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A NEW GENERATION OF SKY STANDARDS

Neue Generation der Himmelsstandarden

Une Nouvelle Génération de Standards pour la Luminance de la Voute Céleste

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SUMMARY

Sky luminance distributions sets containing more than hundered selected cases scanned in Berkeley, CA, Tokyo and Sydney were analysed, tested and compared. New analysis methods for deriving the scattering indicatrix and sky gradation functions were applied. The influence of solar altitude, turbidity, luminance and illuminance parameters as well as typical most frequent daylight conditions were specified and their functional relations modelled. On such base a new generation of sky standards was defined forming a model sky set applicable in various aspects of energy conscious window design, for daylight calculation methods and computer programs as well as for visual comfort and glare evaluations.

SOMMAIRE

Nous avons analysé, testé et comparé plus d´une centaine de mesures de luminance de la voute céleste enregistrées a Berkeley, Tokyo et Sydney, et y avons appliqué de nouvelles methodes de dérivation de l´indicatrice de diffusion et de la fonction de gradation. Ces méthodes prennent en compte

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l´influence de la hauteur du soleil, du trouble atmosphérique, de l´illuminance diffuse et de la luminance au zenith, ainsi que de la fréquence d´occurence des conditions d´ensoleillement. Sur cette base, nous avons préparé de nouveaux standards de luminance de la voute céleste, directement applicables aux calculs d´éclairage naturel, a l´optimization du comfort visuel et des systemes de fenestration.

ZUSAMMENFASSUNG

Ein Satz der Leuchtdichteverteilung von Himmel, der analysiert, testiert und vergleicht wurde, enthält mehr als ein hundert Fälle, die in Berkeley, CA, Tokyo und Sydney „scanniert“ waren. Neue Methoden der Analysen für die Leuchtdichteindikatrix und die Gradationsfunktionen wurden appliziert. Der Einfluß solcher Parameter wie Sonnenhöhe, Trübung, Leuchtdichte und Beleuchtungsstärke bei typischen am meisten vorkomenden Bedingungen des Tageslichts war spezifiziert und ihre Funktionsbeziehungen waren modelliert. Eine neue Generation der Himmelsstandarden war definiert, die das Modell des Himmelssatzes bildet, das für den Energieentwurf der Fenster nach verchiedenen Gesichtspunkten, die Berechnung des Tageslichts in den Computersprogrammen und auch für den Sehkomfort und die Bewertung der Blendung verwendet wird.

WHY ARE SKY STANDARDS NECESSARY

In building investment procedures and architectural design practice the daylight predictions and calculations are the basic prerequisites to predetermine the design consequences or to create an agreeable visual environment in interiors. Due to this aim during the first stages of the design process a series of decisions has to be made oriented towards the evaluation of the best alternative solution. If alternative designs or already realised solutions (i.e. daylight systems) have to be compared, equivalent exterior conditions have to be assumed or standardised. Even more strict is this requirement in judicable cases and for hygienic checks where a precise norm and comparability is essential for the verdict as basic rules and standards are expressing the physiologic and ergonomic needs of man influencing his health and visual performance on a certain level of civilisation.

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Comparative conditions for daylight predictions were established in various international or national standards (e.g. ISO-CIE standards, German DIN or STN-Slovak Technology Norms) and codes of practice by professional organisations (e.g. IESNA recommendations in U.S.A or CIBSE codes in U.K.). In the current daylight theory, calculation methods, and graphical design means/protractors, the sky as a large area source was already standardised by its relative luminance either of uniform unity value over the whole sky hemisphere or by its gradation 1:1/3 (zenith:horizon) expected under an overcast sky. Such simple standard skies have been used for window/skylight designing purposes and comparisons world-wide although these do not correspond somewhere with frequent real conditions. Nowadays, due to new requirements these standards are not sufficient for the comparison of visual environments/comfort, glare or energy performance/trade-off as a constant steady state does not represent the reality and actual daily or seasonal daylight changes. The dynamic variations of insolation conditions due to moving solar position, cloudiness or atmospheric turbidity together with changing sky luminance patterns vary in daytime periods as well as in various climates. The problem is even more complicated by the fact that windows in vertical house fronts and skylights on roofs are arbitrarily oriented, sloped and obstructed/shaded, thus exposed to sky and sun effects directionally at varying inclination/solid angles respectively.

However, although exterior conditions seem to be varied in the same patterns world-wide, in different climate zones and due to various evaluation purposes several sky states have to be chosen and recommended as critical. For the detail allocation of a particular standard to a certain evaluation aim are needed further local long-term data information as well as further studies of purpose-orientated critical situations. Anyhow, a preliminary set of standard skies covering a wide occurrence range would mean a considerable step forward in the trial of modelling unsteady daylight conditions. At the same time with the sky standardisation in relative luminance terms has to be determined also the relative definition of sunlight (i.e. direct solar illuminance under various turbidity and cloudiness conditions) with the possibility of linking relative and absolute values.

Keeping in mind this vast field of necessary future research imposed by practical needs of an energy-efficient and visually friendly building design, the following particular problems are treated within this report:

- with the aim to define the basic modelling capabilities of simulating the scattering and gradation influences in typical sky states, reliable and complex sky scan and complimentary data were gathered and analysed,
- a world-wide comparability and mutual proportion of sunlight and skylight under the same turbidity conditions were tested,
- a trial to detect basic parameters characterising sky luminance patterns and skylight illuminance levels under various solar position and relative beam presence was made,

- to find out the significance/importance of different sky types, their range and frequency of occurrence in relation to insolation conditions, seasonal or weather changes were analysed and sorted out the regularly recorded minute data in a long period of four years,
- general and abstractly modelled sky standards derived from ideal scan measured cases were formed by the combination of characteristic exponential gradation and indicatrix functions,
- the basic set of sky standards should incorporate the current already used standards and should be capable to represent a continuos spectrum/range of sky patterns linking the overcast and clear skies.

Two research projects sponsored by the European Union have recently studied European exterior daylight conditions. One suggested the possibility to predict the availability of daylight in relation to average monthly sunshine duration in the European Daylighting Atlas (EDA). The other, currently in progress SATELLIGHT project would like to give daylight data for any particular site in Europe on a WWW server based on the processing of Meteosat data.
In contrast and in complement to these efforst abstract and relevant sky standards with additional information and occurrence frequency data, a world-wide simulation of long-term averages can be recommended. These can enable cross-checks and comparison studies of the life-span energy-efficiency of buildings or their various design alternatives. Due to the current computer capabilities the extreme simplification of sky luminance distribution is not any more necessary because illuminance calculations can be use very precise summation or integration procedures within any solid angle of arbitrary apertures even though mathematically complex modelling is inevitable. So, the most complicated analysis and computer programs as well as research solutions and tests can be left „behind the scene“, the practical results and guidelines can be disseminated in quite simple terms.

SKY STANDARDISATION CONCEPT

In the history of daylight theory the prime aim to standardise sky patterns was either the theoretical need for a simple luminance characterisation of the sky as a large area source for calculation methods or the practical need of window design followed by its measurement check of the daylight level in real interiors. Due to the former aim the oldest and simplest sky standard was a sky of unity luminance with a constant uniformity on the whole sky vault (i.e.

with a constant unity gradation and indicatrix functions), while the latter need influenced by the frequent minimum overcast conditions in Europe introduced the gradation 1:0.33 as critical.
Thus defining a new generation of sky standards it must not be forgotten to incorporate into the new set also the most abstract unity sky on which the whole knowledge of theoretical photometry is still based. Since Lambert´s Photometria was published in 1760 [1] all photometric calculation methods were derived from his principles given:
- in par.97, i.e. „in an arbitrary case the illuminance is dependent on: 1. the angle of incidence, 2. the solid angle of the light source, 3. its luminance",
- in par. 166, i.e. „all calculation methods are based on the assumption that the surface of the light source is of uniform (same) luminance... If this is not the case it has to be specified how the luminance is changing and the influence of every element has to be multiplied by its luminance and then using the integration throughout the whole surface or its part the resulting illuminance is calculated".

Of course, Lambert could not have guessed that it would take more than 235 years until the CIE Overcast Sky became a standard [2] with a simple cosine gradation and another twenty years to standardise the CIE Clear Sky [3] with the exponentially determined gradation and indicatrix functions. Only the further development of sky scanners, establishment of first regular daylight measurement stations [4] as well as new methods of analysing the measured data and sky scans [5,6] enabled recently a more detailed study of different sky types [7]. The resulting conclusions and current daylighting design needs for standard skies have initiated the development and draft of a new generation of sky standards.

Although the uniform unity luminance of the sky hemisphere was considered a basic prerequisite assumption of all daylight calculations a long time ago no proof was given whether it is only an abstract constant or also a real existing case. After analysing the bright overcast skies it is evident that there are unique situations of ideal uniform and absolute scattering especially in fog (quite often in inversion sites and periods) when the gradation and indicatrix influences are reduced to minimum and can be taken as constant. Furthermore this unity sky stands for an ideal mean sky linking the decreasing gradation tendency of overcast and the increasing gradation of clear skies respectively.
The gradation and indicatrix analysis have fully justified the current CIE standards for the overcast as well as the clear skies although these seem to be rather extremes of homogeneous atmospheric conditions than averages. Furthermore the whole spectrum of gradation and indicatrix changes fully justifies also their exponential modelling now which means a convenient unification and logical regularity in sky „behaviour". This fact presumes that

the cosine expression of the CIE Overcast Standard is to be substituted by a more suitable exponential expression which should be a best fit for the 1:0.33 gradation. In this respect two possible substitutes were found and documented [8,9].

Although there are some arguments against the CIE Overcast Sky Standard reasoning that such conditions are infrequent or even absent in tropical or arctic climate, its world-wide use for window design and comparisonal studies of daylighting systems is universally accepted. But its priority stems from the fact that overcast skies are the most frequent prevailingly occurring types in temperate regions and also everywhere during rainy seasons when even more extreme gradations can occur. It has to be noted here that gradations around 1:0.2 were found quite typical but due to the practical need to reduce the draft standards to a quite reasonable number this gradation of a very dark overcast sky was left out. However, if in some regions (monsoon or maritime west coast very rainy climates) would prove the dark thunderstorm dense overcast sky as very important or in some seasons frequent, such an extreme gradation could be

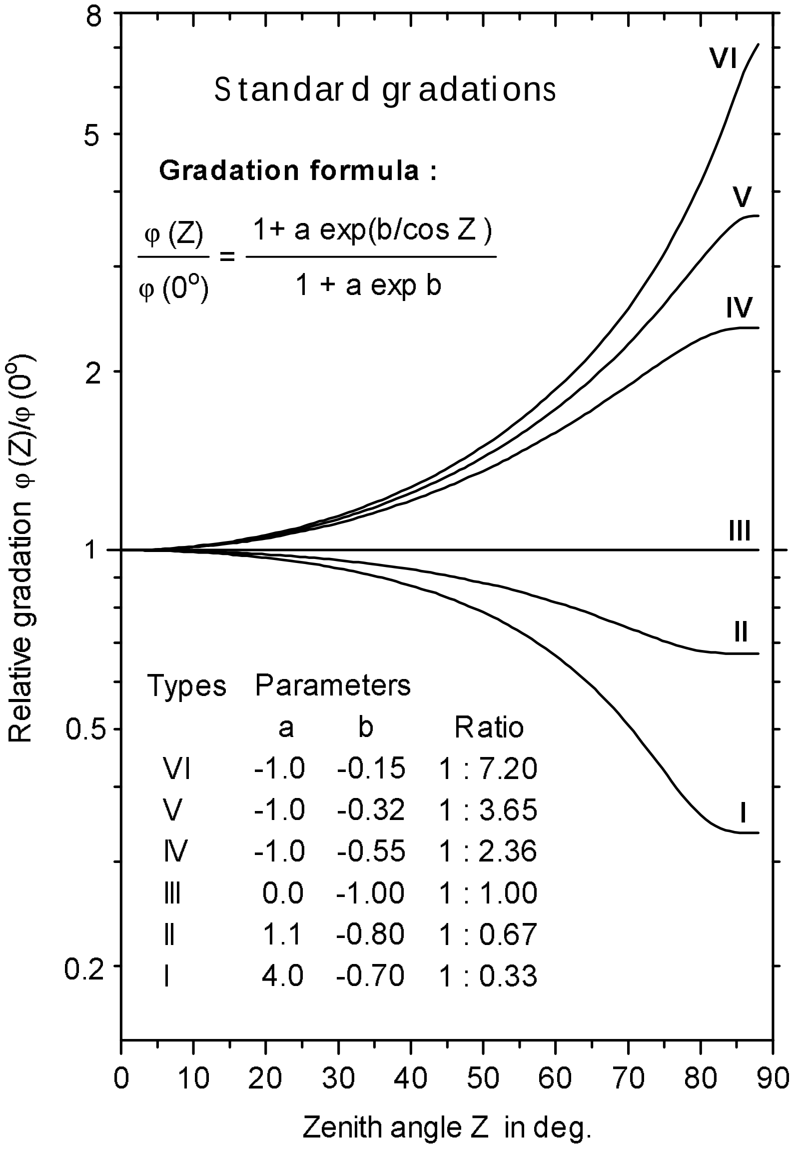

Figure 1 Representation of six standard gradations by applying standard parameters a and b in the general gradation formula

taken an additional standard too.

Under homogeneous conditions six main standard gradations and corresponding spreading regions can be chosen as represented in Fig. 1 and 2. These were numbered by Roman numerals I to VI, and can be determined by appropriate a and b parameters in the general formula for relative gradations :

$$\varphi(Z)/\varphi(0°) = [1+a \exp(b/\cos Z)]/(1+a \exp b) \qquad (1)$$

where : $\varphi(0°)$ and $\varphi(Z)$ are gradation functions for zenith and the sky element defined by its zenith angle Z respectively.

It has to be noted that the current CIE standard gradations 1:0.33, 1:1, 1:3.65 are included in this draft while gradation 1:0.5 for overcast skies with snow-covered ground is forming a border between the dark and bright overcast skies [9].

Superimposing the proposed six regions and standard curves in Fig. 2 shows the most probable area of occurrence while both sides of the extent allow for the extreme spread zone where very seldom extraordinary cases would take place. Note that diagrams have the horizontal

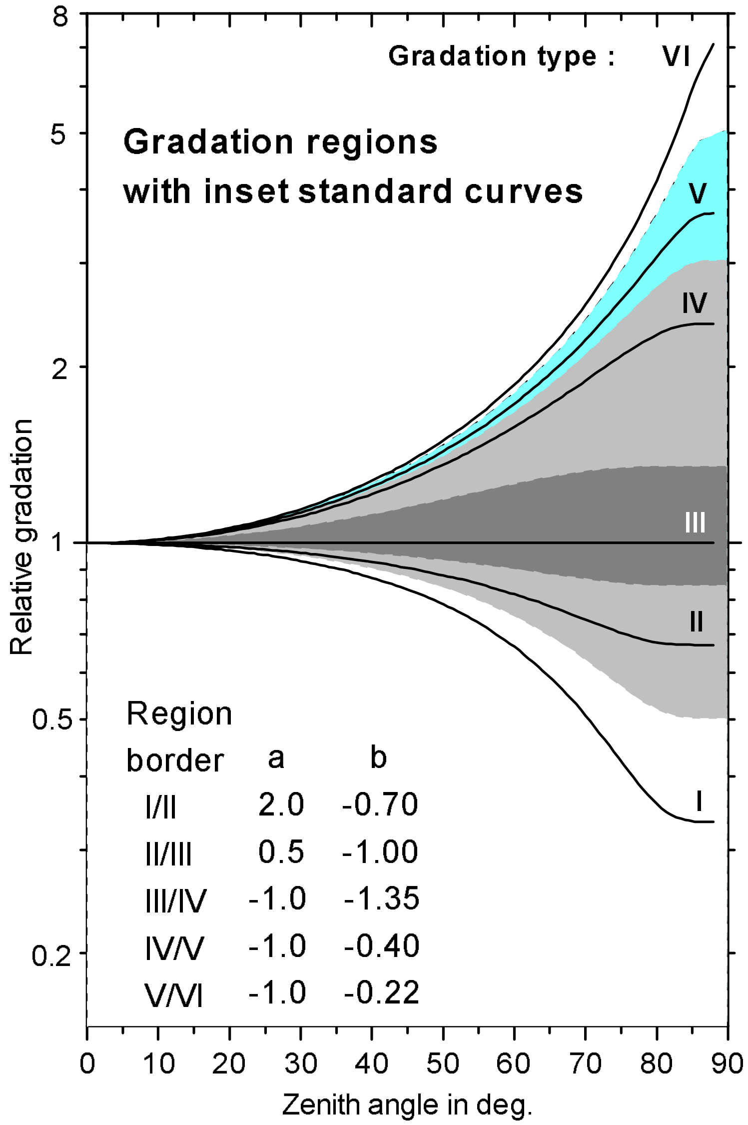

Figure 2 Proposed gradation regions for which appropiate gradation curves apply

unity level without any gradation which combined with the unity indicatrix can represent a basis. The unity indicatrix function expresses the ideally absolute scattering uniformity of the atmosphere diffusing an incoming solar beam into all directions regularly, i.e. an ideally perfect Lambertian diffuser created by Mie´s scattering in an ideal turbid media. Under abstract conditions the corresponding fictitious luminance solid is a sphere and its section called the indicatrix is a circle of unity radius if expressing the relative indicatrix normalised to luminance perpendicular to sun beams. This is the case of a multilayer overcast sky covered usually by a combination of cloud types including mainly Stratus cloudiness and/or fog. It is real and quite often

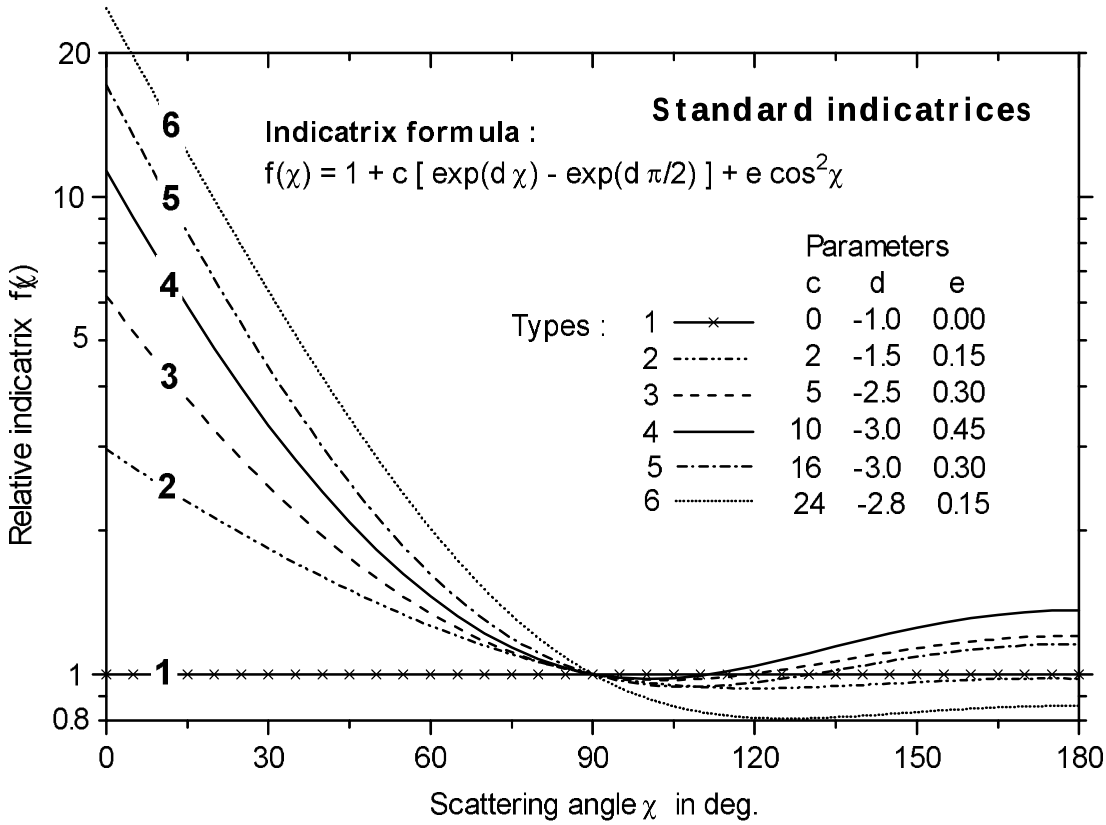

Figure 3 Six standard indicatrix curves

occurring under low pressure situations in rainy or humid temperate climates. The thinner is the air mass or less cloudy and turbid the atmosphere the less profound is the sideways directed scattering and more extended and relatively higher is the sky luminance close around the sun beam. Thus with the decreasing is gradually increasing the prolongation of the scattering indicatix in the forward direction of sunlight flow. So the distortion of the luminance solid follows from the sphere/ball shape to a pearlike form with a swelled „tail“. This transformation of the relative scattering indicatrix can be modelled by an exponential formula

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

where $f(\chi)$ is the indicatrix function for the sky element with the angular

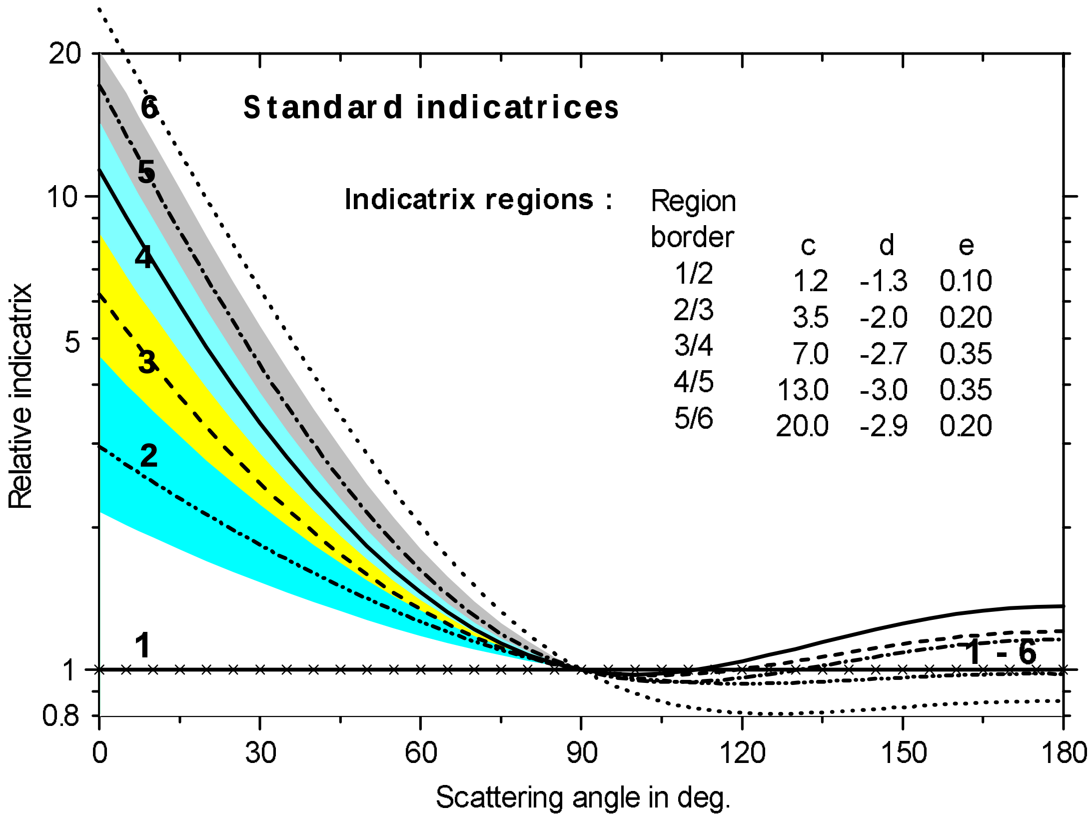

Figure 4 Indicatrix regions with inset standard indicatrix curves

distance χ from the sun.
The indicatrix function is modelled by appropriate c, d and e parameters.
Note that the most prolonged and relatively wide around the sun indicatrices producing the brightest solar corona effect are associated with higher turbidities Tv between 6 and 9 while in very clean or unpolluted sites or periods a lower and sharply peaked indicatrices have to be expected [10].In consequence some indicatrices have to overlap in the upper region in Fig. 3

and standard indicatrices shown in Fig. 4 have to be chosen to fit both clean and cloudy cases. This was the reason why different d parameters were not used for clear skies with low turbidities.The draft of the standard indicatrices contains again six archetypes numbered in Arabic numerals 1 to 6 and these cover the usual range of homogeneous cases from overcast through cloudy to very clear/clean.

A NEW SET OF STANDARD SKIES

On the assumption of the prevailing homogeneous skies and after a thorough analysis [7] a new set of standards can be recommended incorporating all previously standardised skies as well as the functional formula already adopted by the CIE for clear skies [3], i.e. the standard formula defining the relative luminance distribution on any standard sky is:

$$\frac{L}{Lz} = \frac{f(\chi)\,\varphi(Z)}{f(Zs)\,\varphi(0°)} \qquad (3)$$

where L and Lz is luminance in an arbitrary sky element and in zenith respectively,

both φ are indicatrix functions after eq. (1) with a and b parameters for any standard given by values in the Table of Standard Sky Luminance Distributions - SSLD or in Figure 2,

both indicatrix functions f after eq. (2) are defined by parameters c, d and e in the SSLD Table.

Actual combinations of six standard gradations and six indicatrices can form quite many sky standards but only fifteen relevant skies were chosen to be recommended in the new standard set summarised in the SSLD Table.

To test the placement of these chosen standards in the whole spectrum of homogeneous skies (linking the dark overcast with clear on both ends of this spectrum) a ratio Lz/Dv was chosen. Of course under the assumption of homogeneity this Lz/Dv ratio is defined quite exactly when taking into account the appropriate gradation and indicatrix functions in accordance with the formula :

$$\frac{Lz}{Dv} = \frac{\varphi(0°)\,f(Zs)}{\int_{Z=0}^{\pi/2}\int_{\alpha=0}^{2\pi}\left[\varphi(Z)f(\chi)\sin Z\cos Z\right]dZ\,d\alpha} \qquad (4)$$

where Lz is zenith luminance and Dv sky/diffuse illuminance,
f(Zs) is the indicatrix function defined for the solar zenith angle Zs,

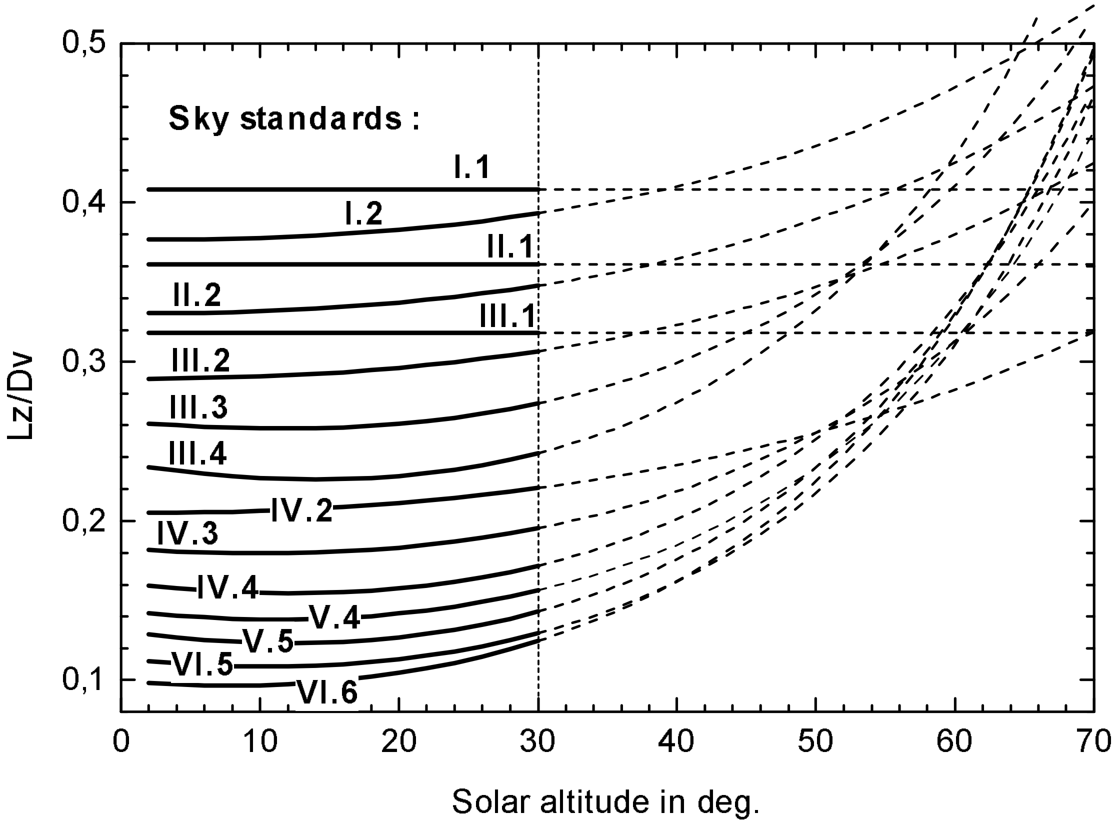

Figure 5 Coverage of the Lz/Dv range by proposed sky standards
α is the azimuth angle from the solar meridian.

If the sunheight is under 30° the Lz/Dv parameter all standards are covering very evenly the whole occurrence field of homogeneous skies as shown in Fig. 5. There might be some problems with diverse unhomogeneous irregular cloudy and partly cloudy skies with distinct cloud edges. These should be classified in accordance with their Lz/Dv and Dv/Ev characteristic close to the same for each standard.
Note that Lz and/or Dv can also be obtained directly from basic irradiance data as suggested in [11].

CONCLUSIONS AND THE FUTURE APPLICATION OF NEW SKY STANDARDS

While the historic or current sky standards represent rather ideal and fictitiously simplified sky distributions now available sky scan luminance data enable to study and represent real or typical sky patterns in more details. Although there are only first sky frequency documentation and analysis in progress using regularly measured data sets in different daylight climate regions the new sky set presumes the possibility of simulating regional or local sky types and also their seasonal or yearly changes by a suitable combination of the recommended fifteen standards. Furthermore the set is also meant to cover the spectrum of intermediate and cloudy skies as a draft of sky luminance models for the CIE TC 3-15 which was set „to determine sky luminance distributions characteristic of intermediate skies between the two already standardised clear sky and overcast sky distributions“ (as cited from this TC terms of reference).

Although the new generation of standard skies has to provide some flexibility of application at the same time a more detailed description of conditions and parametrisation is introduced to specify more exactly relevant cases and standards.

Some recent research results [12 – 15] indicate a relative wider variety of quasi clear, quasi cloudy and bright overcast skies matching with homogeneous distributions with slightly distorted but relatively fluent indicatrix and gradation characteristics. These facts together with the high frequency of Lz/Dv ratios within the span shown in Fig. 5 provide definitive hope that the recommended sky set will express the luminance distributions of the most frequent and characteristic skies world-wide.

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A set of fifteen basic types representing **Standard Sky Luminance Distributions - SSLD**

SSLD Code	Type of sky	Standard gradation parameters	Standard indicatrix parameters	Frequent range Dv/Ev	Usual range Δ	Tv range	Gradation Standard : Range:zenith: horizon	Indicatrix prolongation f(0°)/f(90°) Standard : Range :	Lz/Dv range *)	Comments
I.1	**Overcast with the steep gradation and azimuthally uniform**	: a=4 b= -0.7	**1** : c=0 d= -1 e= 0	0.02-0.25 seldom 0.25-0.4	<0.18 **)	over 40 over 20	1:0.33 1:0.1 - 1:0.5	1:1 0.8:1 - 1.2:1	about 0.38	Including the current CIE Standard
I.2	**Overcast with a steep gradation and slight brightening toward sun**	: a=4 b= -0.7	**2** : c= 2 d= -1.5 e= 0.15	0.2 - 0.4 seldom >0.4	0.18-0.3	over 15	1:0.33 1:0.1 - 1:0.5	3:1 1.2:1 - 3.5:1	about 0.35	No direct sunlight sometimes darker or brighter skies
II.1	**Overcast moderately gradated, azimuthally uniform**	**I** : a= 1.1 b= -0.8	**1** : c=0 d= -1 e= 0	0.2 - 0.4 usually brighter	0.12-0.3	usually around 20	1:0.66 1:0.5 - 1:0.85	1:1 0.8:1 - 1.2:1	0.33-0.38	No direct sunlight sometimes darker or brighter skies
II.2	**Overcast moderately gradated and slightly brightening toward sun**	**I** : a= 1.1 b= -0.8	**2** : c= 2 d= -1.5 e= 0.15	0.3 - 0.6 usually brighter	0.25-0.5	usually around 20	1:0.66 1:0.5 - 1:0.85	3:1 1.2:1 - 3.5:1	0.32-0.35	No direct sunlight exceptionally darker skies
III.1	**Overcast overall uniform**	**II** : a=0 b= -1	**1** : c=0 d= -1 e= 0	around 0.35	0.2-0.3	usually around 20	1:1 1:0.85-1:1.35	1:1 0.8:1 - 1.2:1	0.30-0.33	No direct sunlight sometimes darker or brighter skies
III.2	**Cloudy or quasiover-cast with a uniform gradation and slight brightening toward sun**	**II** : a=0 b= -1	**2** : c= 2 d= -1.5 e= 0.15	usually over 0.3	0.25-0.5	usually around 15	1:1 1:0.85-1:1.35	3:1 1.2:1 - 3.5:1	0.27-0.32	No direct sunlight exceptionally darker skies
III.3	**Cloudy or quasiover-cast with a brighter circumsolar effect and uniform gradation**	**II** : a=0 b= -1	**3** : c= 5 d= -2.5 e= 0.3	usually 0.40 - 0.6	>0.35	usually around 10	1:1 1:0.85-1:1.35	6:1 3.5:1 - 7:1	0.25-0.30	Filtered direct sunlight exceptionally darker skies

Note *) For nonovercast types the Lz/Dv range is valid only if Zs is over 60 degrees
**) Exceptional are brighter cases >0.18

SSLD Code	Type of sky	Standard gradation parameters	Standard indicatrix parameters	Frequent range Dv/Ev	Usual range Δ	Tv range	Gradation Standard : Range:zenith: horizon	Indicatrix prolongation f(0°)/f(90°) Standard : Range :	Lz/Dv range *)	Comments
III.4	**Cloudy rather uniform with a clear solar corona**	**II :** a=0 b= -1	**4 :** c=10 d= -3 e= 0.45	usually over 0.3	over 0.25	usually 6 - 15	1:1 1:0.85-1:1.35	11:1 7:1 - 13:1	0.21-0,26	Filtered or no direct sunlight
IV.2	**Partly cloudy with a shaded sun position**	**IV :** a= -1 b= -0.55	**2 :** c= 2 d= -1.5 e= 0.15	usually over 0.3	over 0.25	over 15	1:2.5 1:1.35 - 1:3	3:1 1.2:1 - 3.5:1	0.18 - 0.23	Filtered or no direct sunlight
IV.3	**Cloudy with brighter circumsolar effect**	**IV :** a= -1 b= -0.55	**3 :** c= 5 d= -2.5 e= 0.3	usually 0.3 - 0.5	0.25-0.43	usually 6 - 12	1:2.5 1:1.35 - 1:3	6:1 3.5:1 - 7:1	0.16 - 0.20	Filtered direct sunlight
IV.4	**Cloudy or partly cloudy **) with a clear solar corona**	**IV :** a= -1 b= -0.55	**4 :** c=10 d= -3 e= 0.45	usually 0.1 - 0.4	0.06-0.32	usually 1.5 - 4	1:2.5 1:1.35 - 1:3	11:1 7:1 - 13:1	0.14 - 0.18	Direct sunlight in acordance with Tv
V.4	**Very clear (unturbid) with a clear solar corona**	**V :** a= -1 b= -0.32	**4 :** c=10 d= -3 e= 0.45	usually 0.08 - 0.2	0.05-0.12	usually 1.5 - 4	1:3.5 1:3 - 1:5	11:1 7:1 - 13:1	0.12 - 0.17	Corresponding to the current CIE Clear Standard
V.5	**Cloudless polluted with a broader solar corona**	**V :** a= -1 b= -0.32	**5 :** c= 16 d= -3 e= 0.3	usually 0.15 - 0.45	0.10-0.37	usually 3 - 8	1:3.5 1:3 - 1:5	17:1 13:1 - 20:1	0.12 - 0.16	Corresponding to the current CIE Polluted Standard
VI.5	**Cloudless turbid with a broader solar corona**	**VI :** a= -1 b= -0.15	**5 :** c= 16 d= -3 e= 0.3	usually 0.15 - 0.5	0.10-0.43	usually 4 - 10	1:7 over 1:5	17:1 13:1 - 20:1	under 0.13	Direct sunlight in acordance with Tv
VI.6	**Quasi-cloudy **) and turbid with a wide solar corona effect**	**VI :** a= -1 b= -0.15	**6 :** c=24 d= -2.8 e= 0.15	usually 0.2 - 0.6	0.12-0.55	usually 6 - 12	1:7 over 1:5	25:1 over 20:1	under 0.12	Direct sunlight in acordance with Tv

Note : **) Quasi-cloudy skies are usually more homogeneous formed by a certain degree of turbidity and diffuse cloudiness (Cs or As cloud types) in contrary to broken cloudiness (e.g. Cu, Ac or Cc types) which in acordance with actual cloud cover can be considered either as cloudy (white with blue patches) or party cloudy (blue - white)