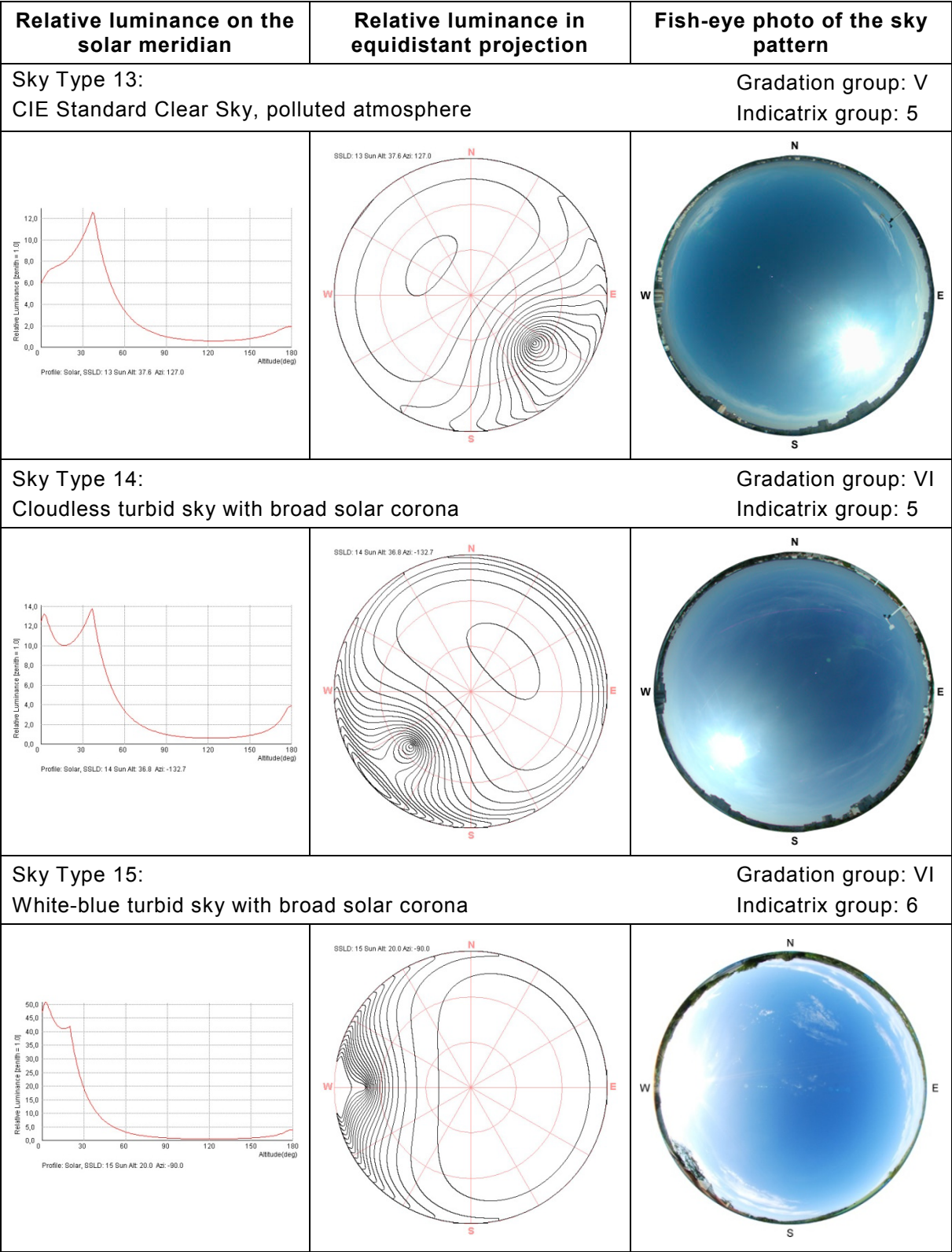


Figure 2 — (Continued)

5.4 Parameterization

For some practical and research tasks the global horizontal illuminance, E_{vg} , and the diffuse horizontal illuminance, E_{vd} , or the direct solar illuminance, E_{vs} , as well as the zenith luminance, L_{vz} , are required or measured. However, if these absolute values are measured or available then parameterization is used to identify:

- CIE sky types according to the classification parameter L_{vz}/E_{vd} as shown in Figures 3 and 4;
- proportional components of the horizontal extraterrestrial illuminance, E_{voh} , in ratios E_{vd}/E_{voh} , E_{vs}/E_{voh} or their summation $E_{vg}/E_{voh} = E_{vd}/E_{voh} + E_{vs}/E_{voh}$;
- the luminous turbidity factor, T_v , in direction of sunbeams as determined according to the respective Equation in Table A.1.

5.5 Selection of Sky Model and Sky Classification

The ISO/CIE Standard was published in 2004. Few computer programs already used the Perez ASRC sky model (Perez et al., 1990, 1992) at that time, which does not correspond correctly with the SSLD model, the basis for the ISO/CIE Standard. In fact the Perez ASRC sky model is using an interpolation between overcast, intermediate, cloudless clear and turbid sky. The “solutions” to this problem that have been employed thus far fall into two categories:

- the automatic solution provided by the Perez All-Weather model (Perez et al., 1993),
- a bespoke solution using selections and/or blends of a small subset of the CIE Standard General Sky and/or other types.

The Perez All-Weather model was designed to automatically select and generate the most suitable sky type from only those parameters found in annual climate datasets typically used for dynamic thermal modelling (e.g. those available in simulation programs like ‘EnergyPlus’ (<http://apps1.eere.energy.gov/buildings/energyplus>) or ‘Radiance’ (radsite.lbl.gov/radiance)). Thus the problem of selection is dealt with by the sky model itself. This is undeniably an attractive feature of the Perez All-Weather model. However, validation tests comparing model sky luminance patterns against those measured with a sky scanner have shown that the Perez formulation may not be suitable for all climates (Littlefair, 1994). This may be because the coefficients for the Perez model were derived from measured data collected at one locale (Berkeley, California, USA). Therefore this model does not contain either the uniform Lambert sky (Sky Type 5) or CIE Overcast Sky with dark and snow covered ground (Sky Types 1 and 2). Indeed, a major part of the rationale behind the creation of the CIE Standard General Sky was to have a schema that could apply to all locales world-wide.

What is not yet clear however is how to select the most suitable sky type and/or blend on a time-step basis from the data contained in climate files. In the modelling chain which begins with basic climatic data and results in the prediction of absolute illuminance values, this is perhaps the “weakest link”. Thus, in the absence of any generalized scheme for using the CIE Standard General Sky, the application examples that follow bespoke sky model blends to generate luminance patterns from the basic data contained in climate files. Evidently, sky model usage for climate-based daylight simulation needs to be further developed in this area. Nevertheless, valuable performance evaluation data can be generated through daylight simulation using proven, relatively simple sky model blends, and this situation will further improve once additional locale-specific formulations for the CIE Standard General Sky have been devised and validated. Tregenza (1999) found that five sky types account for nearly 80 % of the scanned data sets; some types are rarely applicable or not used at all. Using measured data in Hong Kong, Ng et al. (2007a) found that a simplified set of three sky types can reasonably represent the sub-tropical skies of Hong Kong. This suggests that the daylight climate could be characterized by a small subset of standard types without significant loss of accuracy.

In keeping with the tenor of the above, detailed descriptions of the bespoke sky model blends used are not provided in the application examples that follow. Rather, the purpose of the

examples is to encourage the wider consideration of climate in daylighting analyzes since that is surely the logical end-use for the CIE Standard General Sky.

Several methods for CIE sky type determination were developed and published. Their procedures are based on the:

- L_{vz}/E_{vd} ratio and 2,5 % strip of significance,
- gradation and indicatrix function measurements,
- luminance scan element statistics,
- normalized luminance distribution,
- measured vertical diffuse illuminance,
- factor or cluster analysis of scan data,
- neural network techniques,
- CCD images.

5.6 Sky Classification Parameter L_{vz}/E_{vd} Ratio

For identification and selection of the SSLD the most important is the parameter L_{vz}/E_{vd} which is characteristic for every single standard in the set and is dependent on solar altitude as shown in Figure 3 (Darula et al., 2006). To derive the L_{vz}/E_{vd} ratio for each SSLD the denominator E_{vd} was calculated by integrating the standardized gradation and indicatrix functions, resulting in the L_{vz}/E_{vd} solid curves as shown in Figures 3 and 4, according to the following formula:

$$L_{vz} / E_{vd} = \frac{f(Z_s) \varphi(0^\circ)}{\int_{Z=0^\circ}^{90^\circ} \int_{\alpha=0^\circ}^{360^\circ} f(\chi) \varphi(Z) \sin Z \cos Z d\alpha dZ} \quad (5)$$

This integration is valid for any solar altitude γ_s (as in Figure 3), but if the solar altitude is below 70° (as shown in Figure 4), an empirical formula (6) is also applicable (Kittler et al., 1998b):

$$L_{vz} / E_{vd} = \frac{1}{133,8 \text{ klx}} \left[\frac{B (\sin \gamma_s)^C}{(\sin \gamma_s) (\cos \gamma_s)^D} + E \right] \quad (6)$$

Recommended parameters B , C , D and E are shown in Table C.1 in Annex C, and the results are indicated in Figure 4 by crosses.¹

Note, that this empirical formula is valid only for locales in geographical latitudes over $38,5^\circ$ N or $38,5^\circ$ S, i.e.:

- North of the line connecting cities Sacramento – Colorado Springs – Kansas – St. Louis – Washington D.C. – Lisabon – Ibiza Island – North of Sicily – Athens – Izmir – North of Iran – Ashgabad – Dushanbe – North of Tibet – Beijing – Pyongyang – North of Japan on the Northern Hemisphere,
- South of the line between cities Bahia Blanca in Argentina – Temuco in Chile and Tasmania in Australia as well as South of Lake Taupo in New Zealand on the Southern Hemisphere.

¹ Note that for the uniform sky (Sky Type 5) the parameters are such that Eq. (6) can be converted to Eq. (2) – see 4.2.1.