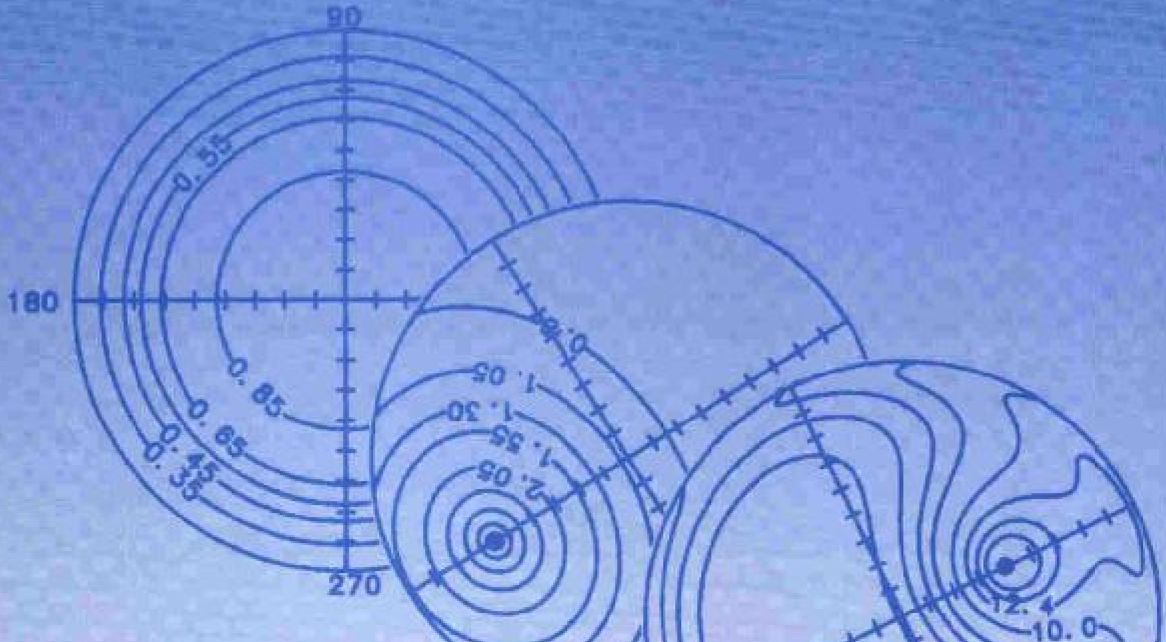
A set of standard skies



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A set of standard skies

characterizing daylight conditions for computer and energy conscious design

FINAL REPORT

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Abstract: A set of standard skies characterising daylight conditions for computer and energy conscious design

The original project specification has mentioned at least three main purpose-conscious concepts justifying the task to develop a new set of sky standards:

- the discrepancies and absence of standards to characterise unsteady-state daylight climates and solar energy use in buildings with respect to new measured data recorded under the CIE IDM Programme,
- the need of linking the whole spectrum of skies between the already standardised CIE Overcast and CIE Clear Skies covering the real conditions, frequency of occurrence as well as absolute levels,
- the trend to evaluate and accept also cloudy and partly cloudy sky models which were seldom specified due to the complete absence of parametrisartion and measured sky luminance distributions.

In this respect sky luminance distribution data containing more than hundred 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.

Furthermore a new set of empirical formulae to predetermine zenith luminance and sky illuminance was developed to facilitate the use of new sky standards not only in relative terms but also using the resulting absolute levels. Utilising selected clusters representing minute data gathered at Bratislava IDMP station during two years 1995 and 1996 general formulae for zenith luminance (Lz) and horizontal diffuse illuminance (Dv) were found as well as a set of suitable parameters by computer best fit programs with a high accuracy in Lz/Dv approximation. Thus modelled exterior daylight conditions are predictable under all fifteen standard skies and arbitrary solar altitude that can be used for various design purposes or expert comparisons and evaluations. While the ideal standards cover the whole range of expected/normal skies defined by their Lz/Dv ratios their arbitrary ´brightness´ level corresponds to the cluster spread expressed by the ratio Dv/Ev, i.e. the sky illuminance at ground level normalised by its simultaneous extraterrestrial level (Ev). This placing within the Dv/Ev cluster is caused mainly by cloudiness and atmospheric turbidity but it is also influenced especially under homogeneous and clear conditions by the presence, filtering or absence of sunlight associated with a particular sky standard and the luminous turbidity in the direction of sun beams (Tv). Thus the simultaneous direct, horizontal solar illuminance (Pv) in absolute or ratio form (Pv/Ev) can be determined.

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.

Considering these possibilities of using a new set of standard skies a more realistic method to model daylight is available for all future energy optimisation studies as well as in their environmental and economic consequences. Long term approximations of yearly daylight changes and variations can be simulated in relation to local sunshine duration data. Even better modelling can be achieved when minute measurements at a near IDMP general station can be studied by the help of cluster analysis documented in this Final Report. These advantages of a new generation of sky types can be appreciated by designers during the first stages of the design process when several possible project solutions of window and daylight arrangements or more alternatives have to be compared and evaluated under the same local exterior conditions and universally accepted standards.

The adoption of a new generation of sky standards will enable a more accurate prediction of daylight climate with its particular character in specific climate zones or locations as well as a better simulation of illuminance changes to calculate energy savings in daylit buildings. For a more realistic model of daylighting dimming systems the Lz/Dv ratio seems to provide a base of the photosensor evaluation and a useful parameter for the computer driven simulation and regulation system. It is also quite important to implement a new system of comparative sky luminance and direct solar illuminance values linked to sky/diffuse illuminance levels for the computer simulation of the daylight performance in interiors. Thus a better insight into the prediction of interior daylighting using either traditional or advanced daylight systems during the design stage predetermine higher quality results in environmental comfort, health and ergonomic conditions in building interiors world-wide.

Introduction: History and development of sky standards

Ever since the first photometric concepts had to characterise light sources, under everyday experience several different types were considered:
- sunlight as propagation of parallel beams with a strong directional effect on illuminated objects,
- skylight as a multidirectionally diffuse and large area illuminant,
- candle-light and later incandescent bulb light representing artificial point sources in closer vicinity from illuminated surfaces,
- reflected light from various surfaces usually diffuse in nature.

The coexistence of sunlight and skylight as well as their quantitative and qualitative mixtures and changes were taken as natural but in theoretical studies had to be simplified, modelled by abstraction and separation as demonstrated by the different development and assumptions in the theory of daylight and insolation of interiors.

So since the publication of Photometria by Lambert, 1760 all calculation methods were derived from his principle given 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 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 to be calculated".

Although the uniform unity luminance of the sky hemisphere was considered a basic prerequisite and dogmatic assumption of all daylight calculations and graphical means for a long time no proof was give whether it is only and abstract constant fiction or also a really existing case. Now after analysing the bright overcast sky scans it is evident that there are unique situations of ideal uniformity and absolutely diffuse scattering especially in dense fog when the gradation and indicatrix changes and influences are reduced to minimum and can be taken as constant. Furthermore such unity skies can represent an ideal mean skies linking the decreasing gradation tendency of overcast and the increasing gradation of clear skies respectively. Thus defining the 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.

Of course, Lambert could not have guessed that it would take more than 235 years until the Overcast Sky with a simple cosine gradation was adopted by CIE, 1955 as a standard. It is true that quite many measured luminance distributions on overcast skies by Schramm, 1901, Kähler, 1908 or Kimball and Hand, 1921 have noted a gradual luminance decrease from zenith to horizon in ratios 1:0.5 to 1:0.3, but only after the influential paper by Moon and Spencer, 1942 and final tests by Hopkinson, 1954 decided the CIE move.

In contrary for clear skies the gradation 1:3.65 and larger was considered already by Pokrowski, 1929 modelled by an exponential function while another exponential relation was recommended by Krat, 1943 to simulate the scattering indicatrix. Boldyrev, 1935 expressed the clear sky luminance pattern via tabulated values resembling gradation and indicatrix influences. These ideas were later used by Kittler, 1967 for the CIE recommendation to standardise the CIE, 1973 Clear Sky.

Since 1987 a special CIE Technical Committee TC 3-15 „Standardisation on intermediate sky luminances" was established „to determine sky luminance distributions characteristic of intermediate skies between the two already standardised clear and overcast sky distributions" which was renamed in 1995 to „Sky luminance models" with the same terms of reference.

Although no considerable progress was achieved in this committee in the mean time several different approaches and concepts were published defining sky luminance patterns under various intermediate conditions:
- a simulation of a single intermediate or mean sky was suggested by several authors, e.g. by Littlefair, 1981, Pierpoint, 1983, Nakamura and Oki, 1983, Nakamura, Oki and Hayashi, 1985, Nakamura, et al., 1986 or Matsuura and Iwata, 1990,
- the simplest set of linked five sky standards was proposed by Perraudeau, 1988,
- a functional model of all existing homogeneous skies based on the influence of luminous turbidity Tv on the diffusion indicatrix (Kittler, 1985) was suggested by Kittler, 1986,
- the so called all-weather models were derived from measured sky scans and are based on a complex system of parameters (Perez, Seals and Michalsky, 1993) or recently by Igawa et al., 1997,
- even more complicated simulation procedures are prescribed for the modelling of real skies with random cloud patterns by Perez, Seals, Michalsky and Ineichen, 1993.

Thus a variety of models is available for the standardisation purposes and was tested in comparison to various measured data already by Perez et al., 1992, Ineichen et al., 1994 or Littlefair, 1994.

Reasons: 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.

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 orientated, 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.

Using abstract and relevant sky standards with additional information and occurrence frequency data, a world-wide simulation of long-term averages can be recommended which 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 use very precise summation/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.

Methods: Analysis and partial results concerning sky classification and identification of sky types with their relevant parametrisation documented in the Appendices

The set of standard skies is based on a thorough analysis of selected luminance scans measured in Berkeley during 1985-6 supplemented by data from scans recorded in Tokyo and Sydney during 1992. All these luminance patterns were associated with simultaneously measured illuminance data which enabled additional analysis using different parametrisations. Thus a cross-check with parametrised one-minute data collected during 1994-1996 in Bratislava was possible to study the frequency of occurrence with comparison to American data recorded during 1985-1986 at Berkeley, Cal. and during 1993-1995 at Albany, NY.

Due to the project aim the selection priority was orientated towards homogeneous states and close to steady conditions when the purest interconnections and influences could be detected and modelled to simulate typical sky patterns. In this respect the first selection from the 16000 Berkeley all-sky scans (gathered by LBL, 1988 between June 1985 and December 1986) was done by the American partner Dr. Richard Perez. Because the analysing processes were quite tedious and elaborate with several computer programs to be used, the decision was made to restrict the number of selected cases to 90-100, then supplemented and compared with several similar newer cases from Tokyo (Igawa, 1992) and Sydney (Hayman, 1992). To identify possible irregularities and review the overall luminance distribution in first place, a computer program was developed to draw all complete sky patterns evaluating measured scan data. Two examples of this sort are in Figure 1 and 2, in the former visualising a relatively regular pattern except for a small cloud patch, while the latter represents a cloudy sky with many irregularities. Then two different computer programs were utilised for the analysis of the gradation and relative indicatrix tendencies from the sky scan data after Kittler, 1993. So in Appendix A all selected Berkeley scans were analysed and compared to current sky standards (CIE, 1994) and to

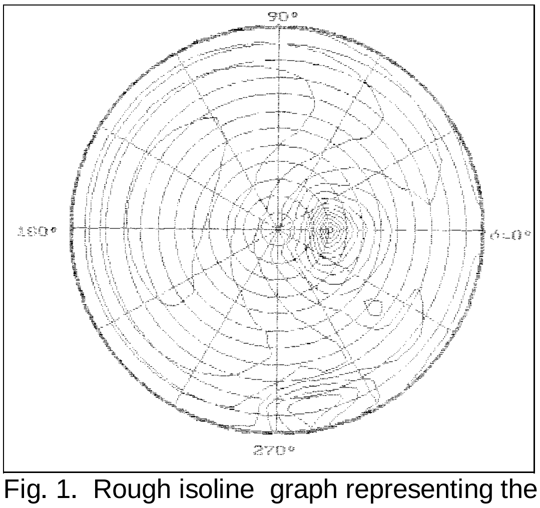

Fig. 1. Rough isoline graph representing the measured Berkeley case 220/85

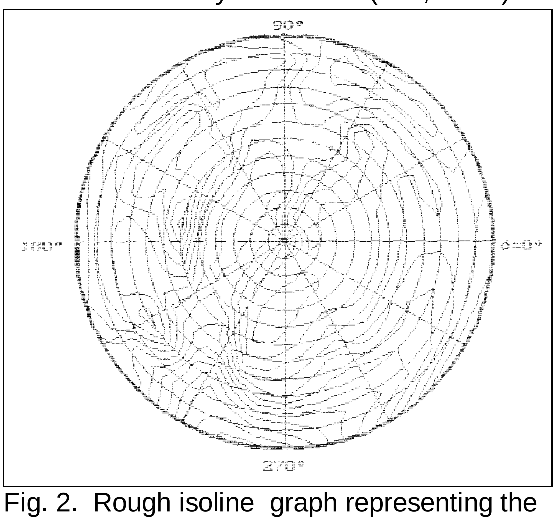

Fig. 2. Rough isoline graph representing the measured Berkeley case 201/85

some additional gradation and indicatrix functions as shown in Appendix A on Figure 0.

Then the Dv/Ev cluster position of all Berkeley cases was tested and shown in a set of P-G-D diagrams for actual 5° solar altitude steps with a simultaneous check of all three measured components in Appendix B on Fig. 3-13. To document the Dv/Ev clusters formed during longer measurement periods, various Bratislava, Albany and Berkeley data were analysed and are presented in Appendix B on 54 tables with their occurrence frequency, which was calculated by a special sorting computer program developed for this purpose.

As each scan represents only a singular momentary state, the expectancy of its time stability or repetition with the identification of changes or steadiness was studied in respect to Lz/Dv parameters

and examples in Appendix C are shown using Bratislava one-minute data. At the same time long-term, one or three year data were used to verify the coexistence and interdependence of Tv, Pv/Ev Lz/Dv and Dv/Ev clusters in Appendix D. Thus specific sky types were selected and documented by ideal cases and were summarised in the following appendices:
Appendix E contains examples of dense overcast, i.e. dark sky patterns,
Appendix F specifies bright overcast skies,
Appendix G tries to document bright cloudy cases,
Appendix H is demonstrating clear sky patterns with examples of different indicatrices and gradations.
After the documentation of these typical sky cases, their characteristic indicatrix and gradation courses as well as their parametrisation all was set to define a set of standards. Choosing an ideal set of six gradation and six indicatrix functions respectively, an optimal set of fifteen sky standards was established using their most important combinations. Following a regular and fluent coverage of the Lz/Dv range of the usual sky spectrum, three groups of overcast, intermediate and clear skies were recommended each containing five sky types, all exactly specified by gradation and indicatrix parameters and common functions (see in the next chapter).
Furthermore, the best fit Lz/Dv approximations as well as the specification of Dv/Ev and Tv cluster expectancy associated with each sky standard enabled the elaboration of a definition system to calculate the absolute zenith luminance and diffuse illuminance using general formulae expressing the interconnection of Lz/Dv with actual Lz and Dv levels respecting Dv/Ev and Tv influences by a set of fan formations (see Appendix I and J). Thus all main results of this project could be summarised in a condensed form in the practical Catalogue chapter with specific information about each proposed standard in the sky set.
Finally, using Bratislava data the frequency distribution of the fifteen sky standards was evaluated and is documented in Appendix K, while their relation to the relative sunshine duration was reported in papers by Kittler, 1997a and 1997b.

Models: Sky standardisation concept and draft standards

Nowadays it is important to realise that due to energy and environmental design problems the relative fictive and stable sky standards cannot match reality or express dynamic daylight changes without the natural interdependence of sunlight and skylight. Furthermore, because sun is the primary source of daylight whether in the form of sunbeams and/or skylight, it is also the fundamental reference unit in all locations on globe as it determines relative common conditions to be met everywhere. Of course the actual sun position especially the solar altitude in a particular moment, hour or day due to local horizon (or horizontal earth surface at ground level) defines the intensity and direction of sunbeams as well as the overall daylight availability and effectiveness. At the same time momentary cloudiness and turbidity within the atmosphere influence the diffusion and redirection of sunbeams in the form of skylight. So when analysing the daylight climate or its availability the reference or normalisation has to be done against the extraterrestrial available horizontal illuminance, i.e. Ev. It is important to note that this extraterrestrial illuminance is the global and universal criteria to which possible local effectiveness of utilising available natural light is to be expressed, compared or normalised.
At ground level the extraterrestrial illuminance is reduced and split due to air attenuation, turbidity and clouds into parallel beam horizontal illuminance Pv and diffuse sky horizontal illuminance Dv, together forming global illuminance Gv, which sometimes is the only one recorded. When all these illuminances are normalised by the simultaneously present extraterrestrial Ev value, Pv/Ev, Dv/Ev and Gv/Ev can be represented in the triangular P-G-D diagram recommended by Kittler et al, 1992.
Though the comparison or visualisation of measured Pv/Ev, Dv/Ev and Gv/Ev proportions can show an overall character, effectiveness and availability range with time changes, it has to be noted that specific conditions occur at different solar altitudes. Due to different presence of clouds, their types, cover and distribution over the sky vault under the same sun position can be measured various Dv/Ev levels even with the same Pv/Ev ratio, i.e. under the same luminous turbidity Tv in the direction of sun beams. So, clusters of points can be expected in the P-G-D diagram, i.e. Dv/Ev clusters indicating the nonhomogeneity of atmospheric conditions and cloudiness as described by Kittler and Darula, 1996. Such clusters indicate not only the usual, frequent cases but also more extreme and more effective sky patterns caused by white clouds or whitish turbidities which give considerable rise to the Dv/Ev ratio. Under very favourable conditions with added sunlight reflected from clouds quite high Dv level are recorded (see App. F and G).
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. Only the further development of sky scanners, establishment of first regular daylight measurement stations (Dumortier et al., 1994) as well as new methods of analysing the measured data and sky scans (Kittler, et al., 1992 and Kittler, 1993, 1994) enabled recently a more detailed study of different sky types. The resulting conclusions and current daylighting design needs for standard skies have initiated the development and draft of a new generation of sky standards.

The world-wide standardisation of skies is based on an assumption that under the same atmospheric conditions the same sky luminance distribution will exist in any location on Earth. This assumption is valid especially under homogeneous skies with even turbidity or cloudiness, which is true for dense overcast as well as cloudless sky luminance patterns.

For such extremes several differences are typical and these can be identified:

- very high Gv/Ev values are associated with clear skies with sunshine while lower without sunlight or under cloudy skies,
- under cloudless skies the Pv/Ev ratio is high and associated with low Dv/Ev components while under cloudy skies can be Pv/Ev levels the same but due to cloud filtering also quite low or zero,
- the most often relation under overcast skies is Gv/Ev = Dv/Ev with a quite high levels 0.2-0.6 under bright overcast and very low levels 0.02-0.2 under dark and dense multilayer of clouds,
- for overcast skies is characteristic the luminance gradation from darker horizon to brighter zenith, while a vice versa luminance gradation has to be expected under clear and cloudy skies,
- while the overcast sky pattern has close to quite uniform distribution in different aspects, in contrary clear sky patterns are in any orientations different although more or less symmetrical against the solar meridian,
- under sunshine especially on clear skies the brightest luminance patches are around the sun position, i.e. within the so called solar corona, while on dense overcast skies the sun position is absolutely hidden and often uncertain,
- in consequence for such extreme luminance patterns a typical value of the ratio of zenith luminance to diffuse illuminance Lz/Dv exists and can characterise the case in relation to Pv/Ev, Dv/Ev and Gv/Ev levels,
- however the basic phenomena associated with the penetration of sunbeams through the atmosphere influence its momentary filtering and scattering properties which can be identified or specified by the gradation and indicatrix functions.

The gradation and indicatrix analysis (in Appendix A for all chosen American scans) 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 in papers by Kittler and Valko, 1993 and Kittler, Perez and Darula, 1997a. 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 and prevailingly occurring types in temperate regions and 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 standards to a reasonable number this gradation of very dark overcast conditions was left out. However, if in some regions, e.g. monsoon or maritime west coast very rainy climates, would prove the dark thunderstorm overcast sky as important or seasonally frequent, such an extreme gradation could be taken as an additional standard too.

Under relatively homogeneous conditions there are six relevant standard gradations represented in Figure 3 and corresponding spreading regions in Figure 4 numbered by assigned Roman numerals I to VI respectively. All can be determined by appropriate a and b parameters in the formula for relative gradation:

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

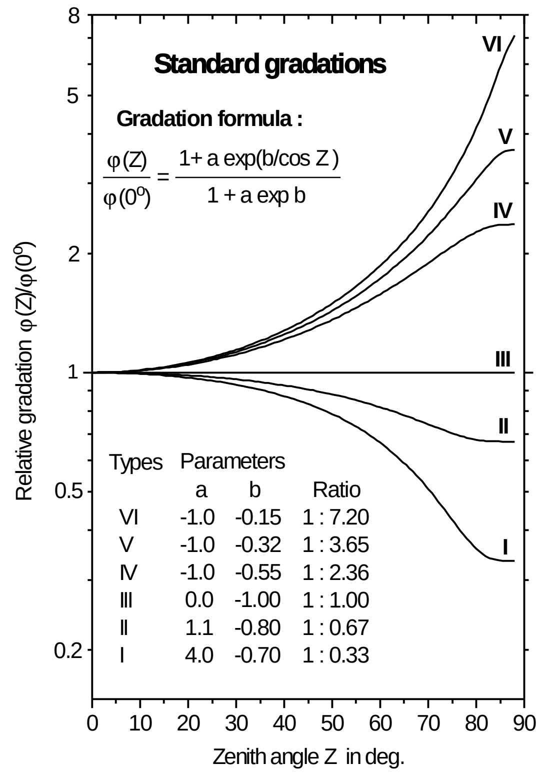

Fig. 3. Standard gradation formula, parameters and profiles

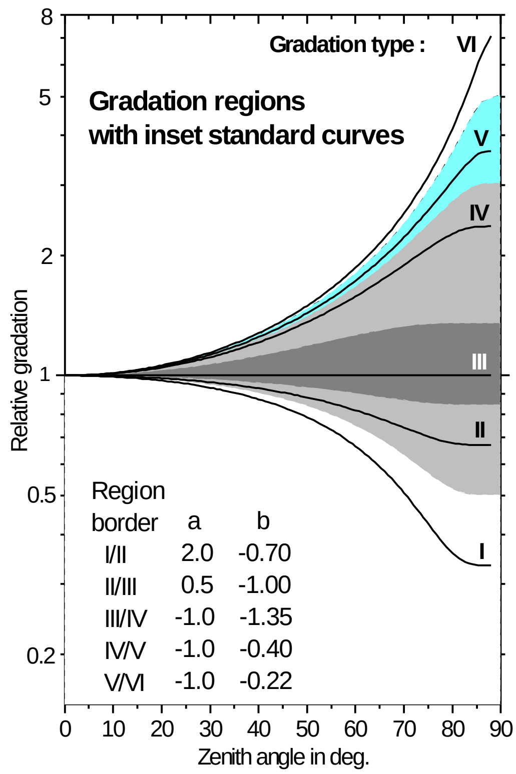

Fig. 4. Regions occupied by the set of standard gradations

where Z is the zenith angle or the angular distance of the sky element from zenith,
$\varphi(0°)$ is the gradation function for zenith, i.e. when Z = 0°.

It has to be noted that the current CIE standard gradations 1:0.33, 1:1 and 1:3.65 are included in this draft while the gradation 1:0.5 for overcast skies with snow-covered ground (Petherbridge, 1955) forms roughly the border between the dark and bright overcast skies.
Superimposing the regions and standard curves in Figure 3 shows the most probable area of occurrence while both sides of the extent allow for the extreme spread zone where seldom extraordinary cases would take place. The unity indicatrix function expresses the absolute scattering uniformity of the atmosphere diffusing the incoming solar beam into all directions, i.e. a perfect Lambertian diffuser created by Mie scattering in an ideal turbid media. Under such 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 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 χ is the scattering angle, i.e. the smallest angular distance of an arbitrary sky element from the sun position which is given by the formula

$$\cos \chi = \cos Zs \cos Z + \sin Zs \sin Z \cos Az \qquad (2a)$$

where Zs is the solar zenith angle and Az is the azimuth of the Z meridian from the sun meridian.

The appropriate c, d and e parameters for the standard set are defined in Figure 5 and 6.
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 10 while in very clean or unpolluted sites or periods a lower and sharply peaked indicatrices have to be expected (Kittler, Perez and Darula, 1997b).
Thus some indicatrices have to overlap in the upper region in Figure 6 and standard indicatrices 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 various lower turbidities.
The draft of the standard indicatrices contains again six archetypes now numbered in Arabic numerals 1 to 6 and these cover the usual range of homogeneous cases from overcast through cloudy to cloudless skies with different turbidities or very clear/clean.
Actual combinations of six standard gradations and six indicatrices can form quite many sky standards but only fifteen relevant were chosen to be contained in the new standard set summarised in Table 1 of Standard Sky Luminance Distributions also called SSLD.

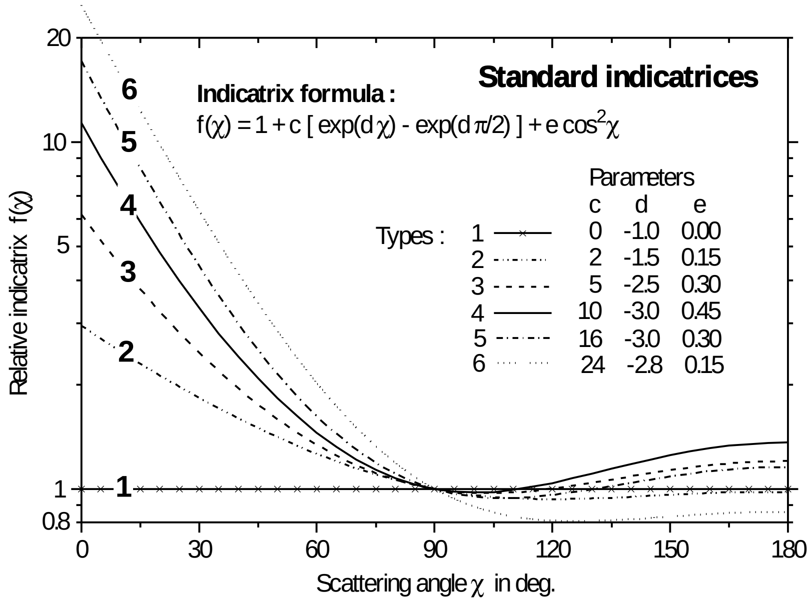

Fig. 5. Standard indicatrix formula and profiles

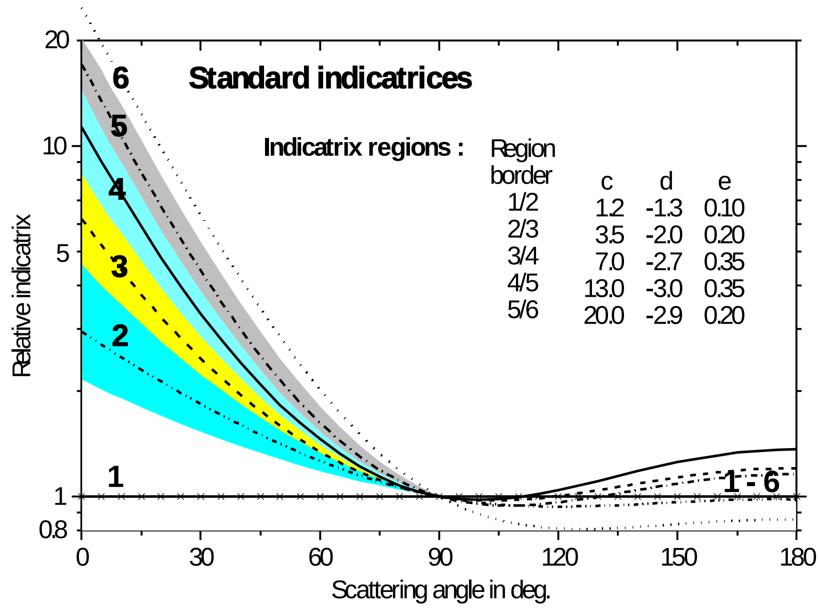

Fig. 6. Standard indicatrix regions

There might be problems with the diverse nonhomogeneous irregular cloudy and partly cloudy skies especially those with distinct cloud edges. These should be classified in accordance with their Lz/Dv and Dv/Ev characteristic close to the same for each homogeneous sky type. If the sunheight is under 30° the Lz/Dv parameter for all standards is covering very evenly the whole occurrence field of homogeneous skies as shown in Figure 7. It has to be noted that the exact fit of the curvature of Lz/Dv curves (see in Figure 1. in Appendix J) enabled the development of Lz and Dv calculation formulae in absolute units as well as the matching of interconnecting relation of Lz/Dv with Dv/Ev and Tv fans for different standards expressing the cluster existence. However, it must not be forgotten that under nonhomogeneous skies and especially under partly cloudy conditions due to the Dv/Ev cluster phenomena the Lz/Dv ratio can be distorted as well as the most frequent proportion between Pv/Ev and Dv/Ev, i.e. also Gv/Ev. Irregular cloud distribution on the sky vault can accidentally produce extreme or unusual Dv/Ev ascendencies which might result in very high Gv/Ev effectiveness even close or over 1(see App. G or Kittler and Darula, 1998). In fact ex-treme situations

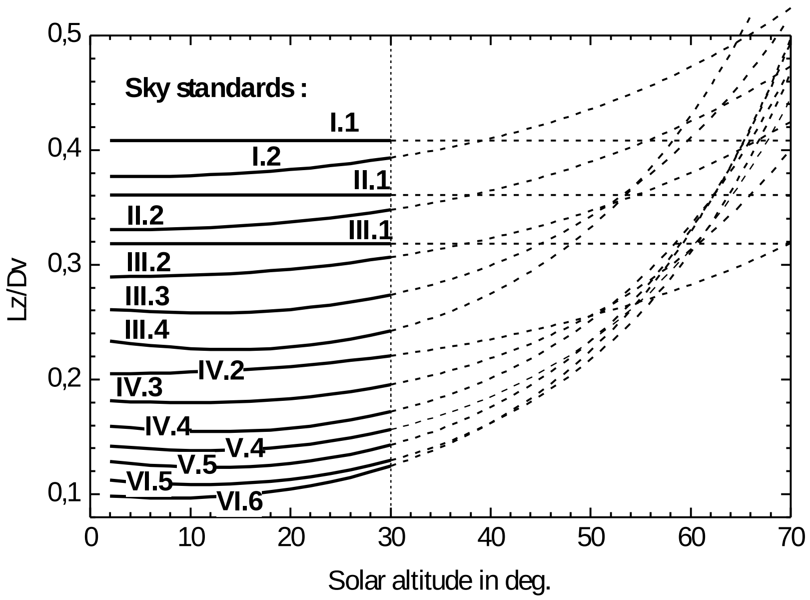

Fig. 7. Determination of standard skies from the Lz/Dv ratio (This is effective only at low solar altitude as Lz/Dv becomes corrupted by the circumsolar aureole as the sun rises to zenith)

characteristic for the Dv/Ev cluster tail, i.e. a very high proportion of Dv/Ev in Gv/Ev is distorting also the Nvg value assumed as basic ´sorting´ criterion by Igawa et al., 1997. Furthermore in such cases also the absolute luminance in zenith can be effected locally by moving clouds and thus the Lz/Dv ratio could indicate unrealistic situations and the obstruction of the sun position by a local cloud can momentarily contradict the actual sky type present. In this sense it has to be realised that even a pure blue sky with a small white cloud sitting on the sun and/or in zenith could be classified by the distorted Lz/Dv and Nvg values probably as dark overcast. Realising such risks it has to be taken into account that such occasions are rare and last usually only for few moments, so are untypical and unimportant in design concepts. In an abundant pool of measured data such extraordinary situations are often compensated by opposite unusual cases when an overcast sky has a ´window´ at sun position and at zenith and thus can be mistaken for a clear sky due to the high Pv/Ev and low Lz/Dv values respectively.
In spite of these rare irregularities it seems that a substitution of nonhomogeneous skies by homogeneous sky patterns is a practical solution and the Dv/Ev as well as Tv fans available for different sky standards in the following Catalogue are offering a variety of possibilities to take into account also unusual situations if needed.

Results: Guidelines for the application of sky standards and practical use of the SSLD Catalogue

New computer possibilities of building design in the next 21st Century are stimulating novel conceptions and development of a new world-wide applicable system of sky models with a more advanced standardisation of exterior daylight conditions. In contrary to current two sky standards normalised to zenith luminance, i.e. only in relative terms (CIE, 1994) there is a need:
- to express an important coexistence of sunlight and skylight in their different proportions and qualities as well as their link to a new set of sky standards,
- to utilise, compare and evaluate local (IDMP) measured data with their adoption to national, regional and international standards or codes of practice with respect to a more precise simulation of the reality and specific daylight climate features,
- to enable calculations of energy efficiency in trade-off programs in particular climates on the basis of long term availability and occurrence frequency of different sky types,
- to facilitate the determination of absolute sky luminance patterns or luminance levels of any arbitrary sky element from ratio parameters if necessary,
- to determine resulting illuminance levels either by the integration of the sky luminance pattern or via utilising approximation formulae based on the links between Lz/Dv, Dv/Ev as well as Tv and Pv under different sky types/standards.

Therefore a new system of parametrisation defining exterior daylight changes was developed linking the real measured data with a new generation of sky standards. In this sense the concept of the sky standardisation with a simple change of gradation and indicatrix formulae has to be reviewed and some applications have to be demonstrated because all these further applications are linked to sky models.
The set of fifteen standard skies adopts also all existing CIE standards in a system covering the whole probable spectrum of skies existing world-wide while the importance and validity of any particular sky

standard is to be decided in accordance with the local availability, occurrence frequency defined by cluster analysis as well as due to design needs and/or other reasons for a specific application. Thus either one critical sky standard can be applied e.g. in window design or glare studies or a chosen mixture of several standards can simulate the average or extreme, fluent or random changes of the exterior daylight climate e.g. in case of energy trade-off programs, when simulating reference month, season or year courses. If a simple parametric link between sky standards and existing measured conditions is determined, new possibilities in the control, regulation or dimming of artificial lighting systems will exist as well as a more effective supplementation and mixture of daylight and artificial light can be justified.

Using a unified parametrisation in further analysis of long term measurements in different locations and climate zones will enable to detect some of the peculiarities of zonal or local daylight climates in their monthly, seasonal or yearly changes. Thus the universal applicability of the new set of sky standards can be tested or sophisticated.

Furthermore, all particular data, diagrams, figures or equations have to be taken as examples illustrating or visualising the principal functional interrelations although documenting in details or under specific conditions some basic dependence similar or close to general validity. Due to the need of systematic overview and universal compatibility all relations are expressed in a parametrised or normalised ratio form, which when useful yield also absolute values or levels for practical local or zonal application. In this sense all IDMP stations and daylight experts are urged to use their available data to test the new sky models and investigate what standard is characterising local conditions best either in typical days or during longer periods of measurements.

However, all local influences expressing special conditions of cloudiness and pollution/turbidity are ´overlapping´ the basic world-wide influences and transformations, i.e. filtering and scattering of extraterrestrial sunlight. The objectives and main result of this project can be summarised as follows:

The inflow of sunlight reaching the outer border of Earth atmosphere in the form of parallel beams is defined by the universal quantity. It is the luminous solar constant Evo = 133800 lm/m^2 or 133.8 klux if conceived like a fictitious illuminance on an imaginary plane perpendicular to momentary sun beam direction. In the same moment at any location, i.e. at ground level the illuminance level is proportional to horizontal extraterrestrial illuminance Ev, which can be computed as a function of the solar constant and the momentary solar altitude:

$$Ev = F(\check{E}vo, \gamma s) = \check{E}vo \sin \gamma s = \check{E}vo \cos Zs \qquad (3)$$

where Ěvo is the daily corrected solar constant,

γs - the solar altitude or Zs are functionally dependent on γs = Zs = F(φ, J, H)

as

$$\sin \gamma s = \cos Zs = \sin \varphi \sin \delta - \cos \varphi \cos \delta \cos (15° H) \qquad (4)$$

where φ - the geographical latitude of a particular location,

H - the number of the hour in that day.

δ - mean daily declination dependent on the number of the day within a year - J, e.g.

$$\delta = 23.45° \sin [2\pi/365 (J - 81)] \qquad (4a)$$

Note, that the solar altitude is expressing local as well as time influences characterising the momentary ´turn´ /position of the Globe to Sun direction or vice versa the local fictitious sun position on the sky vault. There are available several calculation formulae to compute Ěvo and γs, e.g. in Kittler and Mikler, 1986 or Tregenza and Sharples, 1993.

The most accidental in nature and most difficult to predict is the influence of cloudiness causing the redistribution and transformation of sun beams to sunlight and skylight components at ground level. The multiple changes in cloud type, cloud cover and the distribution of clouds in several layers on the sky predetermine the luminance pattern measured by its scanning. The sky luminance distribution in various sky spots results in the diffuse sky illuminance level Dv on the horizontal plane in accordance with their solid angles and the position with respect to horizon. Simultaneously the cloud position in the direction of sun predetermines the still parallel beam/direct solar illuminance on a horizontal plane (Pv) as this quantity is defined as

$$Pv = F(Ev, av, m, Tv, \gamma s) = Ev \exp(-av\ m\ Tv) \qquad (5)$$

where m is the air mass penetrated and av its luminous ideal extinction, both dependent on solar altitude, while Tv is the luminous turbidity factor which approximates the number of ideally clean atmospheres representing an actual case. In general cases or calculations when there is no link to any date or daytime a yearly average solar constant is applied :

$$Pv/Ev = F(Tv, \gamma s) = \exp(-av\ m\ Tv) \quad (6)$$

as av and m can be also expressed via solar altitude. The recommended formula for av is after Clear, 1982 reproduced by Navvab et al, 1984

$$av = F(m) = F(\gamma s) = \frac{1}{10.1 + 0.045\ m} \quad \text{or} \quad = \frac{1}{9.9 + 0.043\ m} \quad (7)$$

while after Kasten and Young, 1989 the optical mass m is:

$$m = F(\gamma s) = \frac{1}{\sin \gamma s + 0.50572\ (\gamma s + 6.07995°)^{-16364}} \quad (8)$$

If Gv and Dv or Pv are measured, then Pv/Ev = Gv/Ev - Dv/Ev and the luminous turbidity Tv can be calculated as

$$Tv = F(Pv/Ev, \gamma s) = \frac{-\ln Pv / Ev}{av\ m} \quad (9)$$

The actual value of Tv represents the number of absolutely clean atmospheric filter substituting a real, e.g. polluted atmospheres having the same filtering effect on the Pv/Ev ratio under the actual solar altitude and directional air mass. Evidently the lowest Tv value is one and the highest is indefinitely high corresponding to Pv/Ev = 0 in the direction of sun beams.
In other words the ratio Pv/Ev is dependent on only two basic variables and is suitable as the basis for the selection or specification of sunlight and sky conditions. This assumption is absolutely true for homogeneous skies with perfectly even turbidity in the atmosphere, when the diffuse sky illuminance Dv/Ev results from the very regular and smooth sky pattern usually forming the core of the Dv/Ev cluster (Kittler and Darula, 1997) with a definite Lz/Dv ratio. The vector like zenith luminance (Lz) influencing the resulting/scalar Dv/Ev level by its most effective normal position is capable to indicate by the Lz/Dv value the overall character of the sky pattern/type. Under cloudless or overcast sky conditions homogeneity is the most frequent case with a high probability of occurrence. However under arbitrary cloudy skies three parameters are essential for the case identification, i.e. global illuminance (Gv) or direct Pv together with simultaneous diffuse Dv and at least zenith luminance Lz have to be measures and to be interrelated in the normalised form Pv/Ev, Dv/Ev and Lz/Dv. This ´triple´ system in relation to solar altitude changes can be investigated within chosen turbidity ranges/groups in a series of triple diagrams using long term (e.g. 1-minute data within a year, 5-minute data in 3 years, or a year from different stations etc.). A set of twelve standard Tv ranges is recommended. A complete 36 diagram set analysing measured data in one year indicates by the number of cases in each triple set the frequency of occurrence in each range. Due to space limits so many diagrams cannot be placed in this paper. Under low Tv when the sun is unshaded by clouds the Pv/Ev diagrams show a Pv/Ev curve/range gradual increasing with solar altitude, the Dv/Ev clusters are short and Lz/Dv ratios are condensed in a relatively narrow space between 0.1 to 0.15. Typical are almost stable Lz/Dv values around 0.13 within 0 to 30° sun height then rising due to solar corona effect. In contrary, the group of skies with Tv>39 is usually the most numerous one with a relatively broad spreading zone crowded not only with overcast cases but containing also cloudy and even almost cloudless skies with a dense cloud blocking temporarily the sun, thus with Pv/Ev = 0. This overcrowdedness is caused by the fact that Tv is not capable to sort sky types with the common Pv/Ev zero values but different in luminance gradation. Also the Dv/Ev cluster cannot be used to sort the skies as the quite dark overcast with Dv/Ev from 0.1 to 0.3 overlay those occurring under clear skies. The Dv/Ev clusters are long and Lz/Dv ratios are similarly forming clusters although the majority of cases is within the overcast sky range of Lz/Dv between 0.31 to 0.43, i.e. between the uniform and the standard overcast skies. So it seems that under solar altitudes under 30° the Lz/Dv ratio is the only indicator of the typical sky patterns while the Dv/Ev ratio indicates whether this sky is bright or dark.

The proposed new generation of sky standards is utilising the Lz/Dv properties of homogeneous skies in all 15 basic types which cover the whole spectrum of usual skies found in reality. The standardisation concept is using a twin set of gradation functions $\varphi(Z)$ and indicatrix functions $f(\chi)$ each modelled by exponential approximations by the help of a, b, c, d and e parameters, Fig. 1 and 3. The fifteen standards are formed by chosen combinations of both functions (eq. (1) and (2)) defining the relative luminance distribution for luminance (L) in any standard sky element as:

$$\frac{L}{Lz} = \frac{f(\chi)\,\varphi(Z)}{f(Zs)\,\varphi(0°)} = F(Z, Zs, \chi) \qquad (10)$$

where the ratio of gradation functions φ is defined by eq. (1), the indicatrix function $f(\chi)$ by eq. (2) and the same function when $\chi = Zs$ is $f(Zs) = 1 + c[\exp(dZs) - \exp(d\pi/2)] + e \cos^2 Zs$.

Otherwise the Lz/Dv ratio can be calculated using the integration as:

$$\frac{Lz}{Dv} = \frac{\varphi(0°)\,f(Zs)}{\int_{Z=0}^{\pi/2} \int_{\alpha=0}^{2\pi} \left[\varphi(Z) f(\chi) \sin Z \cos Z\right] dZ\, d\alpha} \qquad (11)$$

i.e. $Lz/Dv = F(\varphi(Z), f(\chi), f(Zs)) = F(Z, Zs, \chi)$

Now an interesting fact is evident that for each proposed standard the Lz/Dv ratio is defined only by the angular distances of the sun and sky element from zenith and by the smallest angular distance of the sky element from sun position. For any solar altitude the integration can be done and graphically is represented in Fig. 7.
The following approximation of formula (11) for computing Lz/Dv was developed and has to be applied with different parameters B, C, D and E for every sky standard found by the best fit computer match for γ_s under 75° :

$$Lz/Dv = 1/133.8[\, B (\sin \gamma_s)^C / (\sin \gamma_s)(\cos \gamma_s)^D + E] \qquad (12)$$

As the normalisation has to respect also the cluster implication in Dv, i.e.

$$Dv = F(Dv/Ev, \gamma_s) = 133.8\, (Dv/Ev) \sin \gamma_s \qquad [klx] \qquad (13)$$

the absolute zenith luminance is then

$$Lz = F(Dv/Ev, \gamma_s) = Dv/Ev\, [\, B (\sin \gamma_s)^C / (\cos \gamma_s)^D + E \sin \gamma_s\,] \qquad [kcd/m^2] \qquad (14)$$

Note that in case of overcast skies with a unity indicatrix a constant Lz/Dv ratio results as the value of C=1, D=E=0, thus eq.(12) is simplified to

$$Lz/Dv = B/133.8 \qquad (15)$$

An almost perfect match was found when approximating Lz/Dv ratios for all sky standards by eq. (12) although the curvature of different gradation and indicatrix influences in Fig. 7 is changing. When the indicatrix function does not change the Lz/Dv curves are parallel which is evident in case of the intermediate skies when comparing curves for III.2 and IV.2, III.3 and IV.3 respectively. The curves are much condenser in case of clear sky standards which are very close to each other at solar altitude 30° and collide approximately at 52° to 60°. Thus the Lz/Dv ratio as an indicator of sky type is perfectly selective for solar altitudes under 30° while at higher sunheights all clear sky patterns are almost identical and their differences are very uncertain.
Using the computer best fit routine for all five clear sky standards their B, C, D and E parameters in eq. (12) were found for the modelling of the Dv/Ev fan. While the Dv/Ev ratio is effected mainly by the overall cloudiness and turbidity conditions, Lz/Dv represents also the relation of the cloud influence in zenith with the turbidity in the direction of the sun beams which can be expressed by the luminous turbidity factor Tv. This at the same time indicates the filtering or shading effects of clouds on sunshine and determines the direct sunlight. So an additional approximation of Lz as a function of Tv was found

by a matching best fit for every standard sky which is expressed in a general formula valid for all intermediate and clear cases with a forward prolonged indicatrix:

$$Lz = F(Tv, \gamma_s) = A\sin\gamma_s + 0.7(Tv+1)(\sin\gamma_s)^C / (\cos\gamma_s)^D + 0.04Tv \qquad [kcd/m^2] \qquad (16)$$

where $A = A1\ Tv + A2$ (17)

While C and D exponents are the same as in eq. (12) or (16) both A, respectively A1 and A2 are interconnecting the E parameters and particular Dv/Ev ratios with prevailing Tv influences under an actual sky standard. All these parameters for the fifteen standard skies were defined by the best fit procedures and are summarised in Table 2 as well as in the Catalogue with specification for each sky standard.
When using the new generation of sky standards and predicting corresponding absolute Lz and Dv values there are three possible alternatives of calculation or procedures that can be followed:

Alt. 1. If no other information is available but the assumption of a certain standard sky, then critical Dv/Ev can be taken or assumed to calculate expected Dv after eq. (13) and Lz after eq. (14) and thus define also sky luminance distribution after eq. (10) if necessary. At the same time a check using Lz/Dv ratio is recommended by dividing Lz with resultant Dv obtained by the integration of the sky pattern and a comparison with Lz/Dv calculated after eq. (11) and (12) or (13) respectively.. This checking procedure can match various results under Dv/Ev critical or any arbitrary ratio. Although the Dv/Ev level has to correspond to certain associated turbidity, it is the advantage of the Dv/Ev parametrisation that it is based solely on the sky illuminance level and therefore applicable also under overcast sky conditions.

Alt. 2. If under clear and intermediate skies the solar direct Pv or Pv/Ev is needed then a certain turbidity factor Tv has to be assumed and calculation of Lz is to follow from eq. (16) and the relative luminance distribution applying formula (10) and by its integration the Dv is to be determined if necessary.. Of course again the Lz/Dv check can be made as well as Dv/Ev level corresponding to the Tv factor is predictable. Finally using eq. (5) or (6) Pv or Pv/Ev can be calculated for the forehand known Tv and any solar altitude.

Alt 3. If Lz and Dv are measured or Lz/Dv known then the affiliation of such daylight conditions to a particular sky standard is possible either by the help of Fig. 7 or using eq. (11) or (12). The additional needed information, e.g. Dv/Ev, Dv or Pv and Pv/Ev can again yield eq. (5), (6) and (13) if Tv can be derived from measured Gv. The Dv/Ev level and Tv value can then characterise the case in the Dv/Ev and Tv clusters respectively and indirectly the character and tendecies of the gradation and indicatrix function can be predicted.

The adoption of a new generation of sky standards will enable a more accurate definition of daylight climate with its particular character in specific climate zones or locations as well as a better simulation of illuminance changes to calculate energy savings in daylit buildings. For a more realistic model of daylighting dimming systems the Lz/Dv ratio seems to provide a base of the photosensor control and a useful parameter for the computer driven simulation and regulation system. It is also quite important to implement a new system of comparative sky luminance and direct solar illuminance values linked to sky/diffuse illuminance levels for the computer simulation of the daylight performance in interiors. Thus a better insight into the prediction of interior daylighting using either traditional or advanced daylight systems during the design stage predetermine higher quality results in environmental comfort, health and ergonomic conditions in building interiors world-wide.

Conclusions: A new set of sky standards and calculation means to predetermine sky patterns and resulting sky illuminance

Preserving the previous good experience with the current existing CIE Sky standards a new generation was based on future needs and progressive concepts. Although the old CIE Overcast Sky Standard was redefined using a general exponential approximation formula (instead of cosine relation), both valid CIE Clear Sky Standards for clean and polluted atmospheres were incorporated in this sky set. At the same time representative available sky scan data measured at Berkeley, CA, Sydney and Tokyo were analysed and validated for the selection of typical scattering indicatrices and gradation specifications. These enabled a more precise sky classification and sky pattern definition.

Furthermore minute illuminance and zenith luminance data gathered at Bratislava, SK, Albany NY and Berkeley, CA have been parametrised and sky nonhomegeneity was detected using Lz/Dv ratios as well as Dv/Ev and Tv cluster formations. So a better understanding of covering and structuring of daylight conditions with typical sky type ranges linked with direct sunlight levels enabled their modelling by Dv/Ev and Tv ´fan´ simulations.

In consequence systematic matching of the sky luminance distribution (determined by parametrised indicatrix and gradation functions valid world-wide) with the resulting horizontal sky and sunlight illuminance was achieved, expressed and modelled mathematically. Thus a unique physical system could be approximated by general formulae with specific parameters on a high level of precision and possible computer application. If for practical purposes a certain sky standard can be prescribed, then using the prepared user friendly computer program very easily and quickly will be available complete information on the sky luminance distribution, resulting horizontal sky and sunlight illuminance at any arbitrary solar altitude/position or time. Several examples of this sort are demonstrated in Appendix L indicating possible practical application of the developed computer program with different choices of alternative output.

For the purpose of a quick review there is appended to the main text of this final report also a complete catalogue of all fifteen sky standards in the proposed set.

The choice of a critical standard or a set of standards is to be based on national studies of sky frequency occurrences and on the purpose-oriented codes of practice for several application regions:

- for daylight design needs, e.g. window design, comparison of alternative solutions applying effective daylight systems, proportional side and top-lit apertures, control systems for supplementary artificial lighting etc.,
- for evaluations of solar energy utilisation or energy trade-off issues when temporal and prevailing spatial influences have to be stated with regard to energy and operational economy,
- for environmental studies and discomfort glare predictions especially in cerebral-work interiors for which a sky standard has to simulate extremely bright situations affecting critical work places, e.g. VDU task areas with the need to shade sunlight and filter excessive skylight.

Although this new set of sky standards is to provide more flexibility in application at the same time a more detailed description and specification of daylight conditions will express not only the world-wide systematic unification and comparability but also the locally typical, most frequent or critical sky patterns. Thus applying certain sky standards from this proposed set can form the bases to solve various problems in energy conscious window design or serve to new calculation methods and means to predetermine artificial lighting control systems, visual comfort and glare aspects etc.

In a partial sense the universal sky specification and standardisation basis are important for a better and more effective utilisation of skylight which is a significant source of renewable energy and a significant environmental factor supporting the well-being of humanity. So the aims and results of this US-SK project are partly fulfilling also the resolution of the UNESCO World Solar Summit and its World Solar Programme 1996 - 2005 respectively.

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Table 1. 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	Usual 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 azimuthal uniformity**	**I :** a=4 b= -0.7	**1 :** c=0 d= -1 e= 0	0.05-0.3 seldom 0.25-0.4	0.03-0.25 **)	over 40 over 20	1:0.33 1:0.1 - 1:0.5	1:1 0.8:1 - 1.2:1	over 0.38	Including the current CIE Standard
I.2	**Overcast with the steep gradation and slight brightening toward sun**	**I :** a=4 b= -0.7	**2 :** c= 2 d= -1.5 e= 0.15	0.1 - 0.3 seldom >0.4	0.08-0.3	over 15	1:0.33 1:0.1 - 1:0.5	3:1 1.2:1 - 3.5:1	about 0.38	No direct sunlight sometimes darker or brighter skies
II.1	**Overcast moderately graded with azimuthal uniformity**	**II :** a= 1.1 b= -0.8	**1 :** c=0 d= -1 e= 0	0.1 - 0.35 usually brighter	0.08-0.4	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 graded and slight brightening toward sun**	**II :** a= 1.1 b= -0.8	**2 :** c= 2 d= -1.5 e= 0.15	0.15 - 0.45 usually brighter	0.15-0.5	usually around 15	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, foggy or cloudy with overall uniformity**	**III :** a=0 b= -1	**1 :** c=0 d= -1 e= 0	0.1 - 0.35	0.1-0.3	over 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	**Partly cloudy with a uniform gradation and slight brightening toward sun**	**III :** a=0 b= -1	**2 :** c= 2 d= -1.5 e= 0.15	0.2 - 0.5 usually over 0.3	0.2-0.5	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	**Partly cloudy with a brighter circumsolar effect and uniform gradation**	**III :** a=0 b= -1	**3 :** c= 5 d= -2.5 e= 0.3	usually 0.2 - 0.6	0.2-0.6	usually around 12	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

Table 1. Continued

SSLD Code	Type of sky	Standard gradation parameters	Standard indicatrix parameters	Frequent range Dv/Ev	Usual range Δ	Usual Tv range	Gradation Standard : Range:zenith :horizon	Indicatrix prolongation f(0°)/f(90°) Standard : Range :	Lz/Dv range *)	Comments
III.4	**Partly cloudy, rather uniform with a clear solar corona**	**III :** a=0 b= -1	**4 :** c=10 d= -3 e= 0.45	0.2 - 0.6	0.18 - 0.55	usually 5 - 12	1:1 1:0.85-1:1.35	11:1 7:1 - 13:1	0.22- 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	0.2 - 0.5	over 0.2	over 10	1:2.5 1:1.35 - 1:3	3:1 1.2:1 - 3.5:1	0.19 - 0.23	Filtered or no direct sunlight
IV.3	**Partly cloudy with brighter circumsolar effect**	**IV :** a= -1 b= -0.55	**3 :** c= 5 d= -2.5 e= 0.3	usually 0.2 - 0.5	0.2- 0.43	usually 6 - 12	1:2.5 1:1.35 - 1:3	6:1 3.5:1 - 7:1	0.17 - 0.20	Filtered direct sunlight
IV.4	**White-blue sky **) with a clear solar corona**	**IV :** a= -1 b= -0.55	**4 :** c=10 d= -3 e= 0.45	usually 0.15 - 0.5	0.1- 0.4	usually 2.5-6.5	1:2.5 1:1.35 - 1:3	11:1 7:1 - 13:1	0.15 - 0.17	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 0.1 - 0.4	0.06- 0.32	usually 2 - 5	1:3.5 1:3 - 1:5	11:1 7:1 - 13:1	0.13 - 0.16	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 0.2 - 0.5	0.10- 0.37	usually 3 - 8	1:3.5 1:3 - 1:5	17:1 13:1 - 20:1	0.12 - 0.15	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 - 0.4	0.10- 0.4	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	**White-blue turbid sky **) with a wide solar corona effect**	**VI :** a= -1 b= -0.15	**6 :** c=24 d= -2.8 e= 0.15	usually 0.15 - 0.5	0.12- 0.5	usually 3 - 8	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)

Table 2. A set of fifteen basic sky types/standards and their parametrisation

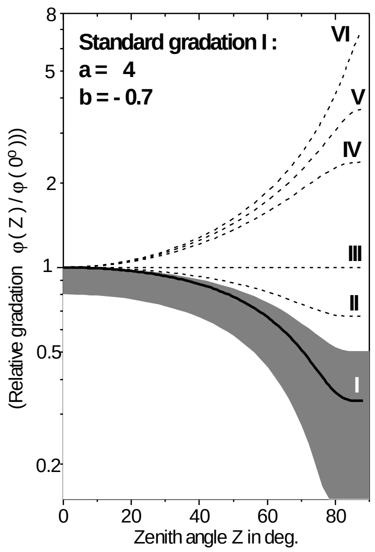
Code	Type of sky	Recommended or standardised parameters								
		for gradation	for indicatrix	typical Dv/Ev	B	C	D	E	for Lz as F(Tv)	typical cases
I.1	Overcast with the steep gradation and with azimuthal uniformity	a= 4 b= -0.7	c= 0 d= -1 e= 0	0.10	54.63	1.00	0.00	0.00	Because these sky standards are associated with no sunlight the relation Lz=F(Tv) is not valid	
I.2	Overcast with the steep gradation and slight brightening toward sun	a= 4 b= -0.7	c= 2 d= -1.5 e= 0.15	0.18	12.35	3.68	0.59	50.47		
II.1	Overcast moderately graded with azimuthal uniformity	a= 1.1 b= -0.8	c= 0 d= -1 e= 0	0.15	48.30	1.00	0.00	0.00		
II.2	Overcast moderately graded and slight brightening toward sun	a= 1.1 b= -0.8	c= 2 d= -1.5 e= 0.15	0.22	12.23	3.57	0.57	44.27		
III.1	Overcast, foggy or cloudy with overall uniformity	a= 0 b= -1	c= 0 d= -1 e= 0	0.20	42.59	1.00	0.00	0.00		
III.2	Partly cloudy with a uniform gradation and slight brightening toward sun	a= 0 b= -1	c= 2 d= -1.5 e= 0.15	0.38	11.84	3.53	0.55	38.78		
III.3	Partly cloudy with a brighter circumsolar effect and uniform gradation	a= 0 b= -1	c= 5 d= -2.5 e= 0.3	0.42	21.72	4.52	0.64	34.56	A1=0.957 A2=1.790	Tv=12.0 A=13.27
III.4	Partly cloudy, rather uniform with a clear solar corona	a= 0 b= -1	c= 10 d= -3 e= 0.45	0.41	29.35	4.94	0.70	30.41	A1=0.830 A2=2.030	Tv=10.0 A=10.33
IV.2	Partly cloudy with a shaded sun position	a= -1 b= -0.55	c= 2 d= -1.5 e= 0.15	0.40	10.34	3.45	0.50	27.47	A1=0.600 A2=1.500	Tv=12.0 A= 8.70
IV.3	Partly cloudy with brighter circumsolar effect	a= -1 b= -0.55	c= 5 d= -2.5 e= 0.3	0.36	18.41	4.27	0.63	24.04	A1=0.567 A2=2.610	Tv=10.0 A= 8.28
IV.4	White - blue sky with a clear solar corona	a= -1 b= -0.55	c= 10 d= -3 e= 0.45	0.23	24.41	4.60	0.72	20.76	A1=1.440 A2=-0.75	Tv= 4.0 A= 5.01
V.4	Very clear / unturbid with a clear solar corona	a= -1 b= -0.32	c= 10 d= -3 e= 0.45	0.15	23.00	4.43	0.74	18.52	A1=1.036 A2=0.710	Tv= 2.5 A= 3.30
V.5	Cloudless polluted with a broader solar corona	a= -1 b= -0.32	c= 16 d= -3 e= 0.3	0.28	27.45	4.61	0.76	16.59	A1=1.244 A2=-0.84	Tv= 4.5 A= 4.76
VI.5	Cloudless turbid with a broader solar corona	a= -1 b= -0.15	c= 16 d= -3 e= 0.3	0.28	25.54	4.40	0.79	14.56	A1=0.881 A2=0.453	Tv= 5.0 A= 4.86
VI.6	White - blue turbid sky with a wide solar corona effect	a= -1 b= -0.15	c= 24 d= -2.8 e= 0.15	0.30	28.08	4.13	0.79	13.00	A1=0.418 A2=1.950	Tv= 4.0 A= 3.62

SKY Standard

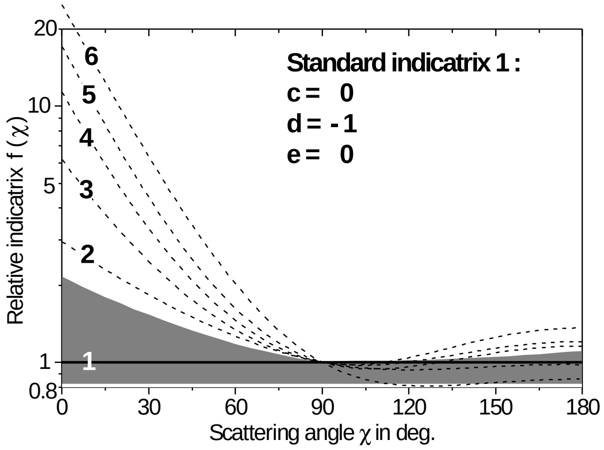
ICA SAS, Bratislava, Slovakia
ASRC, Albany , NY, U.S.A.

Overcast sky with the steep gradation and azimuthal uniformity

SSLD I.1



Place of sky type I.1 in the standard sky set :



Standard formula for relative luminance distribution :

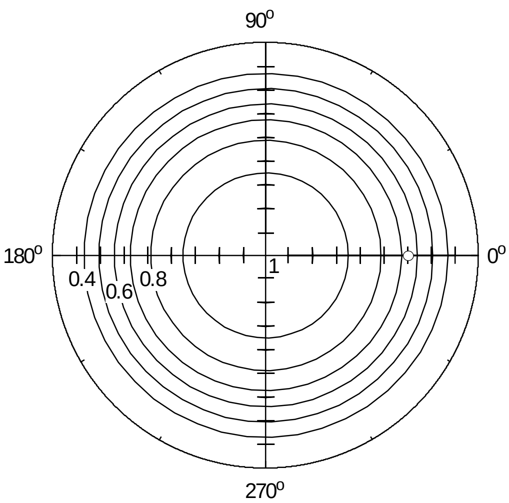
$$\frac{L_{\chi Z}}{L_{ZS}} = \frac{1 + 4\exp(-0.7/\cos Z)}{2.986}$$

where Z is the zenith angle

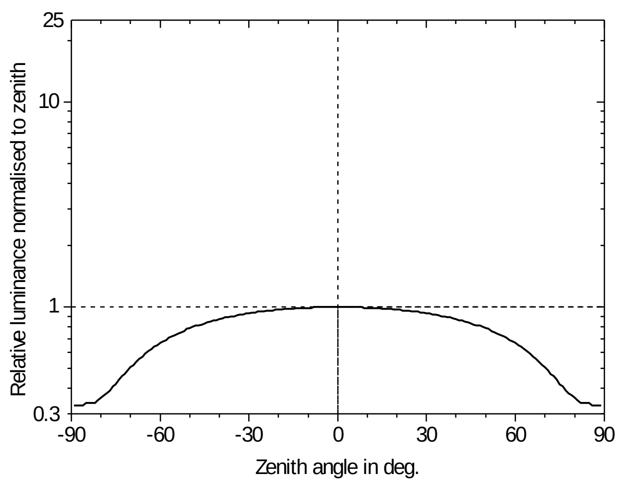
Table of approximate range and auxiliary conditions

Gradation scale zenith:horizon	Indicatrix scale	Frequent range Dv/Ev	Usual range Δ	Usual Tv range	Gradation range zenith:horizon	Indicatrix prolongation range	Probable range Lz/Dv*)
1 : 0.33	around 1	0.05-0.3	0.03-0.25	over 20	1:0.1 - 1:0.5	0.8:1 - 1.2:1	over 0.38
Note : *) The Lz/Dv value for an ideal standard I.1 is 0.408 at every solar altitude							

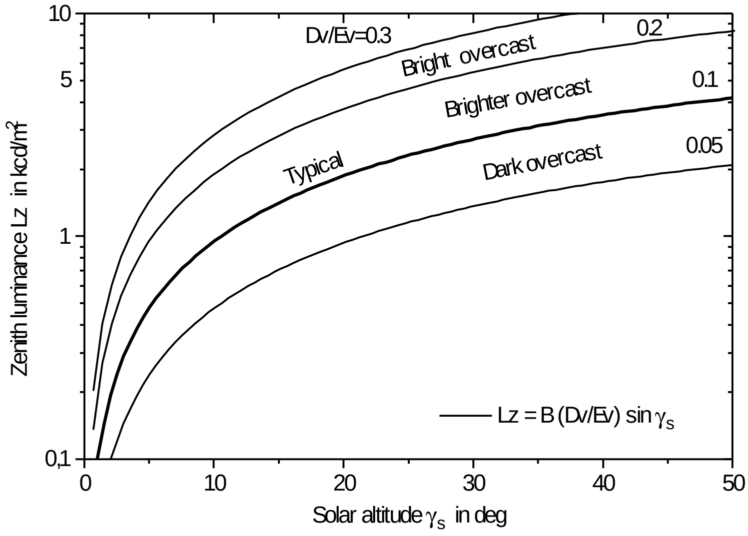
Example for Zs = 60°



Sky profile in solar meridian



SKY Standard ICA SAS, Bratislava, Slovakia ASRC, Albany , NY, U.S.A.	**Overcast sky with the steep gradation and azimuthal uniformity**	SSLD **I.1**



Probable zenith luminance Lz under this sky standard after :

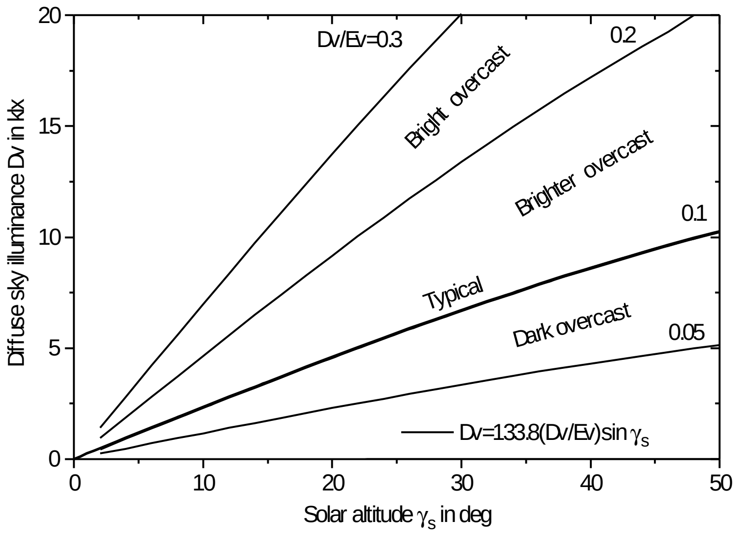
$$Lz = \frac{Dv}{Ev}\left[\frac{B\,(\sin\gamma_S)^C}{(\cos\gamma_S)^D} + E\sin\gamma_S\right]$$

with standard parameters

B	C	D	E
54.63	1	0	0

is simplified :

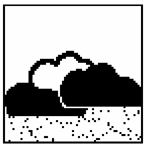
$$Lz = 54.63\,\frac{Dv}{Ev}\sin\gamma_S$$



Probable diffuse horizontal illuminance Dv under this sky standard is :

$$Dv = 133.8\,\frac{Dv}{Ev}\sin\gamma_S$$

Direct solar horizontal illuminance Pv = 0

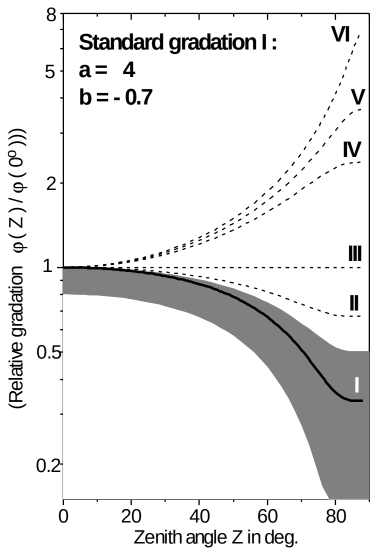


SKY Standard

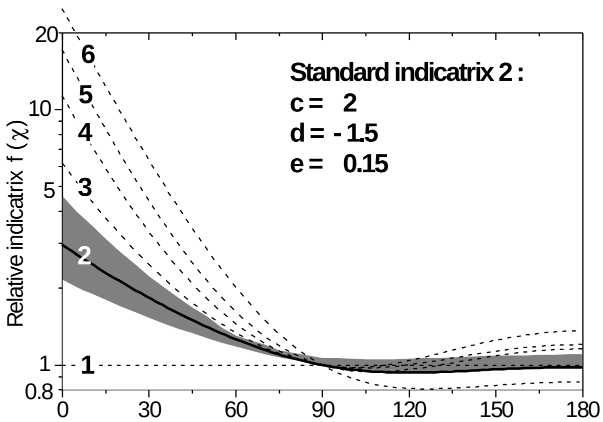
ICA SAS, Bratislava, Slovakia
ASRC, Albany , NY, U.S.A.

Overcast sky with the steep gradation and slight brightening toward sun

SSLD
I.2



Place of sky type I.2 in the standard sky set :



Standard formula for relative luminance distribution :

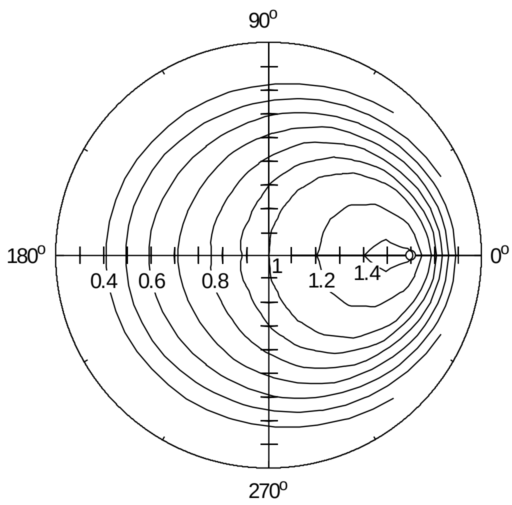
$$\frac{L_{\chi Z}}{L_{ZS}} = \frac{[1 + 4\exp(-0.7/\cos Z)]\left[0.81 + 2\exp(-15\chi) + 0.15\cos^2\chi\right]}{2.986\left[0.81 + 2\exp(-15\,Zs) + 0.15\cos^2 Zs\right]}$$

where χ is an angular distance between sun and sky element, i.e. scattering angle in rad
Zs is the zenith solar angle

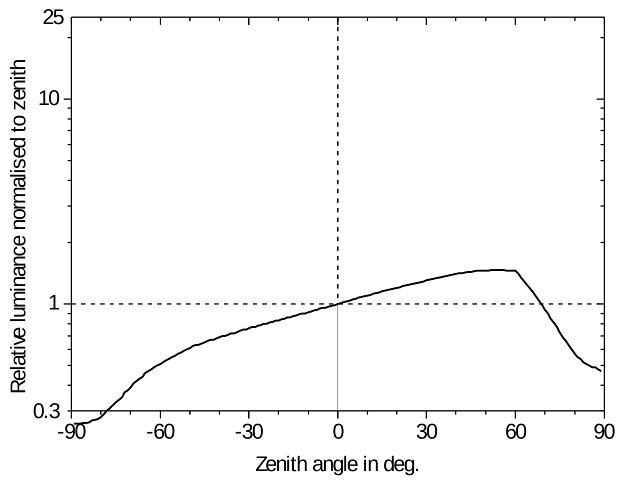
Table of approximate range and auxiliary conditions

Gradation scale zenith:horizon	Indicatrix scale	Frequent range Dv/Ev	Usual range Δ	Usual Tv range	Gradation range zenith:horizon	Indicatrix prolongation range	Probable range Lz/Dv*)
around 0.33	around 3	0.1 - 0.3	0.08-0.3	over 15	1:0.1 - 1:0.5	1.2:1 - 3.5:1	about 0.38
Note : *) The Lz/Dv range is valid only if Zs is over 60 degrees							

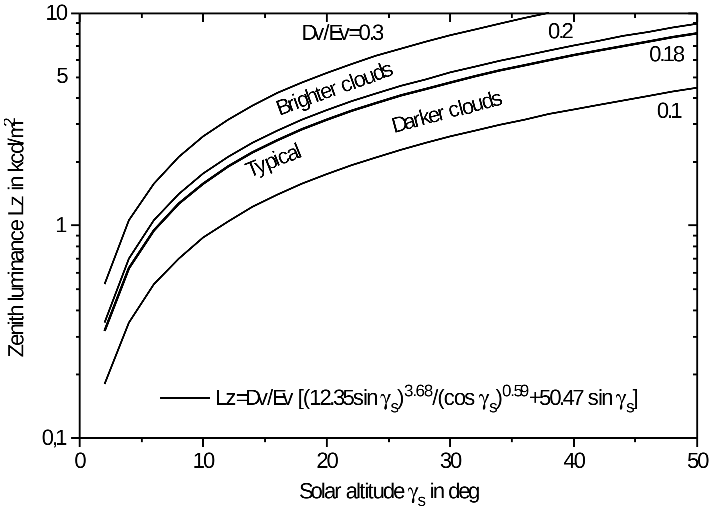
Example for Zs = 60°



Sky profile in solar meridian



	SKY Standard ICA SAS, Bratislava, Slovakia ASRC, Albany , NY, U.S.A.	**Overcast sky with the steep gradation and slight brightening toward sun**	SSLD **I.2**

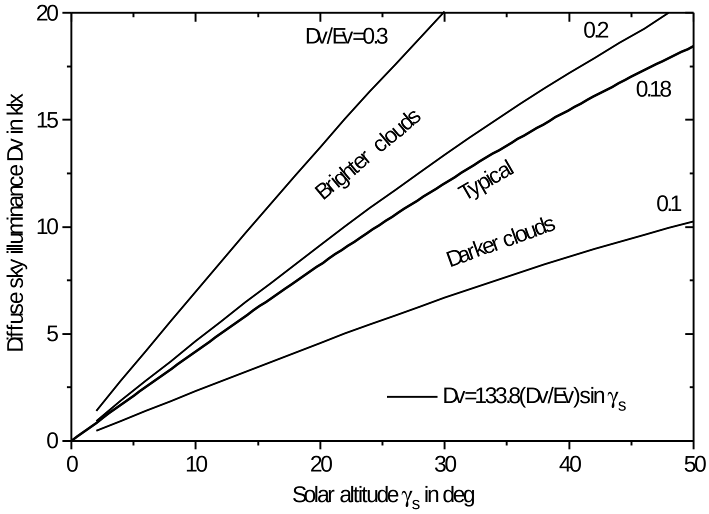


Probable zenith luminance Lz under this sky standard after :

$$Lz = \frac{Dv}{Ev}\left[\frac{B(\sin\gamma_S)^C}{(\cos\gamma_S)^D} + E\sin\gamma_S\right]$$

with standard parameters

B	C	D	E
12.35	3.68	0.59	50.47

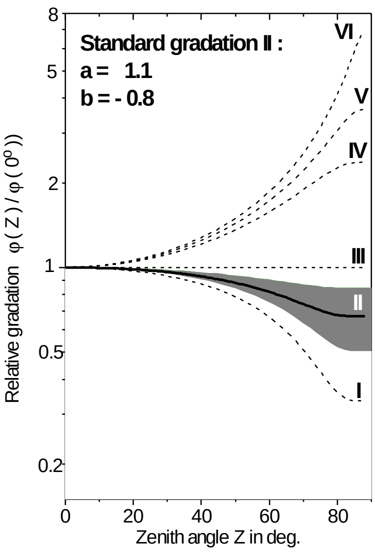


Probable diffuse horizontal illuminance Dv under this sky standard is :

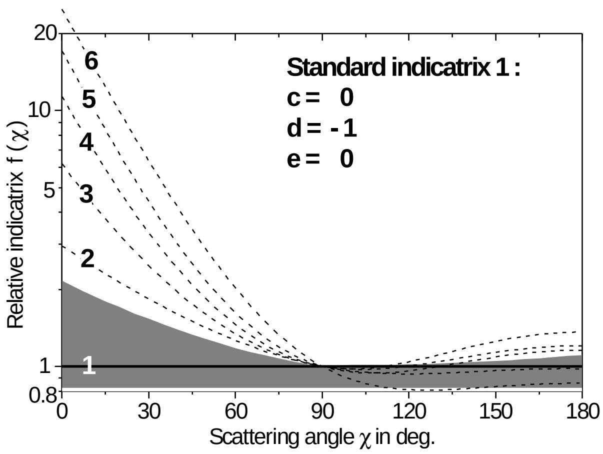
$$Dv = 133.8\frac{Dv}{Ev}\sin\gamma_S$$

Direct solar horizontal illuminance Pv = 0

SKY Standard	Overcast sky moderately graded with azimuthal uniformity	SSLD
ICA SAS, Bratislava, Slovakia ASRC, Albany , NY, U.S.A.		**II.1**



Place of sky type II.1 in the standard sky set :



Standard formula for relative luminance distribution :

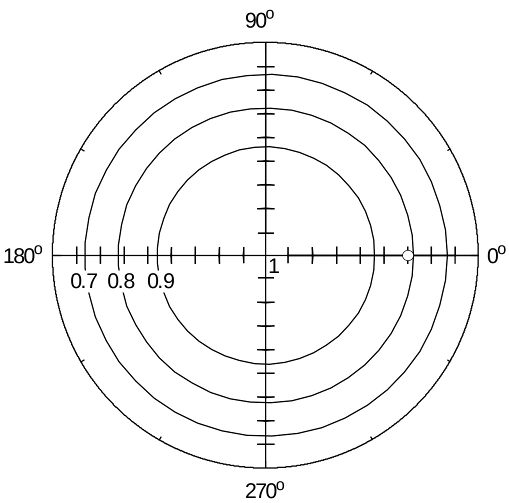
$$\frac{L_{\chi Z}}{L_{ZS}} = \frac{1 + 11\exp(-0.8 / \cos Z)}{1494}$$

where Z is the zenith angle

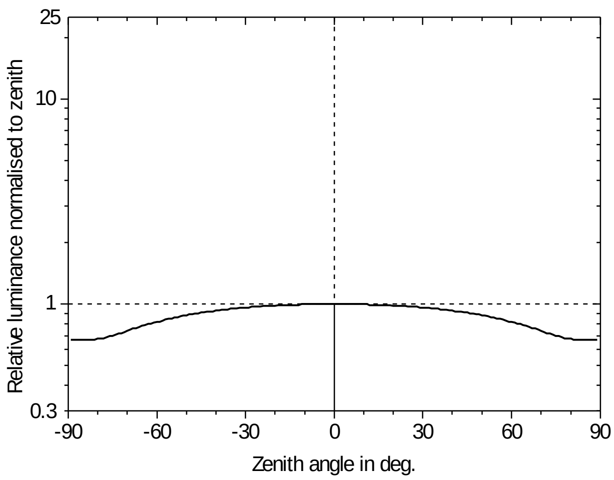
Table of approximate range and auxiliary conditions

Gradation scale zenith:horizon	Indicatrix scale	Frequent range Dv/Ev	Usual range Δ	Usual Tv range	Gradation range zenith:horizon	Indicatrix prolongation range	Probable range Lz/Dv*)
1 : 0.66	around 1	0.1-0.35	0.08-0.4	over 20	1:0.5 - 1:0.85	0.8:1 - 1.2:1	0.33-0.38
Note : *) The Lz/Dv value for an ideal standard **II**.1 is 0.361 at every solar altitude							

Example for Zs = 60°



Sky profile in solar meridian

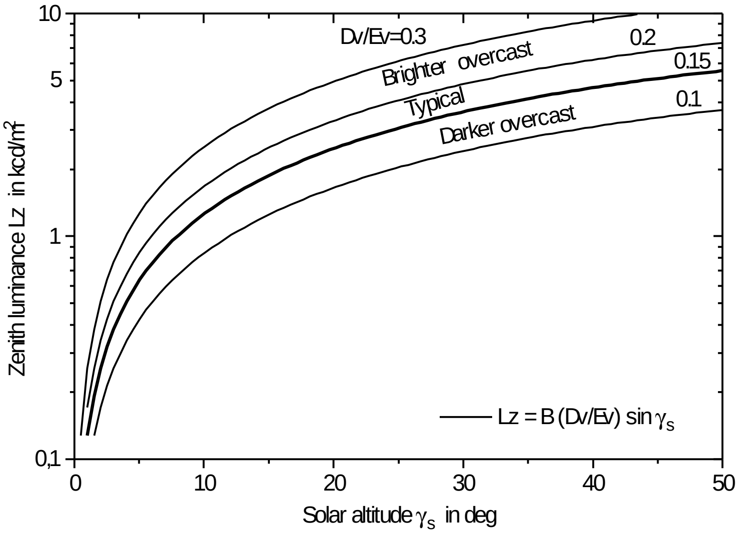


SKY Standard

ICA SAS, Bratislava, Slovakia
ASRC, Albany, NY, U.S.A.

Overcast sky moderately graded with azimuthal uniformity

SSLD II.1



Probable zenith luminance Lz under this sky standard after :

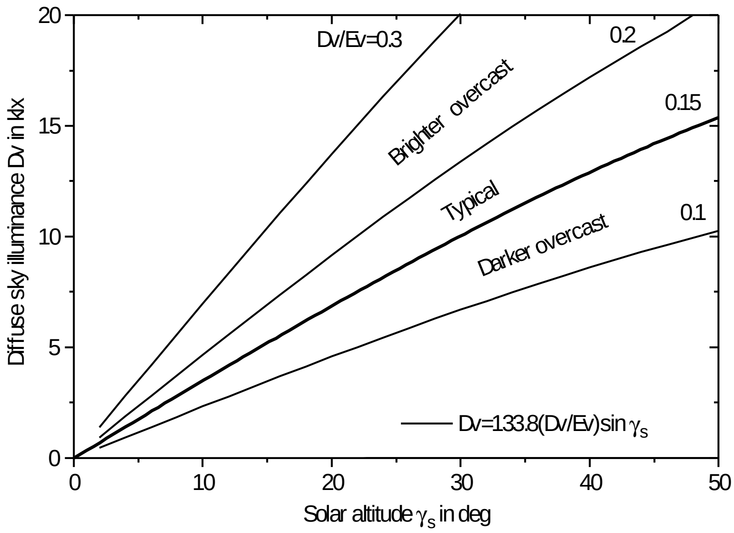
$$Lz = \frac{Dv}{Ev}\left[\frac{B\left(\sin\gamma_S\right)^C}{\left(\cos\gamma_S\right)^D} + E\sin\gamma_S\right]$$

with standard parameters

B	C	D	E
48.30	1	0	0

is simplified :

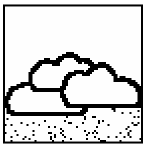
$$Lz = 48.30\,\frac{Dv}{Ev}\sin\gamma_S$$



Probable diffuse horizontal illuminance Dv under this sky standard is :

$$Dv = 133.8\,\frac{Dv}{Ev}\sin\gamma_S$$

Direct solar horizontal illuminance Pv = 0

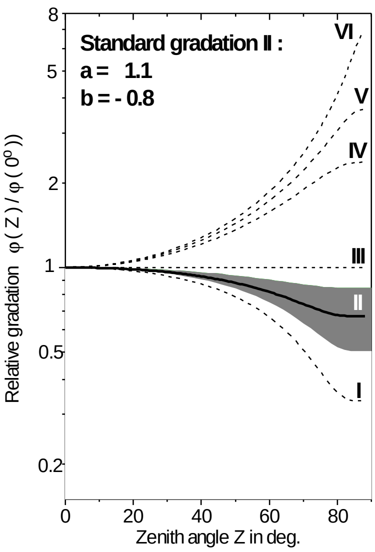


SKY Standard

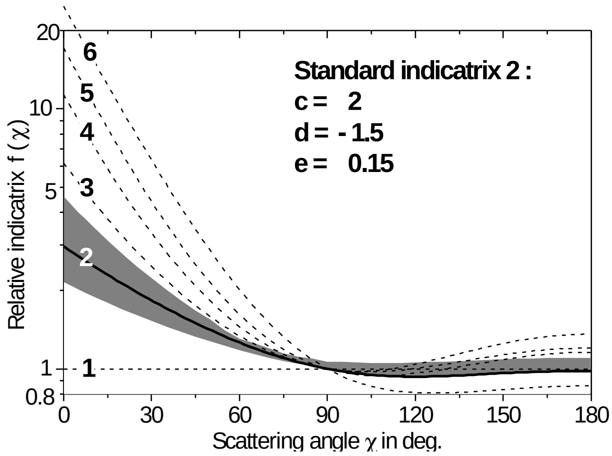
ICA SAS, Bratislava, Slovakia
ASRC, Albany , NY, U.S.A.

Overcast sky moderately graded and slight brightening toward sun

SSLD **II.2**



Place of sky type II.2 in the standard sky set :



Standard formula for relative luminance distribution :

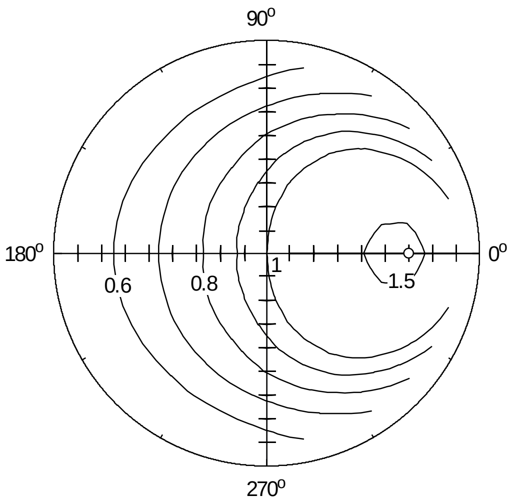
$$\frac{L_{\chi Z}}{L_{ZS}} = \frac{\left[1+11\exp(-0.8/\cos Z)\right]\left[0.81+2\exp(-15\chi)+0.15\cos^2\chi\right]}{1494\left[0.81+2\exp(-15\,Zs)+0.15\cos^2 Zs\right]}$$

where χ is an angular distance between sun and sky element, i.e. scattering angle in rad
Zs is the zenith solar angle

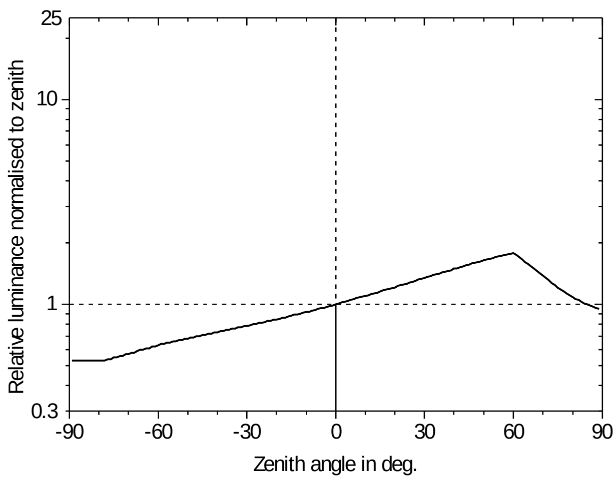
Table of approximate range and auxiliary conditions

Gradation scale zenith:horizon	Indicatrix scale	Frequent range Dv/Ev	Usual range Δ	Usual Tv range	Gradation range zenith:horizon	Indicatrix prolongation range	Probable range Lz/Dv*)
around 0.66	around 3	0.15-0.45	0.15-0.5	over 15	1:0.5 - 1:0.85	1.2:1 - 3.5:1	0.32-0.35
Note : *) The Lz/Dv range is valid only if Zs is over 60 degrees							

Example for Zs = 60°



Sky profile in solar meridian

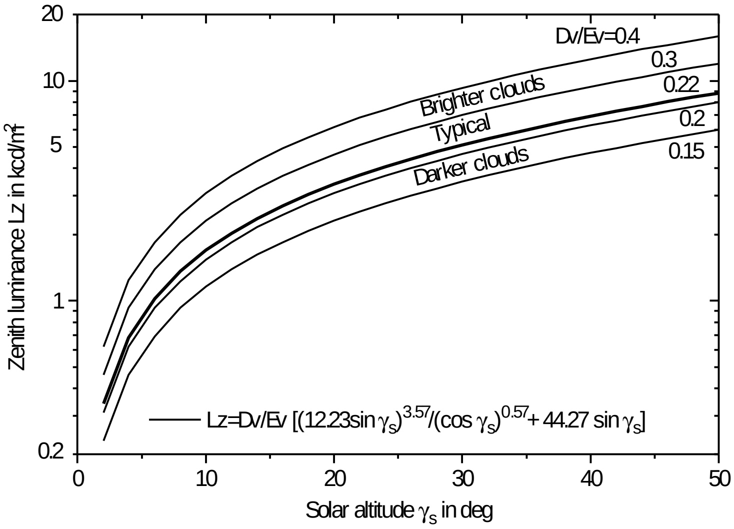


SKY Standard

ICA SAS, Bratislava, Slovakia
ASRC, Albany , NY, U.S.A.

Overcast sky moderately graded and slight brightening toward sun

SSLD **II.2**

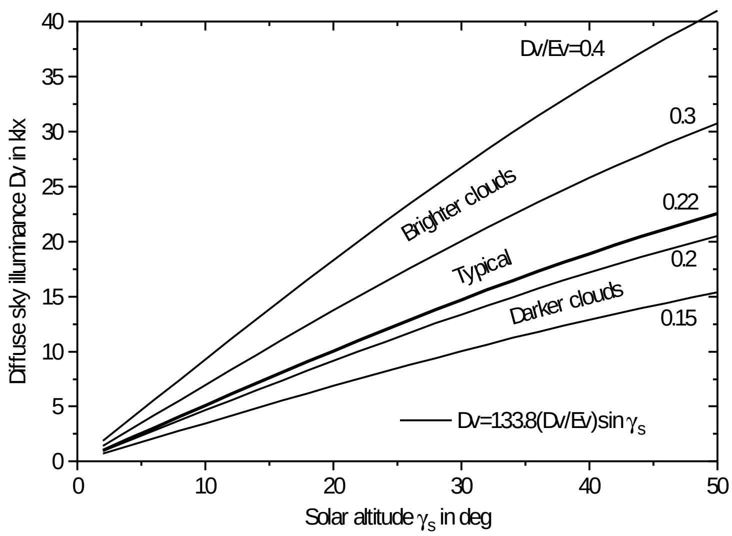


Probable zenith luminance Lz under this sky standard after :

$$Lz = \frac{Dv}{Ev}\left[\frac{B(\sin\gamma_S)^C}{(\cos\gamma_S)^D} + E\sin\gamma_S\right]$$

with standard parameters

B	C	D	E
12.23	3.57	0.57	44.27



Probable diffuse horizontal illuminance Dv under this sky standard is :

$$Dv = 133.8\,\frac{Dv}{Ev}\sin\gamma_S$$

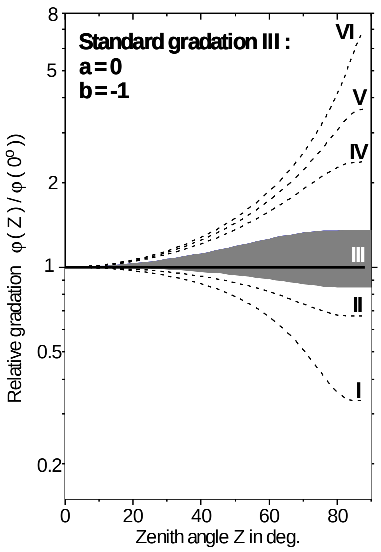
Direct solar horizontal illuminance Pv = 0

SKY Standard

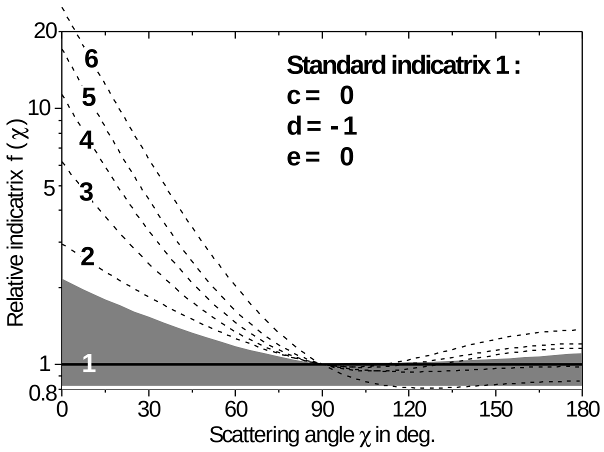
ICA SAS, Bratislava, Slovakia
ASRC, Albany , NY, U.S.A.

Overcast, foggy or cloudy sky with overall uniformity

SSLD III.1



Place of sky type III.1 in the standard sky set :



Standard formula for relative luminance distribution :

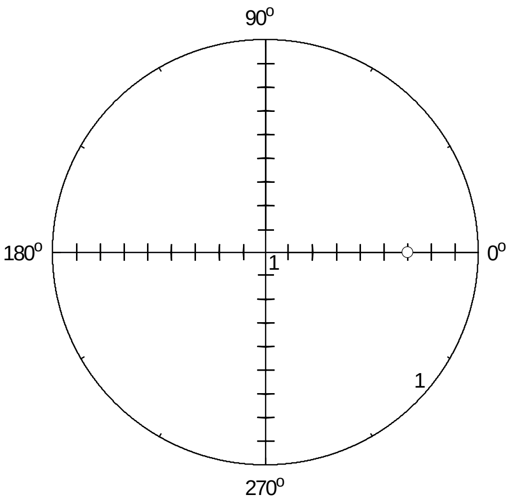
$$\frac{L_{\chi Z}}{L_{ZS}} = 1$$

where Z is the zenith angle

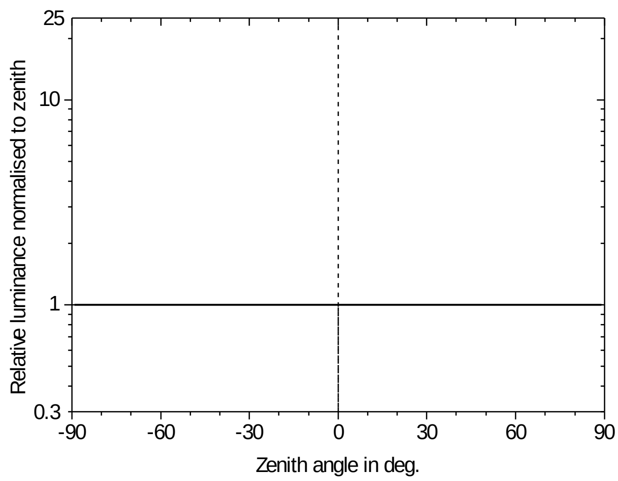
Table of approximate range and auxiliary conditions

Gradation scale zenith:horizon	Indicatrix scale	Frequent range Dv/Ev	Usual range Δ	Usual Tv range	Gradation range zenith:horizon	Indicatrix prolongation range	Probable range Lz/Dv*)
1 : 1	around 1	0.10-0.35	0.1-0.3	over 20	1:0.85 - 1:1.35	0.8:1 - 1.2:1	0.30-0.33
Note : *) The Lz/Dv value for an ideal standard III.1 is 0.318 at every solar altitude							

Example for Zs = 60°



Sky profile in solar meridian

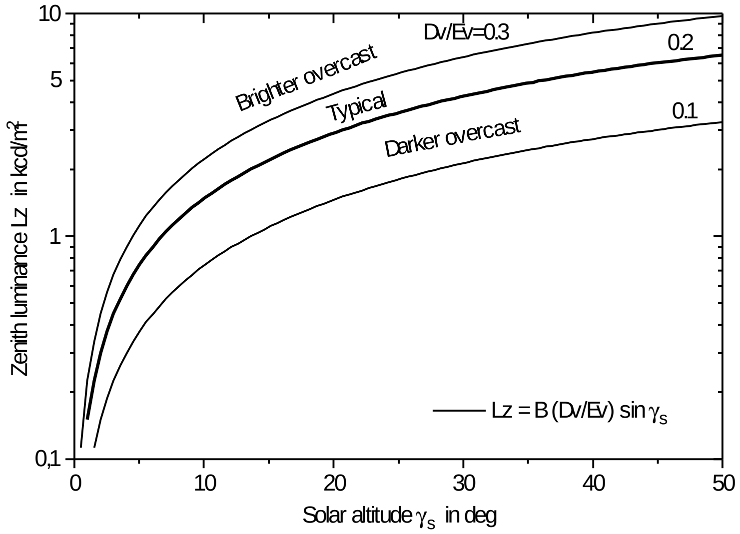


SKY Standard

ICA SAS, Bratislava, Slovakia
ASRC, Albany , NY, U.S.A.

Overcast, foggy or cloudy sky with overall uniformity

SSLD III.1



Probable zenith luminance Lz under this sky standard after :

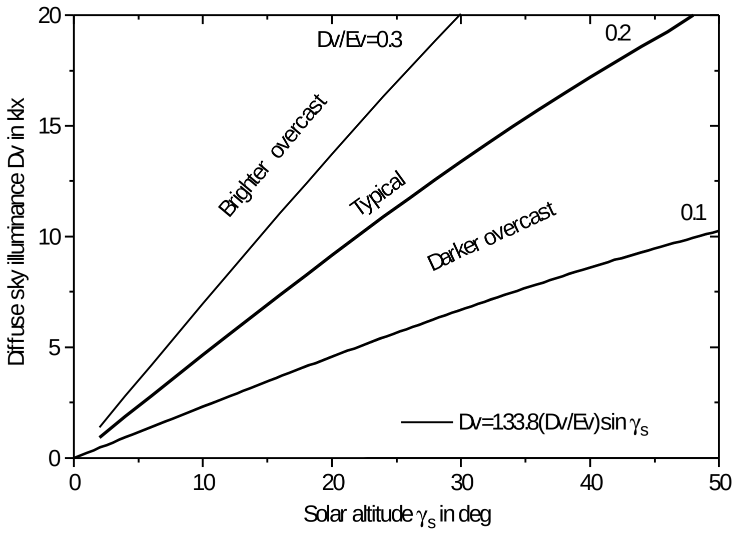
$$Lz = \frac{Dv}{Ev}\left[\frac{B\left(\sin\gamma_S\right)^C}{\left(\cos\gamma_S\right)^D} + E\sin\gamma_S\right]$$

with standard parameters

B	C	D	E
42.59	1	0	0

is simplified :

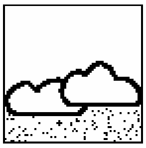
$$Lz = 42.59\,\frac{Dv}{Ev}\sin\gamma_S$$



Probable diffuse horizontal illuminance Dv under this sky standard is :

$$Dv = 133.8\,\frac{Dv}{Ev}\sin\gamma_S$$

Direct solar horizontal illuminance Pv = 0

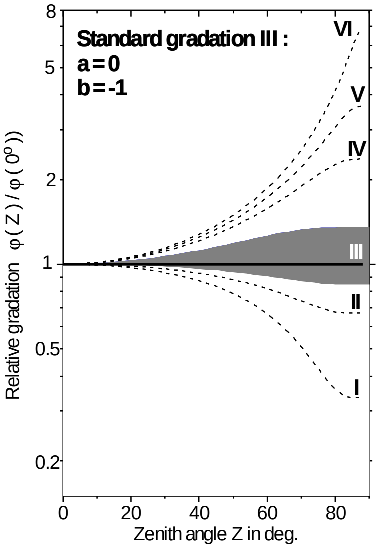


SKY Standard

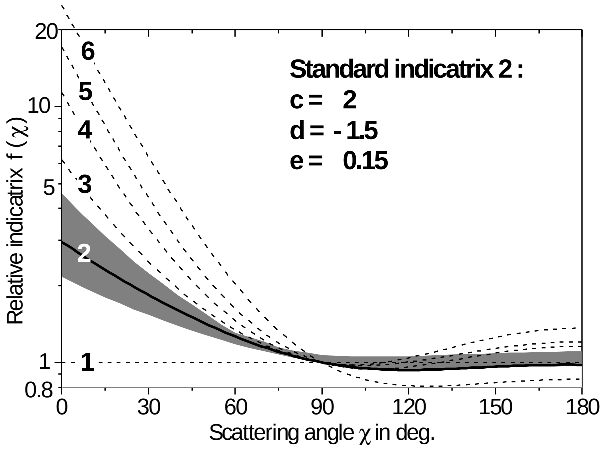
ICA SAS, Bratislava, Slovakia
ASRC, Albany , NY, U.S.A.

Partly cloudy sky with a uniform gradation and slight brightening toward sun

SSLD **III.2**



Place of sky type III.2 in the standard sky set :



Standard formula for relative luminance distribution :

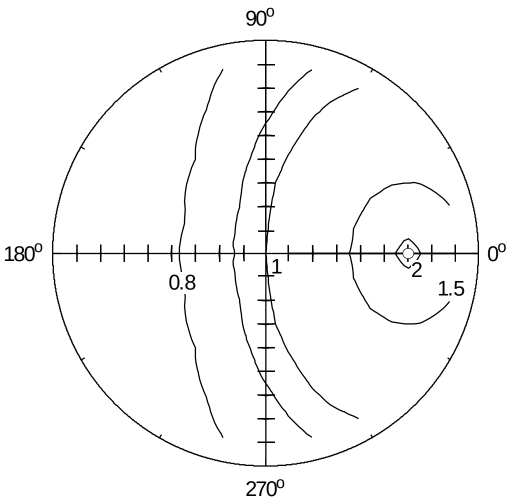
$$\frac{L_{\chi Z}}{L_{ZS}} = \frac{0.81 + 2\exp(-15\chi) + 0.15\cos^2\chi}{0.81 + 2\exp(-15\,Zs) + 0.15\cos^2 Zs}$$

where χ is an angular distance between sun and sky element, i.e. scattering angle in rad
Zs is the zenith solar angle

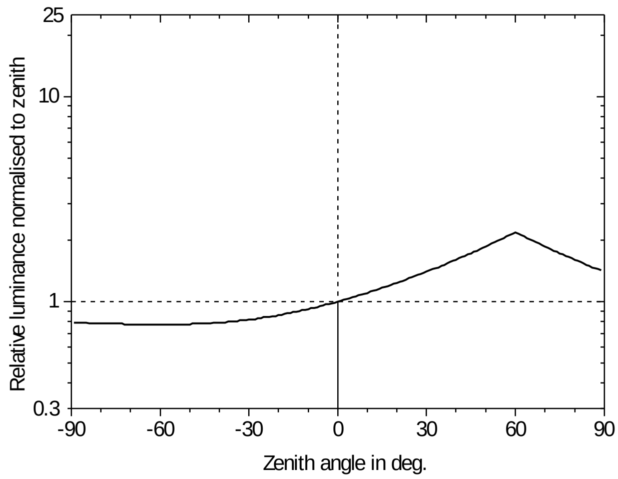
Table of approximate range and auxiliary conditions

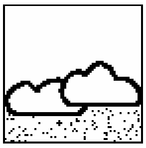
Gradation scale zenith:horizon	Indicatrix scale	Frequent range Dv/Ev	Usual range Δ	Usual Tv range	Gradation range zenith:horizon	Indicatrix prolongation range	Probable range Lz/Dv*)
around 1	around 3	0.2-0.5	0.2-0.5	around 15	1:0.85 - 1:1.35	1.2:1 - 3.5:1	0.27-0.32
Note : *) The Lz/Dv range is valid only if Zs is over 60 degrees							

Example for Zs = 60°



Sky profile in solar meridian



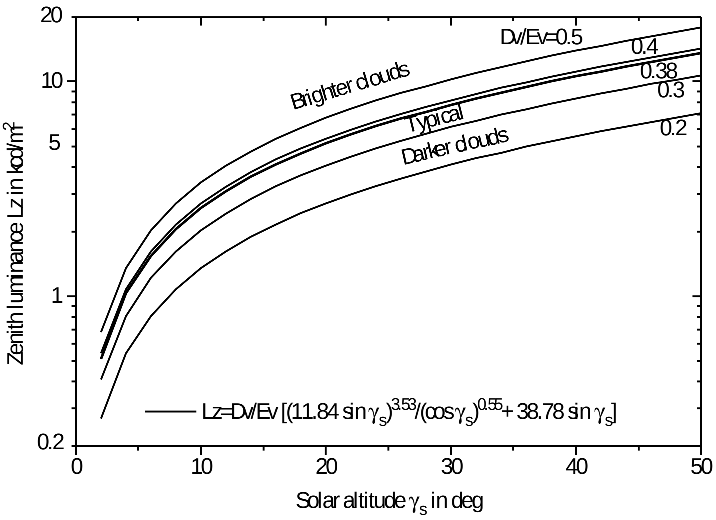


SKY Standard

ICA SAS, Bratislava, Slovakia
ASRC, Albany , NY, U.S.A.

Partly cloudy sky with a uniform gradation and slight brightening toward sun

SSLD III.2

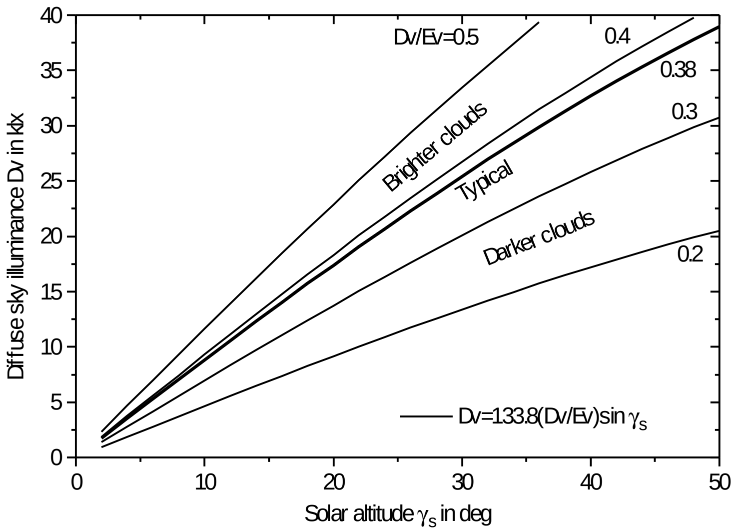


Probable zenith luminance Lz under this sky standard after :

$$Lz = \frac{Dv}{Ev}\left[\frac{B(\sin\gamma_S)^C}{(\cos\gamma_S)^D} + E\sin\gamma_S\right]$$

with standard parameters

B	C	D	E
11.84	3.53	0.55	38.78

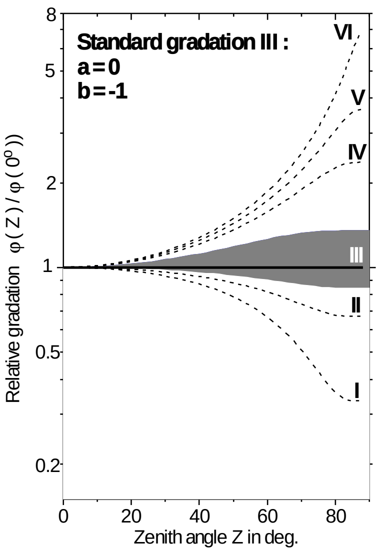


Probable diffuse horizontal illuminance Dv under this sky standard is :

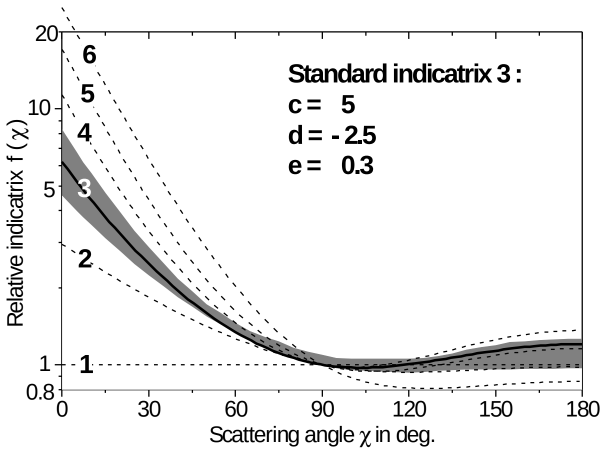
$$Dv = 133.8\frac{Dv}{Ev}\sin\gamma_S$$

Direct solar horizontal illuminance Pv = 0

	SKY Standard ICA SAS, Bratislava, Slovakia ASRC, Albany , NY, U.S.A.	**Partly cloudy sky with a brighter circumsolar effect and uniform gradation**	SSLD **III.3**



Place of sky type III.3 in the standard sky set :



Standard formula for relative luminance distribution :

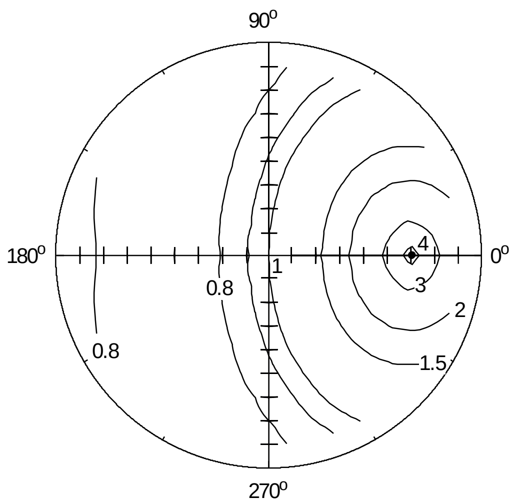
$$\frac{L_{\chi Z}}{L_{Zs}} = \frac{0.901 + 5\exp(-2.5\chi) + 0.3\cos^2\chi}{0.901 + 5\exp(-2.5\, Zs) + 0.3\cos^2 Zs}$$

where χ is an angular distance between sun and sky element, i.e. scattering angle in rad
Zs is the zenith solar angle

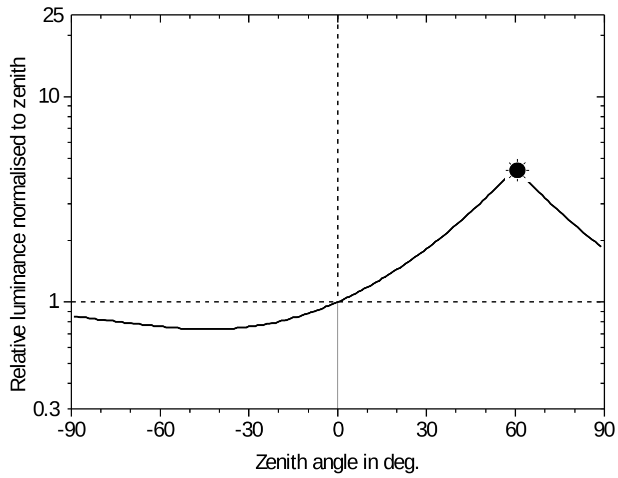
Table of approximate range and auxiliary conditions

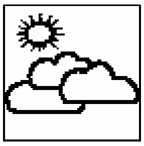
Gradation scale zenith:horizon	Indicatrix scale	Frequent range Dv/Ev	Usual range Δ	Usual Tv range	Gradation range zenith:horizon	Indicatrix prolongation range	Probable range Lz/Dv*)
around 1	around 6	0.2-0.6	0.2-0.6	around 12	1:0.85 - 1:1.35	3.5:1 - 7:1	0.25-0.30
Note : *) The Lz/Dv range is valid only if Zs is over 60 degrees							

Example for Zs = 60°



Sky profile in solar meridian



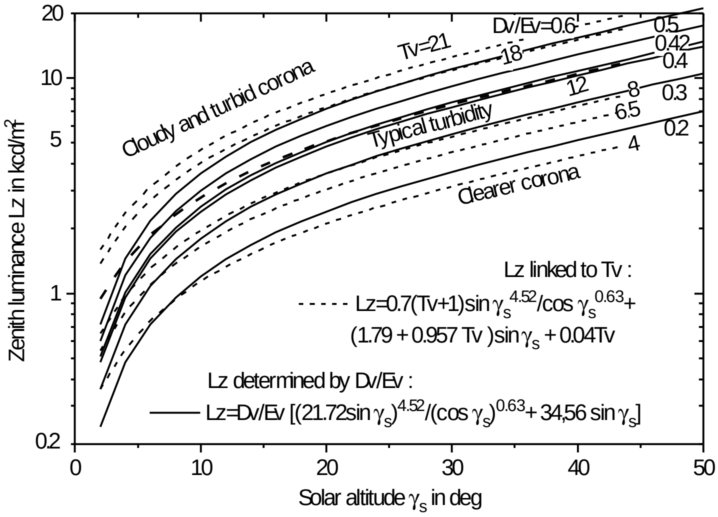


SKY Standard

ICA SAS, Bratislava, Slovakia
ASRC, Albany , NY, U.S.A.

Partly cloudy sky with a brighter circumsolar effect and uniform gradation

SSLD **III.3**



Probable zenith luminance Lz under this sky standard after :

$$Lz = \frac{Dv}{Ev}\left[\frac{B\,(\sin\gamma_S)^C}{(\cos\gamma_S)^D} + E\sin\gamma_S\right]$$

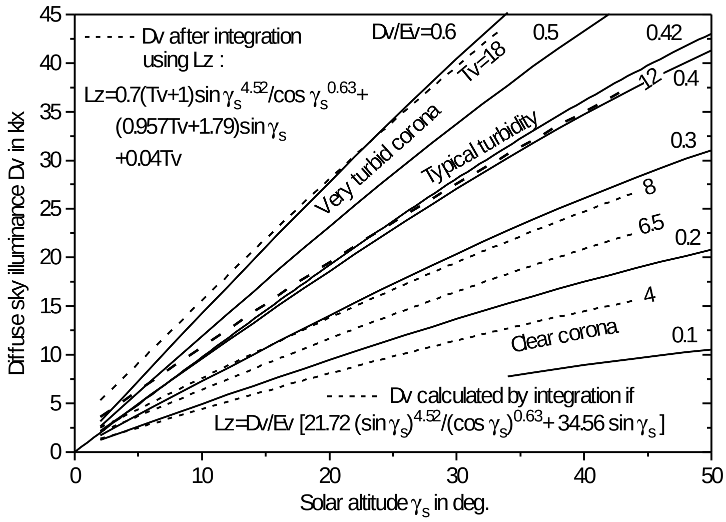
$$Lz = A\sin\gamma_S + \frac{0.7(Tv+1)(\sin\gamma_S)^C}{(\cos\gamma_S)^D} + 0.04\,Tv$$

where $A = A1\,Tv + A2$

i.e. for typical turbidity Tv=12, A=13.27

with standard parameters

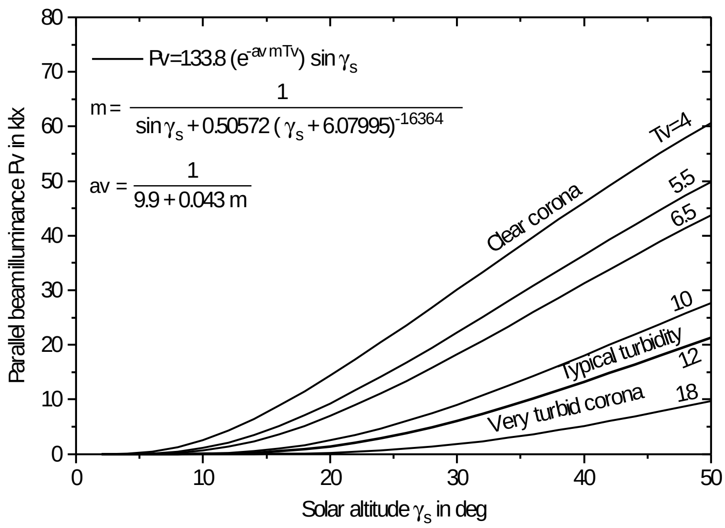
A1	A2	B	C	D	E
0.957	1.79	21.72	4.52	0.64	34.56



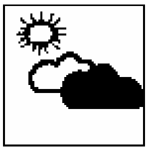
Diffuse horizontal illuminance Dv after a general formula :

$$Dv = 133.8\,\frac{Dv}{Ev}\,\sin\gamma_S$$

is equal to Dv calculated by integration of the luminace pattern



Probable direct solar horizontal illuminance Pv under this sky standard

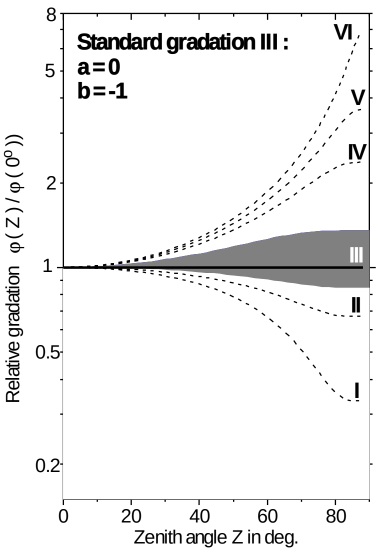


SKY Standard

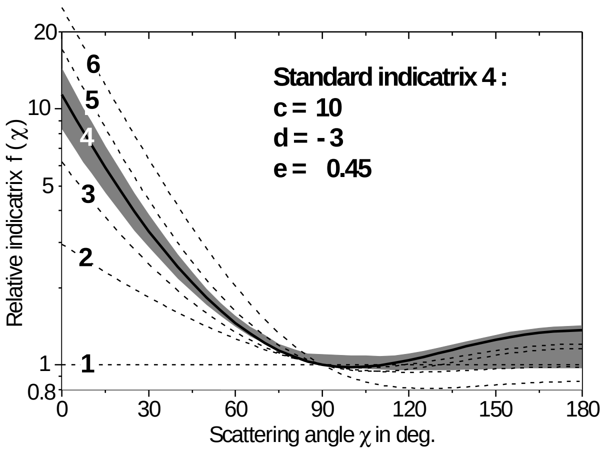
ICA SAS, Bratislava, Slovakia
ASRC, Albany , NY, U.S.A.

Partly cloudy sky rather uniform with a clear solar corona

SSLD **III.4**



Place of sky type III.4 in the standard sky set :



Standard formula for relative luminance distribution :

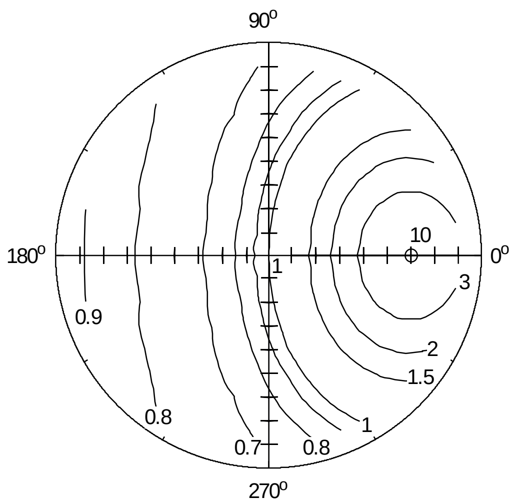
$$\frac{L_{\chi Z}}{L_{Zs}} = \frac{0.91 + 10\exp(-3\chi) + 0.45\cos^2\chi}{0.91 + 10\exp(-3\,Zs) + 0.45\cos^2 Zs}$$

where χ is an angular distance between sun and sky element, i.e. scattering angle in rad
Zs is the zenith solar angle

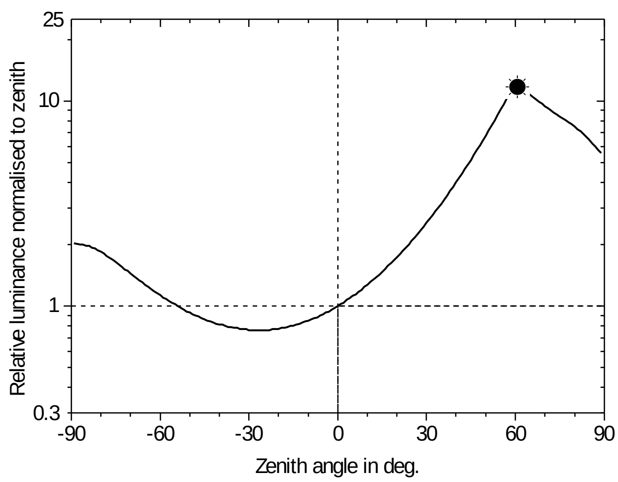
Table of approximate range and auxiliary conditions

Gradation scale zenith:horizon	Indicatrix scale	Frequent range Dv/Ev	Usual range Δ	Usual Tv range	Gradation range zenith:horizon	Indicatrix prolongation range	Probable range Lz/Dv*)
around 1	around 11	0.2 - 0.6	0.18-0.55	5 - 12	1:0.85 - 1:35	7:1 - 13:1	0.22-0.26
Note : *) The Lz/Dv range is valid only if Zs is over 60 degrees							

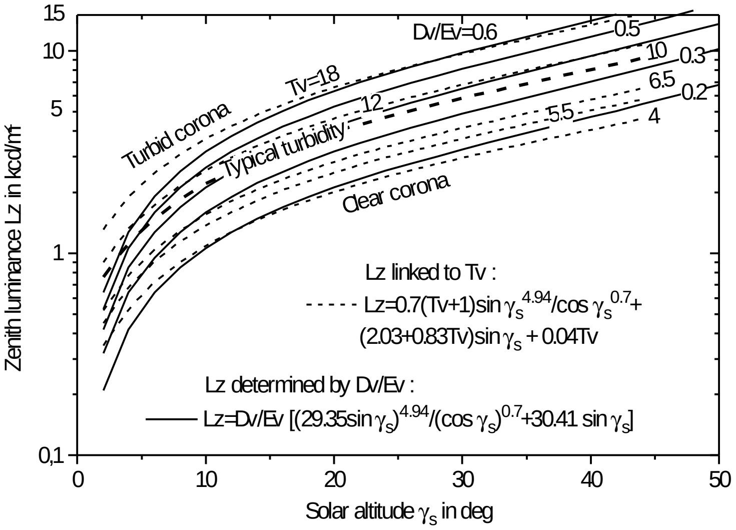
Example for Zs = 60°



Sky profile in solar meridian



	SKY Standard ICA SAS, Bratislava, Slovakia ASRC, Albany , NY, U.S.A.	**Partly cloudy sky rather uniform with a clear solar corona**	SSLD **III.4**



Probable zenith luminance Lz under this sky standard after :

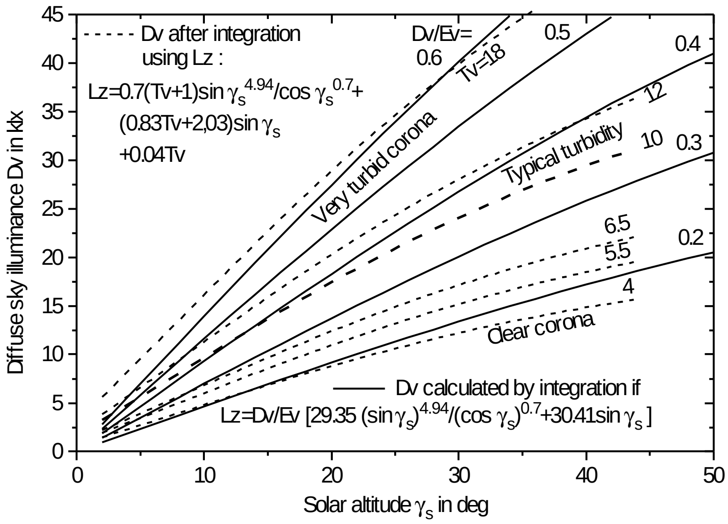
$$Lz = \frac{Dv}{Ev}\left[\frac{B\left(\sin\gamma_S\right)^C}{\left(\cos\gamma_S\right)^D} + E\sin\gamma_S\right]$$

$$Lz = A\sin\gamma_S + \frac{0.7(Tv+1)(\sin\gamma_S)^C}{(\cos\gamma_S)^D} + 0.04Tv$$

where $A = A1Tv + A2$
i.e. for typical turbidity Tv=10,A=10.33

with standard parameters

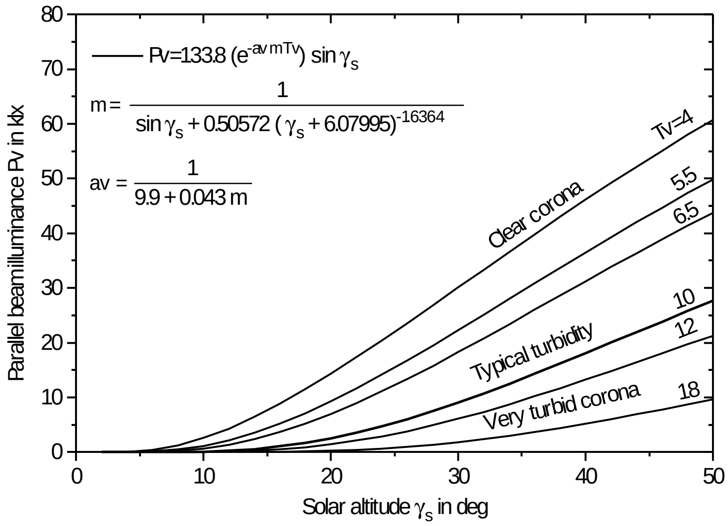
A1	A2	B	C	D	E
0.83	2.03	29.35	4.94	0.70	30.41



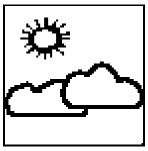
Diffuse horizontal illuminance Dv after a general formula :

$$Dv = 133.8\,\frac{Dv}{Ev}\sin\gamma_S$$

is equal to Dv calculated by integration of the luminace pattern



Probable direct solar horizontal illuminance Pv under this sky standard

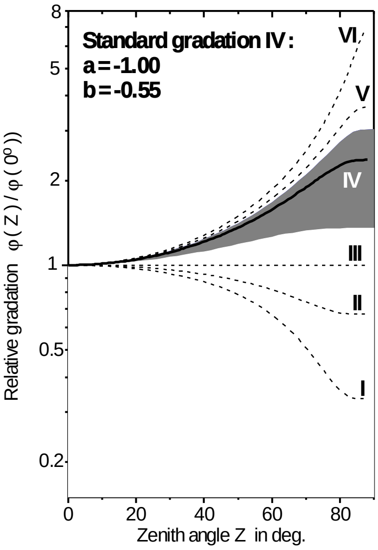


SKY Standard

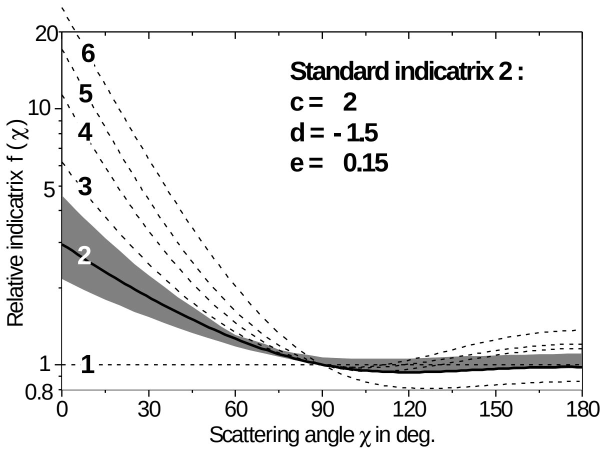
ICA SAS, Bratislava, Slovakia
ASRC, Albany , NY, U.S.A.

Partly cloudy sky with a shaded sun position

SSLD IV.2



Place of sky type IV.2 in the standard sky set :



Standard formula for relative luminance distribution :

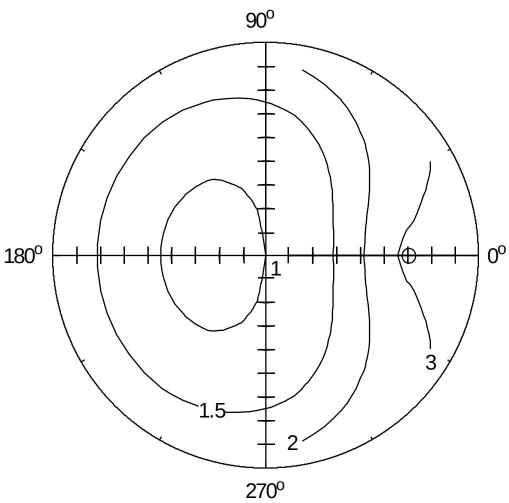
$$\frac{L_{\chi Z}}{L_{ZS}} = \frac{[1-\exp(-0.55 / \cos Z)][0.81+2\exp(-15\chi)+0.15\cos^2\chi]}{0.423[0.81+2\exp(-15\, Zs)+0.15\cos^2 Zs]}$$

where χ is an angular distance between sun and sky element, i.e. scattering angle in rad
Zs is the zenith solar angle

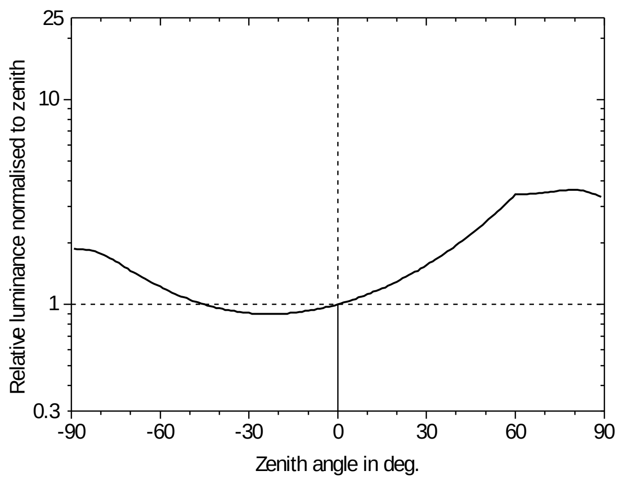
Table of approximate range and auxiliary conditions

Gradation scale zenith:horizon	Indicatrix scale	Frequent range Dv/Ev	Usual range Δ	Usual Tv range	Gradation range zenith:horizon	Indicatrix prolongation range	Probable range Lz/Dv*)
around 1:2.5	around 3	0.2-0.5	over 0.2	over 10	1:1.35 - 1:3	1.2:1 - 3.5:1	0.19-0.23
Note : *) The Lz/Dv range is valid only if Zs is over 60 degrees							

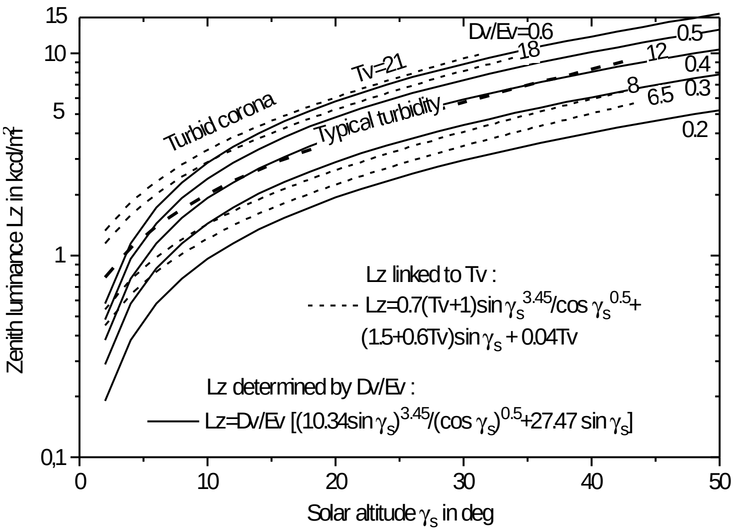
Example for Zs = 60°



Sky profile in solar meridian



SKY Standard	Partly cloudy sky with a shaded sun position	SSLD
ICA SAS, Bratislava, Slovakia ASRC, Albany , NY, U.S.A.		**IV.2**



Probable zenith luminance Lz under this sky standard after :

$$Lz = \frac{Dv}{Ev}\left[\frac{B(\sin\gamma_S)^C}{(\cos\gamma_S)^D} + E\sin\gamma_S\right]$$

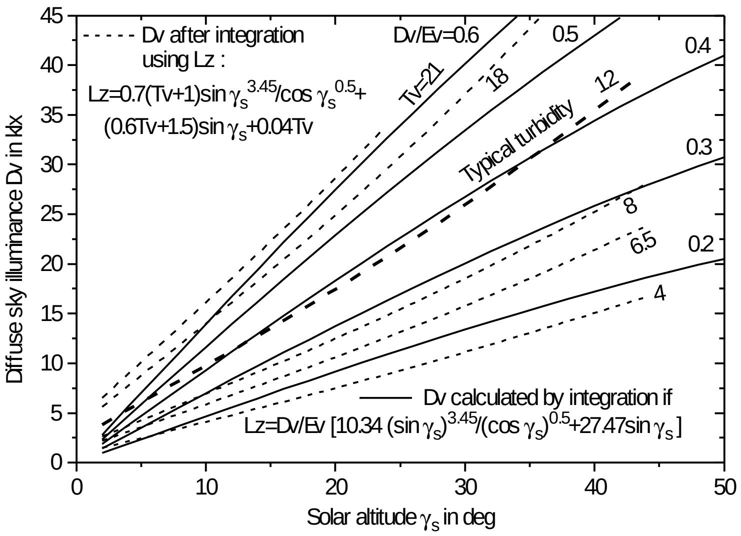
$$Lz = A\sin\gamma_S + \frac{0.7(Tv+1)(\sin\gamma_S)^C}{(\cos\gamma_S)^D} + 0.04\,Tv$$

where $A = A1\,Tv + A2$

i.e. for typical turbidity Tv=12, A=8.7

with standard parameters

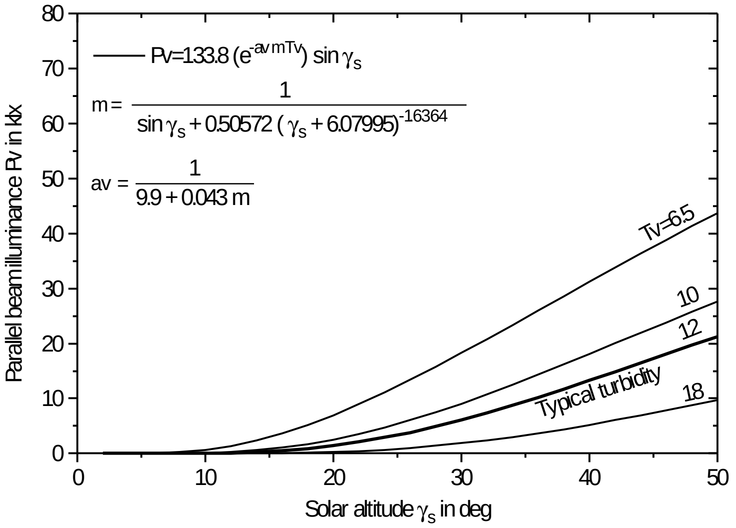
A1	A2	B	C	D	E
0.6	1.5	10.34	3.45	0.5	27.47



Diffuse horizontal illuminance Dv after a general formula :

$$Dv = 133.8\,\frac{Dv}{Ev}\sin\gamma_S$$

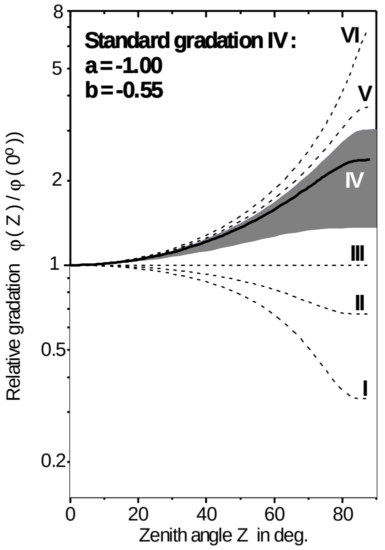
is equal to Dv calculated by integration of the luminace pattern



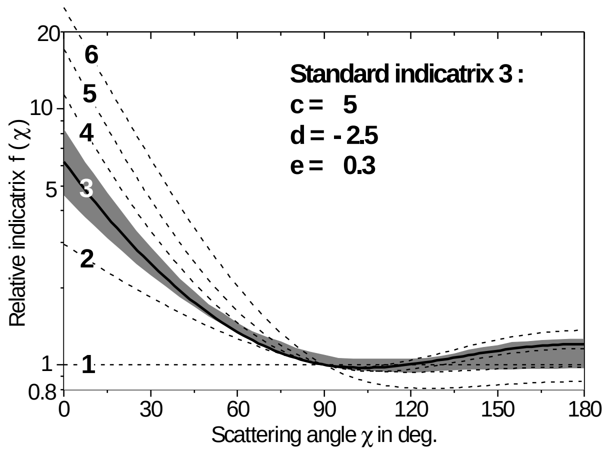
Probable direct solar horizontal illuminance Pv under this sky standard

SKY Standard	Partly cloudy sky with a brighter circumsolar effect	SSLD IV.3

ICA SAS, Bratislava, Slovakia
ASRC, Albany , NY, U.S.A.



Place of sky type IV.3 in the standard sky set :



Standard formula for relative luminance distribution :

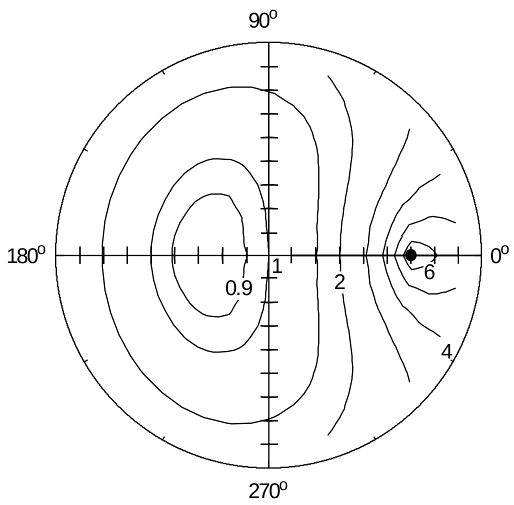
$$\frac{L_{\chi z}}{L_{zs}} = \frac{[1-\exp(-0.55/\cos Z)]\left[0.901+5\exp(-2.5\chi)+0.3\cos^2\chi\right]}{0.423\left[0.901+5\exp(-2.5\,Zs)+0.3\cos^2 Zs\right]}$$

where χ is an angular distance between sun and sky element, i.e. scattering angle in rad
Zs is the zenith solar angle

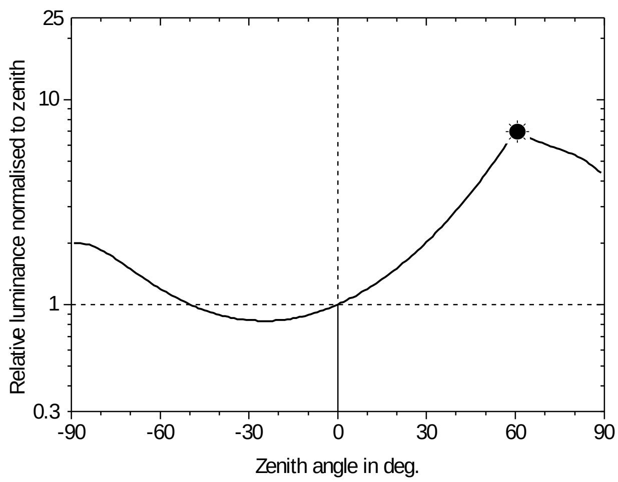
Table of approximate range and auxiliary conditions

Gradation scale zenith:horizon	Indicatrix scale	Frequent range Dv/Ev	Usual range Δ	Usual Tv range	Gradation range zenith:horizon	Indicatrix prolongation range	Probable range Lz/Dv*)
around 1:2.5	around 6	0.2-0.5	0.2-0.43	6 - 12	1:1.35 - 1:3	3.5:1 - 7:1	0.17-0.2
Note : *) The Lz/Dv range is valid only if Zs is over 60 degrees							

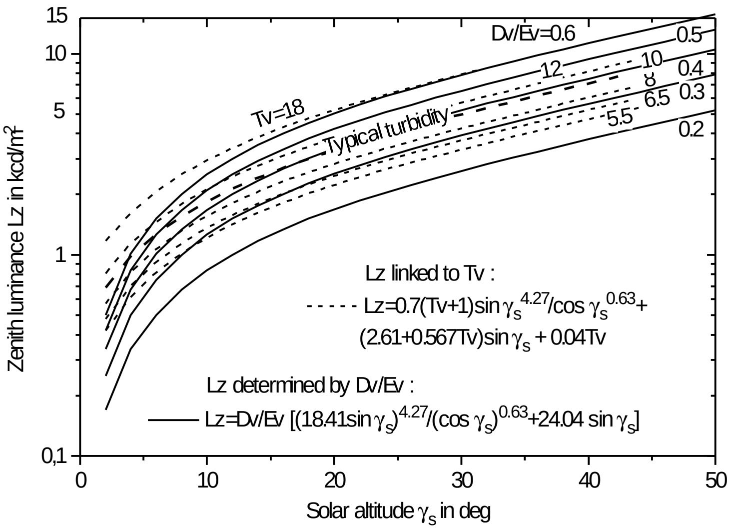
Example for Zs = 60°



Sky profile in solar meridian



SKY Standard	Partly cloudy sky with a brighter circumsolar effect	SSLD IV.3
ICA SAS, Bratislava, Slovakia ASRC, Albany , NY, U.S.A.		



Probable zenith luminance Lz under this sky standard after :

$$Lz = \frac{Dv}{Ev}\left[\frac{B\left(\sin\gamma_S\right)^C}{\left(\cos\gamma_S\right)^D} + E\sin\gamma_S\right]$$

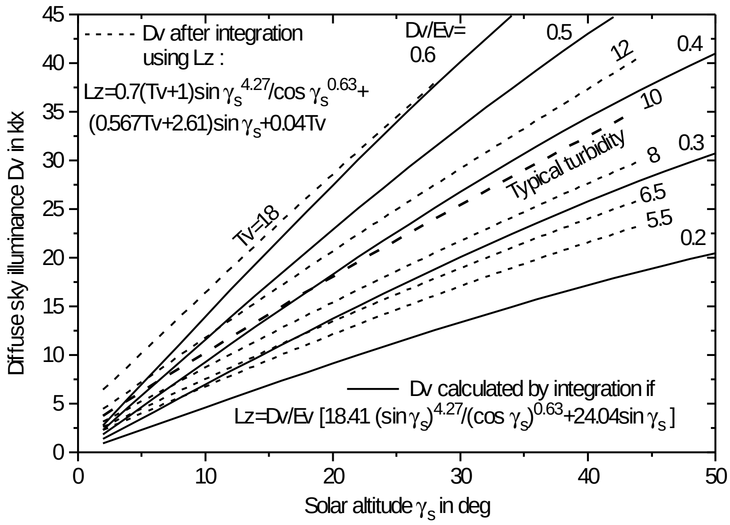
$$Lz = A\sin\gamma_S + \frac{0.7(Tv+1)\left(\sin\gamma_S\right)^C}{\left(\cos\gamma_S\right)^D} + 0.04\,Tv$$

where $A = A1\,Tv + A2$

i.e. for typical turbidity Tv=10, A=8.28

with standard parameters

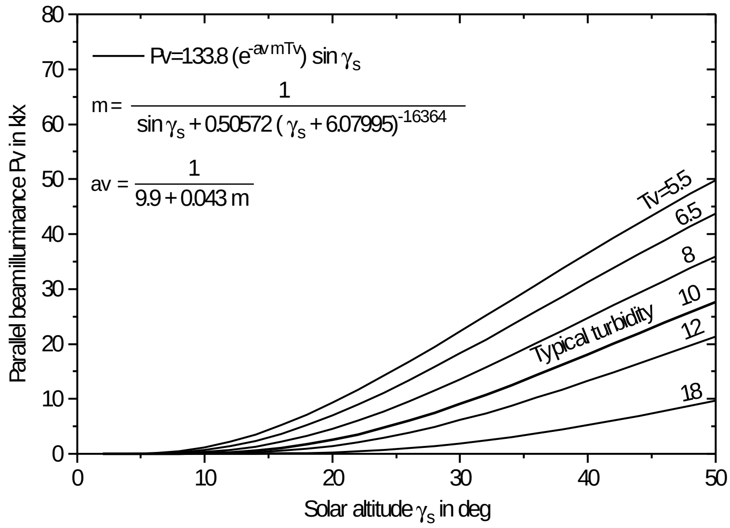
A1	A2	B	C	D	E
0.567	2.61	18.41	4.27	0.63	24.04



Diffuse horizontal illuminance Dv after a general formula :

$$Dv = 133.8\,\frac{Dv}{Ev}\,\sin\gamma_S$$

is equal to Dv calculated by integration of the luminace pattern



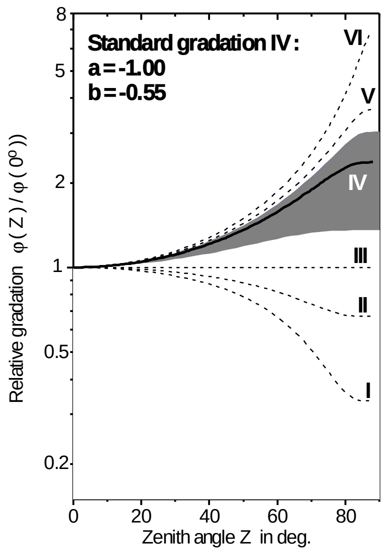
Probable direct solar horizontal illuminance Pv under this sky standard

SKY Standard

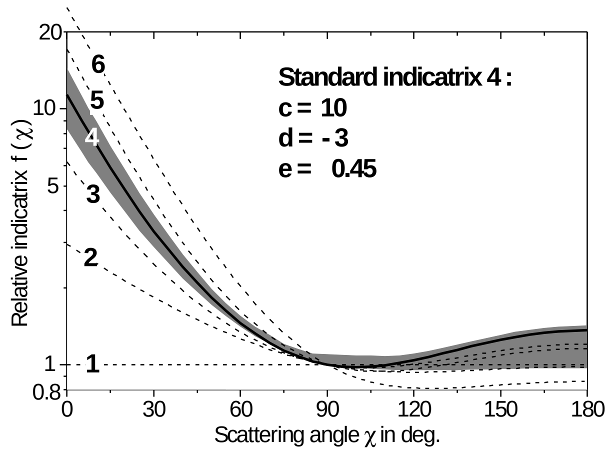
ICA SAS, Bratislava, Slovakia
ASRC, Albany , NY, U.S.A.

White - blue sky
with a clear solar corona

SSLD
IV.4



Place of sky type IV.4 in the standard sky set :



Standard formula for relative luminance distribution :

$$\frac{L_{\chi z}}{L_{zs}} = \frac{[1-\exp(-0.55/\cos Z)]\left[0.91+10\exp(-3\chi)+0.45\cos^2\chi\right]}{0.423\left[0.91+10\exp(-3\,Zs)+0.45\cos^2 Zs\right]}$$

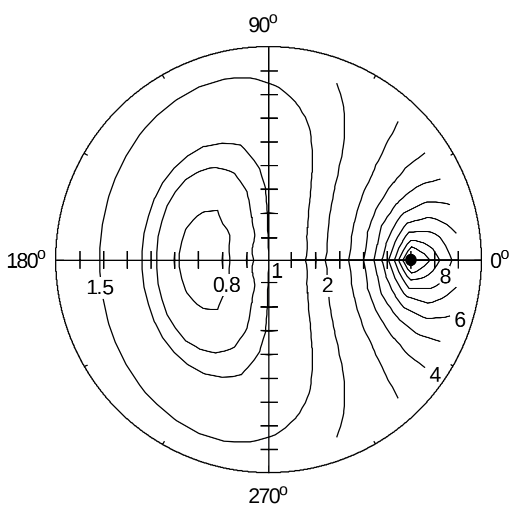
where χ is an angular distance between sun and sky element, i.e. scattering angle in rad
Zs is the zenith solar angle

Table of approximate range and auxiliary conditions

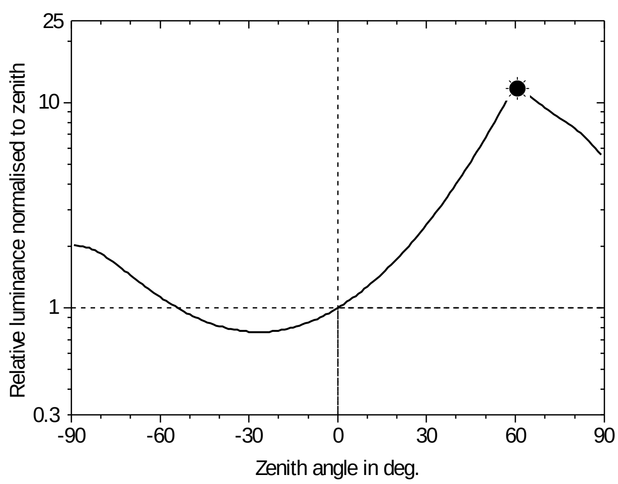
Gradation scale zenith:horizon	Indicatrix scale	Frequent range Dv/Ev	Usual range Δ	Usual Tv range	Gradation range zenith:horizon	Indicatrix prolongation range	Probable range Lz/Dv*)
around 1:2.5	around 11	0.15-0.5	0.1-0.4	2.5 - 6.5	1:1.35 - 1:3	7:1 - 13:1	0.15-0.17

Note : *) The Lz/Dv range is valid only if Zs is over 60 degrees

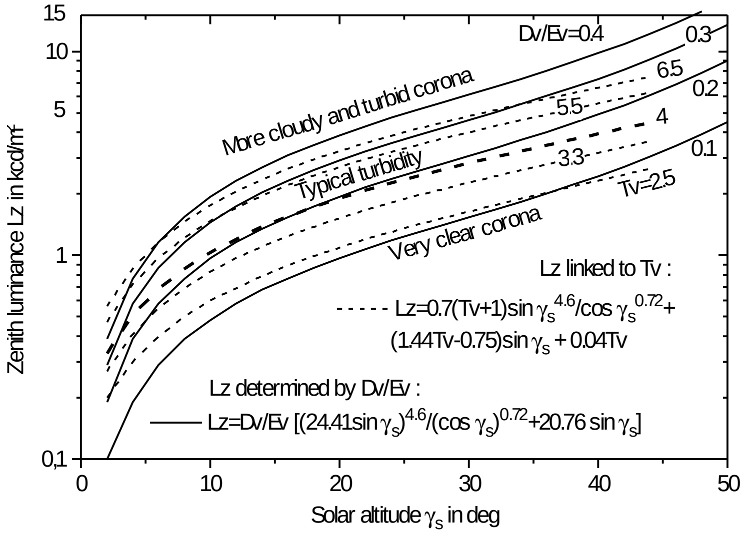
Example for Zs = 60°



Sky profile in solar meridian



SKY Standard ICA SAS, Bratislava, Slovakia ASRC, Albany , NY, U.S.A.	White - blue sky with a clear solar corona	SSLD **IV.4**



Probable zenith luminance Lz under this sky standard after :

$$Lz = \frac{Dv}{Ev}\left[\frac{B(\sin\gamma_S)^C}{(\cos\gamma_S)^D} + E\sin\gamma_S\right]$$

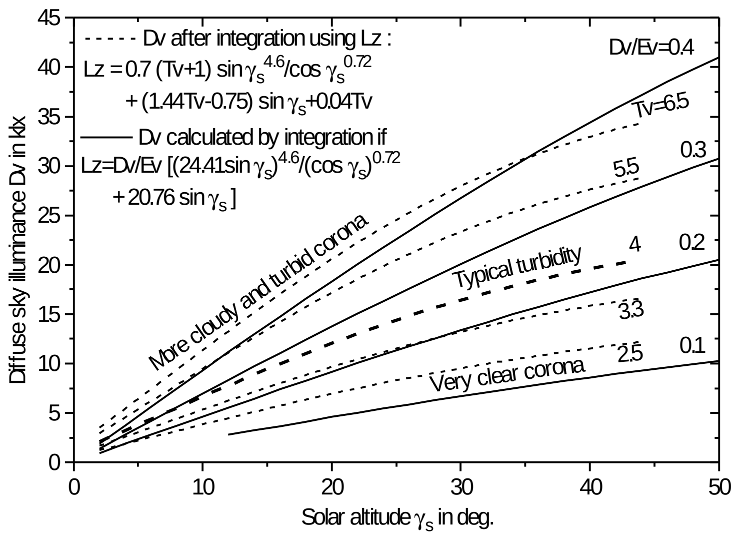
$$Lz = A\sin\gamma_S + \frac{0.7(Tv+1)(\sin\gamma_S)^C}{(\cos\gamma_S)^D} + 0.04\,Tv$$

where $A = A1\,Tv + A2$

i.e. for typical turbidity Tv=4, A=5.01

with standard parameters

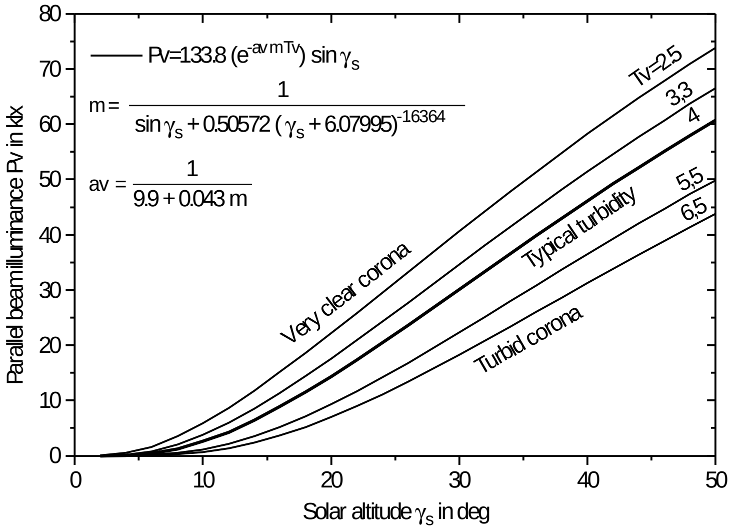
A1	A2	B	C	D	E
1.44	-0.75	24.41	4.60	0.72	20.76



Diffuse horizontal illuminance Dv after a general formula :

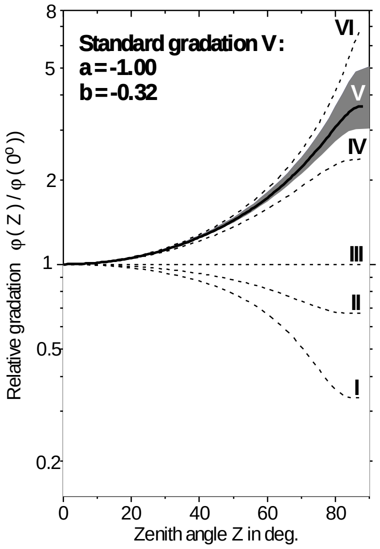
$$Dv = 133.8\,\frac{Dv}{Ev}\sin\gamma_S$$

is equal to Dv calculated by integration of the luminace pattern

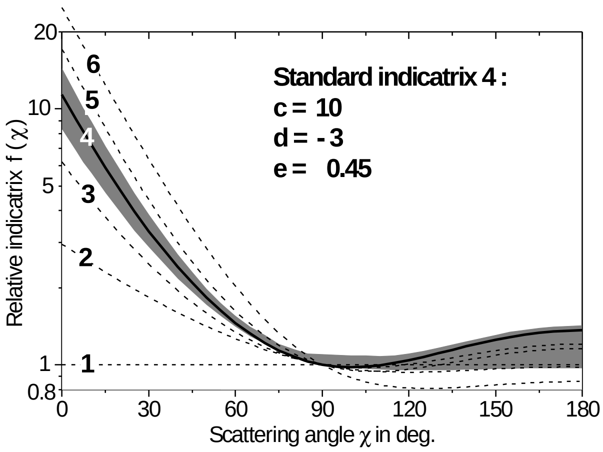


Probable direct solar horizontal illuminance Pv under this sky standard

	SKY Standard	Very clear/unturbid sky with a clear solar corona	SSLD
	ICA SAS, Bratislava, Slovakia ASRC, Albany , NY, U.S.A.		V.4



Place of sky type V.4 in the standard sky set :



Standard formula for relative luminance distribution :

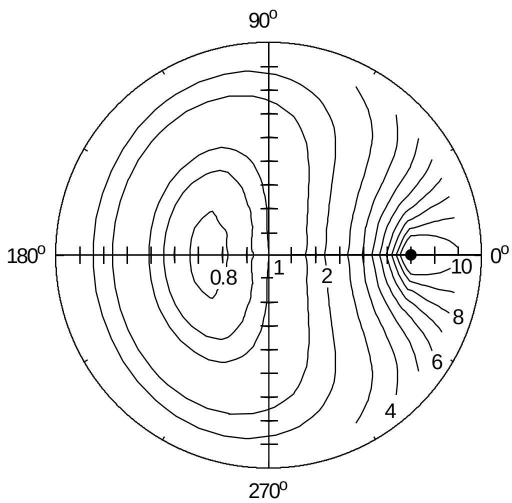
$$\frac{L_{\chi Z}}{L_{Zs}} = \frac{\left[1 - \exp(-0.32 / \cos Z)\right]\left[0.91 + 10\exp(-3\chi) + 0.45\cos^2\chi\right]}{0.274\left[0.91 + 10\exp(-3\,Zs) + 0.45\cos^2 Zs\right]}$$

where χ is an angular distance between sun and sky element, i.e. scattering angle in rad
Zs is the zenith solar angle

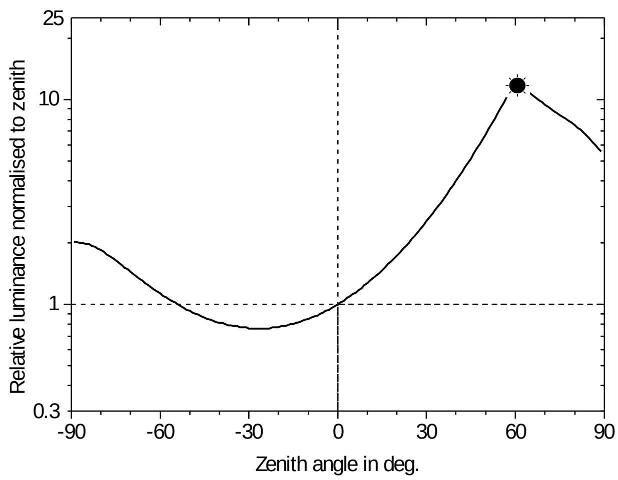
Table of approximate range and auxiliary conditions

Gradation scale zenith:horizon	Indicatrix scale	Frequent range Dv/Ev	Usual range Δ	Usual Tv range	Gradation range zenith:horizon	Indicatrix prolongation range	Probable range Lz/Dv*)
around 1:3.5	around 11	0.1-0.4	0.06-0.32	2 - 5	1:3 - 1:5	7:1 - 13:1	0.13-0.16
Note : *) The Lz/Dv range is valid only if Zs is over 60 degrees							

Example for Zs = 60°



Sky profile in solar meridian

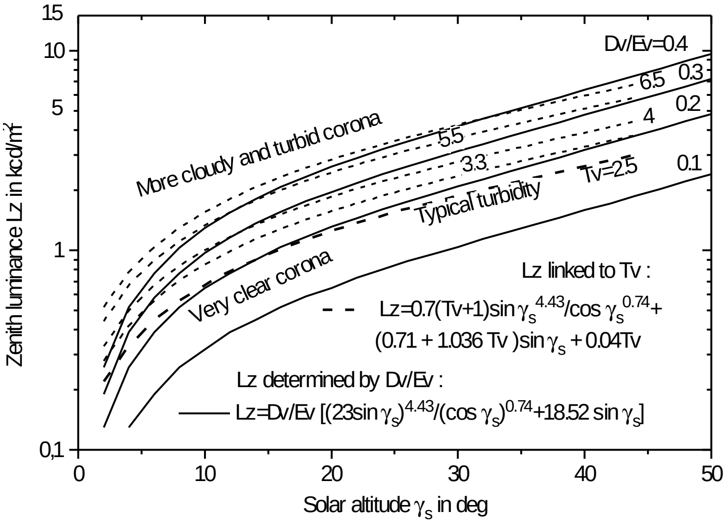


SKY Standard	Very clear/unturbid sky with a clear solar corona	SSLD V.4

ICA SAS, Bratislava, Slovakia
ASRC, Albany , NY, U.S.A.

Very clear/unturbid sky with a clear solar corona

SSLD V.4



Probable zenith luminance Lz under this sky standard after :

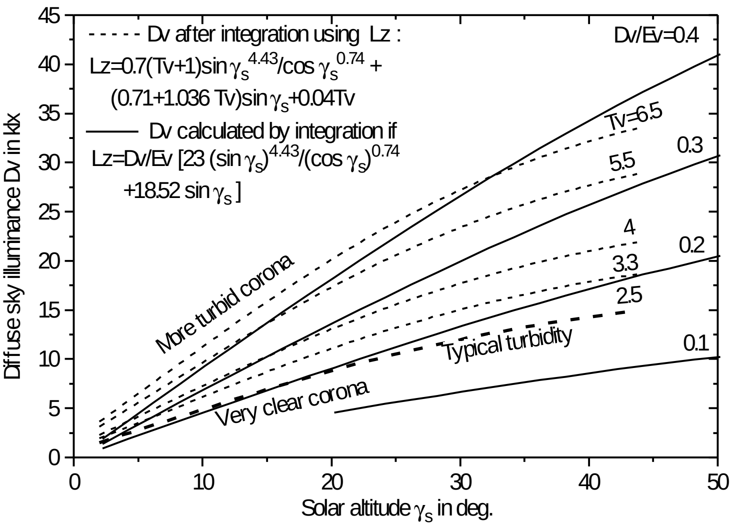
$$Lz = \frac{Dv}{Ev}\left[\frac{B(\sin\gamma_s)^C}{(\cos\gamma_s)^D} + E\sin\gamma_s\right]$$

$$Lz = A\sin\gamma_s + \frac{0.7(Tv+1)(\sin\gamma_s)^C}{(\cos\gamma_s)^D} + 0.04Tv$$

where $A = A1\,Tv + A2$
i.e. for typical turbidity Tv=2.5, A=3.3

with standard parameters

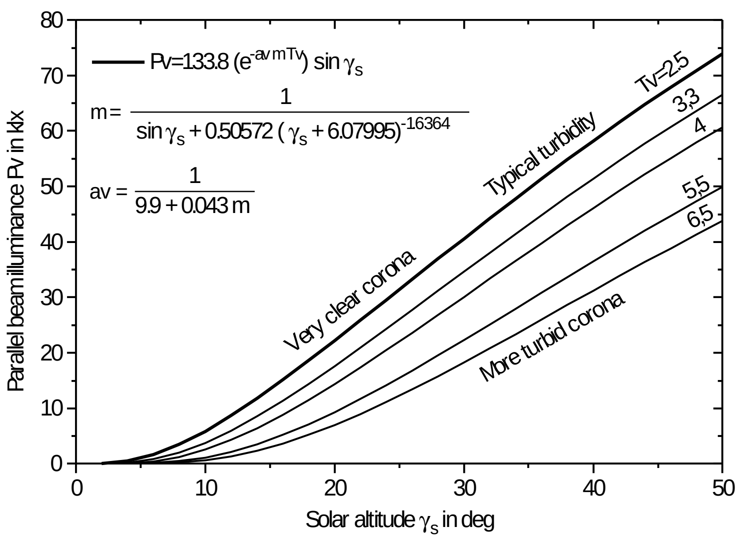
A1	A2	B	C	D	E
1.036	0.71	23.00	4.43	0.74	18.52



Diffuse horizontal illuminance Dv after a general formula :

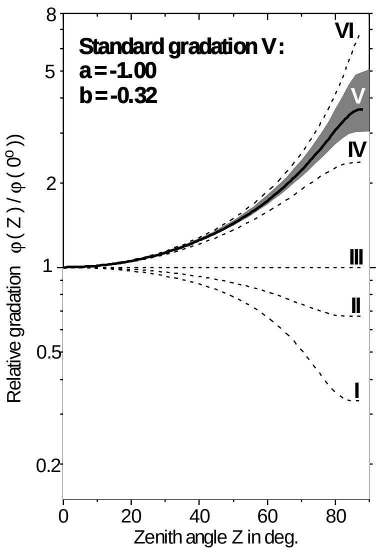
$$Dv = 133.8\,\frac{Dv}{Ev}\sin\gamma_s$$

is equal to Dv calculated by integration of the luminance pattern

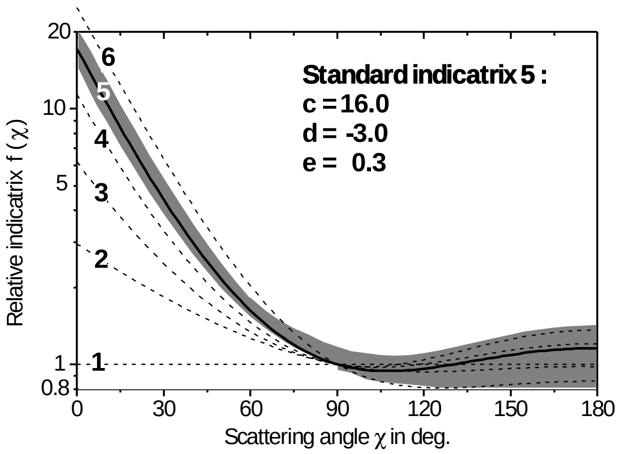


Probable direct solar horizontal illuminance Pv under this sky standard

SKY Standard ICA SAS, Bratislava, Slovakia ASRC, Albany , NY, U.S.A.	**Cloudless polluted sky with a broader solar corona**	SSLD **V.5**



Place of sky type V.5 in the standard sky set :



Standard formula for relative luminance distribution :

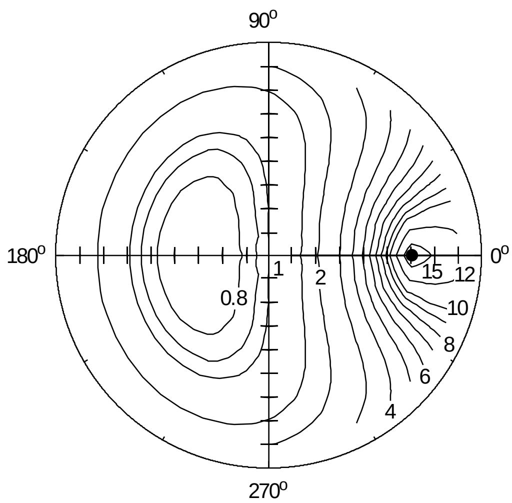
$$\frac{L_{\chi Z}}{L_{ZS}} = \frac{\left[1 - \exp(-0.32 / \cos Z)\right]\left[0.856 + 16\exp(-3\chi) + 0.3\cos^2\chi\right]}{0.274\left[0.856 + 16\exp(-3\,Zs) + 0.3\cos^2 Zs\right]}$$

where χ is an angular distance between sun and sky element, i.e. scattering angle in rad
Zs is the zenith solar angle

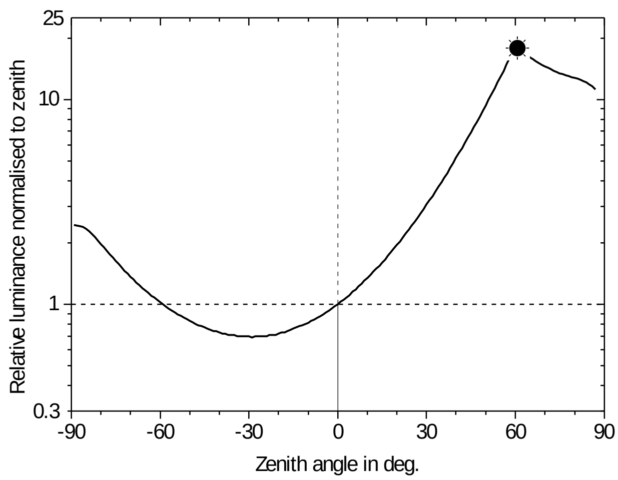
Table of approximate range and auxiliary conditions

Gradation scale zenith:horizon	Indicatrix scale	Frequent range Dv/Ev	Usual range Δ	Usual Tv range	Gradation range zenith:horizon	Indicatrix prolongation range	Probable range Lz/Dv*)
around 1:3.5	around 17	0.2-0.5	0.1-0.37	3 - 8	1:3 - 1:5	13:1 - 20:1	0.12-0.15
Note : *) The Lz/Dv range is valid only if Zs is over 60 degrees							

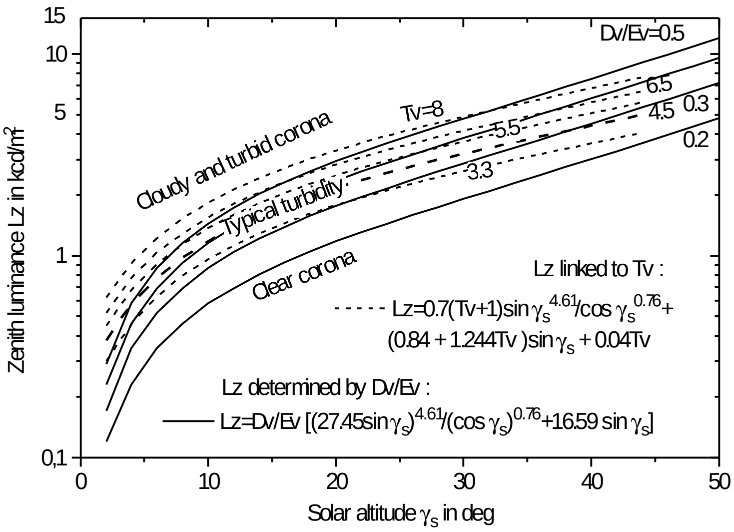
Example for Zs = 60°



Sky profile in solar meridian



	SKY Standard ICA SAS, Bratislava, Slovakia ASRC, Albany , NY, U.S.A.	**Cloudless polluted sky with a broader solar corona**	SSLD **V.5**



Probable zenith luminance Lz under this sky standard after :

$$Lz = \frac{Dv}{Ev}\left[\frac{B\left(\sin\gamma_S\right)^C}{\left(\cos\gamma_S\right)^D} + E\sin\gamma_S\right]$$

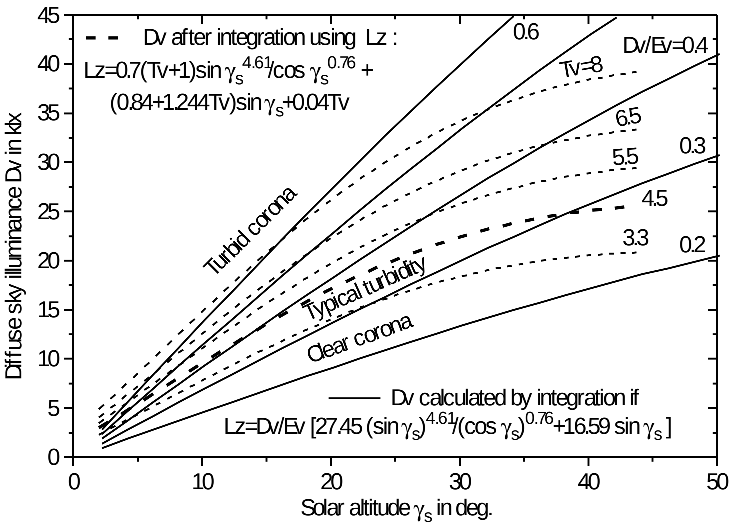
$$Lz = A\sin\gamma_S + \frac{0.7(Tv+1)\left(\sin\gamma_S\right)^C}{\left(\cos\gamma_S\right)^D} + 0.04\,Tv$$

where $A = A1\,Tv + A2$

i.e. for typical turbidity Tv=4.5, A=4.76

with standard parameters

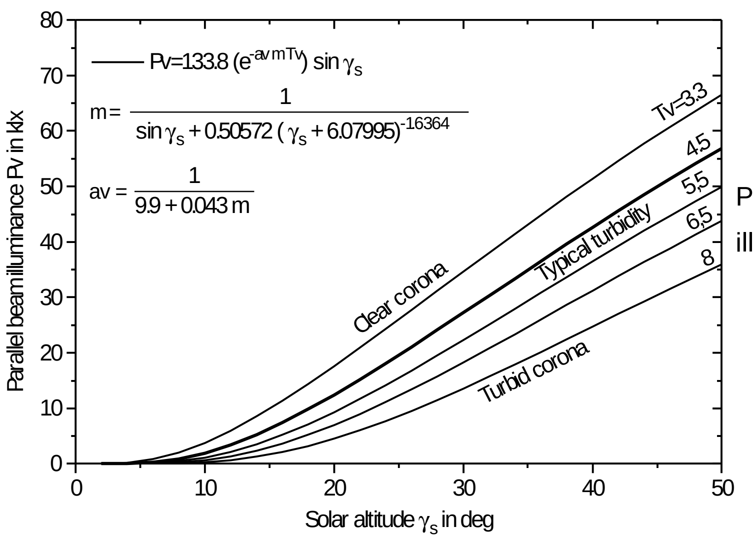
A1	A2	B	C	D	E
1.244	-0.84	27.45	4.61	0.76	16.59



Diffuse horizontal illuminance Dv after a general formula :

$$Dv = 133.8\,\frac{Dv}{Ev}\sin\gamma_S$$

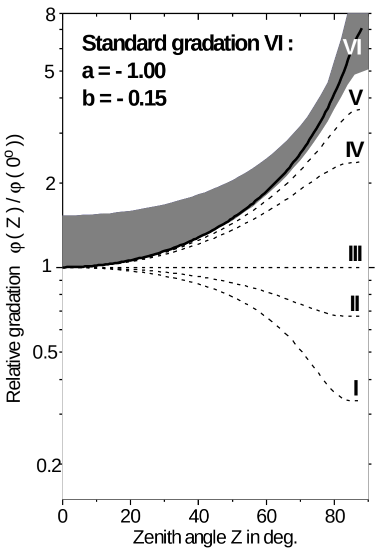
is equal to Dv calculated by integration of the luminace pattern



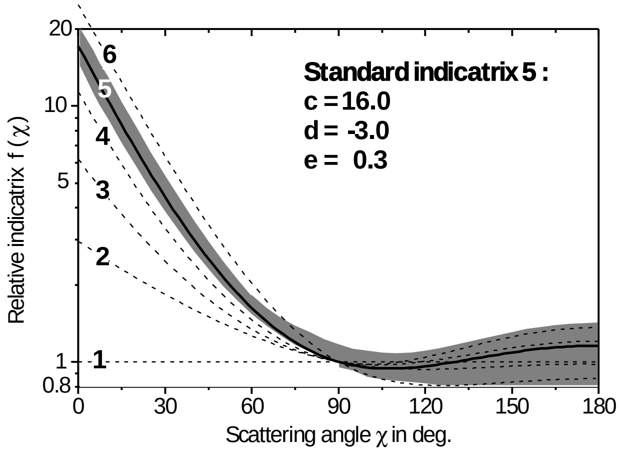
Probable direct solar horizontal illuminance Pv under this sky standard

SKY Standard	Cloudless turbid sky with a broader solar corona	SSLD VI.5

ICA SAS, Bratislava, Slovakia
ASRC, Albany , NY, U.S.A.



Place of sky type VI.5 in the standard sky set :



Standard formula for relative luminance distribution :

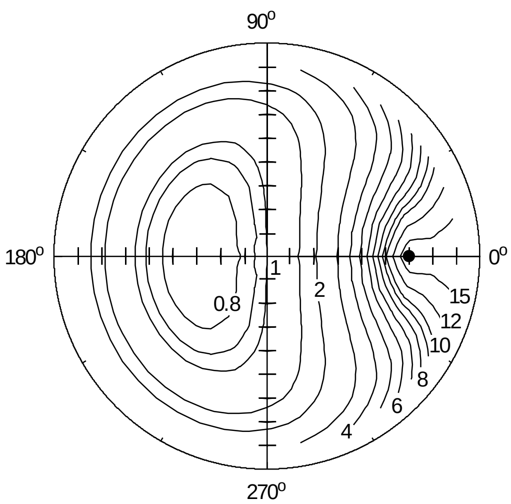
$$\frac{L_{\chi Z}}{L_{ZS}} = \frac{\left[1-\exp(-0.15/\cos Z)\right]\left[0.856+16\exp(-3\chi)+0.3\cos^{2}\chi\right]}{0.139\left[0.856+16\exp(-3\,Zs)+0.3\cos^{2}Zs\right]}$$

where χ is an angular distance between sun and sky element, i.e. scattering angle in rad
Zs is the zenith solar angle

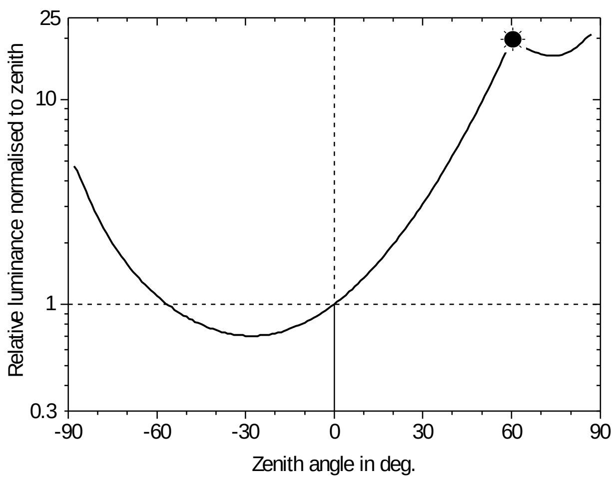
Table of approximate range and auxiliary conditions

Gradation scale zenith:horizon	Indicatrix scale	Frequent range Dv/Ev	Usual range Δ	Usual Tv range	Gradation range zenith:horizon	Indicatrix prolongation range	Probable range Lz/Dv*)
around 1:7	around 17	0.15-0.4	0.1-0.4	4 - 10	over 1:5	13:1 - 20:1	under 0.13
Note : *) The Lz/Dv range is valid only if Zs is over 60 degrees							

Example for Zs = 60°

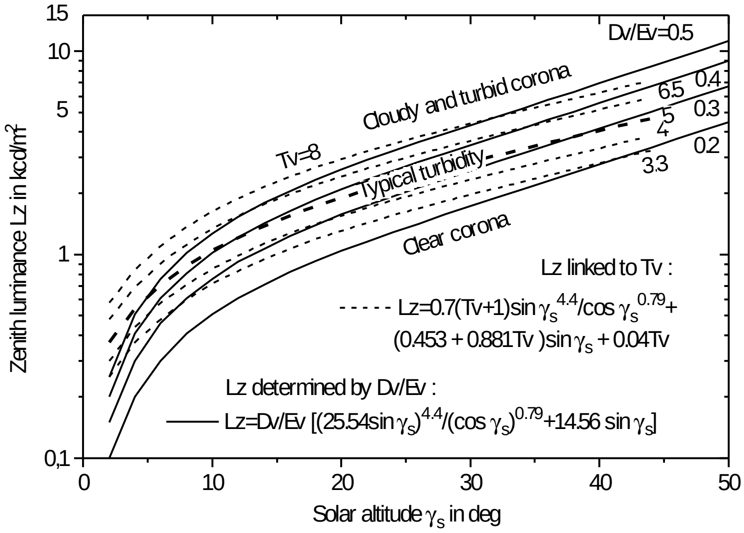


Sky profile in solar meridian



SKY Standard	Cloudless turbid sky with a broader solar corona	SSLD VI.5

ICA SAS, Bratislava, Slovakia
ASRC, Albany, NY, U.S.A.



Probable zenith luminance Lz under this sky standard after :

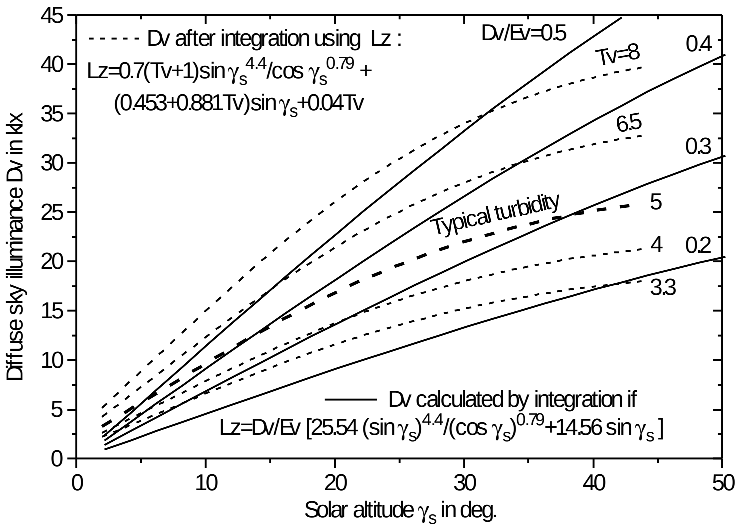
$$Lz = \frac{Dv}{Ev}\left[\frac{B\left(\sin\gamma_S\right)^C}{\left(\cos\gamma_S\right)^D} + E\sin\gamma_S\right]$$

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

where $A = A1\,Tv + A2$
i.e. for typical turbidity Tv=5, A=4.86

with standard parameters

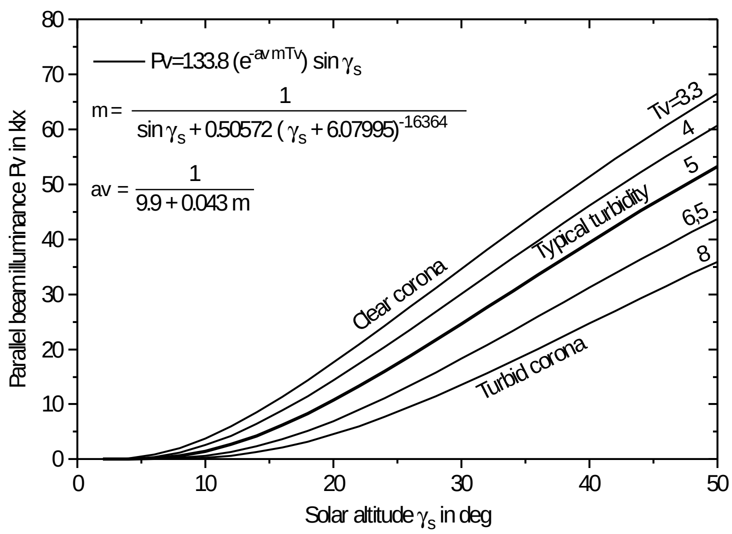
A1	A2	B	C	D	E
0.881	0.453	25.54	4.4	0.79	14.56



Diffuse horizontal illuminance Dv after a general formula :

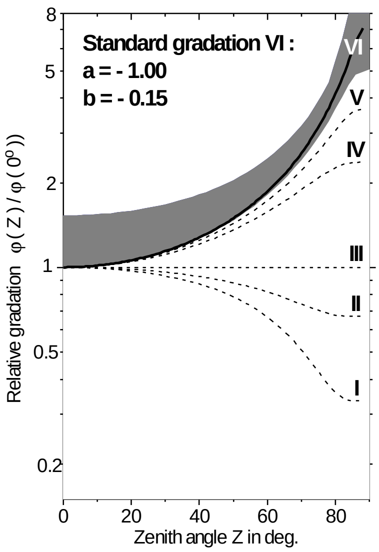
$$Dv = 133.8\,\frac{Dv}{Ev}\,\sin\gamma_S$$

is equal to Dv calculated by integration of the luminace pattern

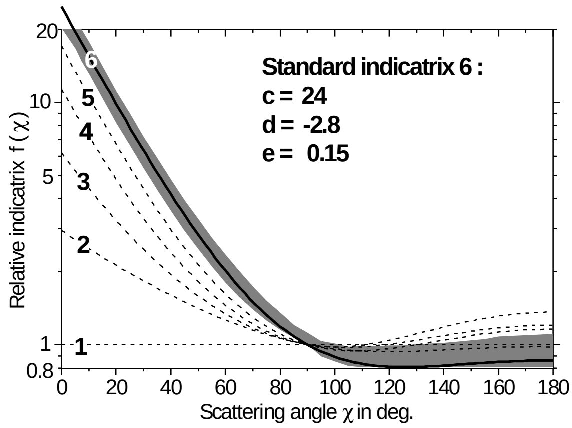


Probable direct solar horizontal illuminance Pv under this sky standard

	SKY Standard	White - blue turbid sky with a wide solar corona effect	SSLD
	ICA SAS, Bratislava, Slovakia ASRC, Albany , NY, U.S.A.		VI.6



Place of sky type VI.6 in the standard sky set :



Standard formula for relative luminance distribution :

$$\frac{L_{\chi Z}}{L_{ZS}} = \frac{\left[1 - \exp(-0.15 / \cos Z)\right]\left[0.705 + 24 \exp(-2.8\chi) + 0.15 \cos^2 \chi\right]}{0.139\left[0.705 + 24 \exp(-2.8\, Zs) + 0.15 \cos^2 Zs\right]}$$

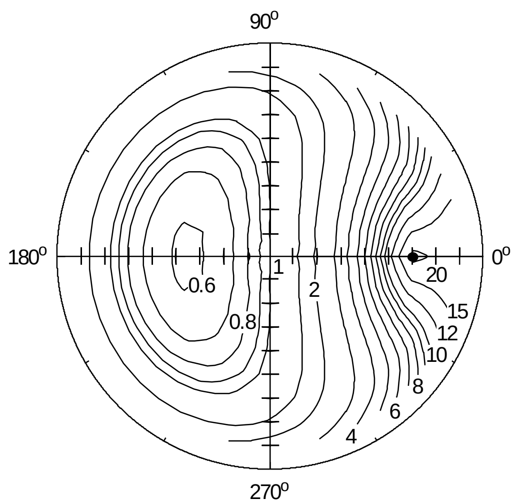
where χ is an angular distance between sun and sky element, i.e. scattering angle in rad

Zs is the zenith solar angle

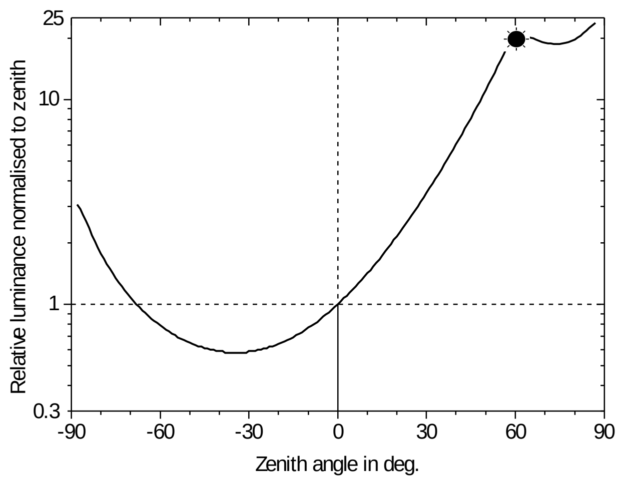
Table of approximate range and auxiliary conditions

Gradation scale zenith:horizon	Indicatrix scale	Frequent range Dv/Ev	Usual range Δ	Usual Tv range	Gradation range zenith:horizon	Indicatrix prolongation range	Probable range Lz/Dv*)
around 1:7	around 25	0.15-0.5	0.12-0.5	3 - 8	over 1:5	over 20:1	under 0.12
Note : *) The Lz/Dv range is valid only if Zs is over 60 degrees							

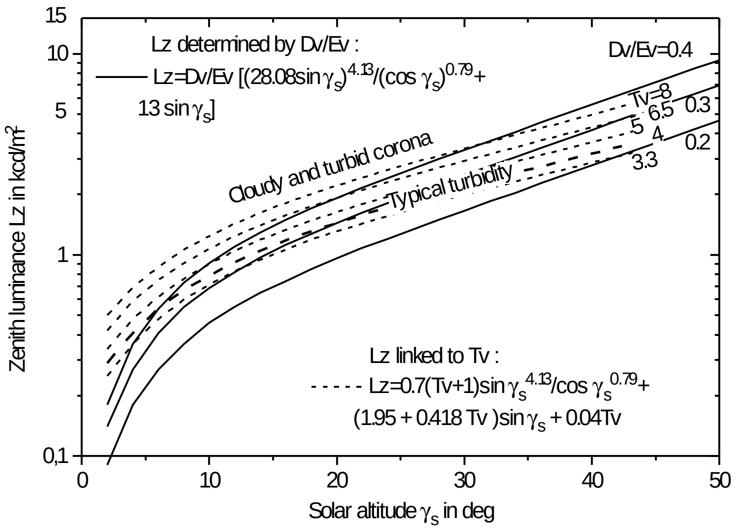
Example for Zs = 60°



Sky profile in solar meridian



SKY Standard ICA SAS, Bratislava, Slovakia ASRC, Albany , NY, U.S.A.	**White - blue turbid sky** **with a wide solar corona effect**	SSLD **VI.6**



Probable zenith luminance Lz under this sky standard after :

$$Lz = \frac{Dv}{Ev}\left[\frac{B(\sin\gamma_s)^C}{(\cos\gamma_s)^D} + E\sin\gamma_s\right]$$

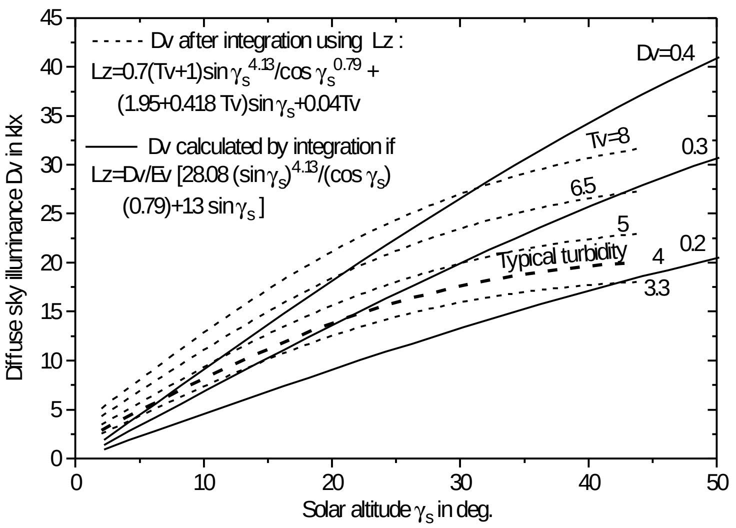
$$Lz = A\sin\gamma_s + \frac{0.7(Tv+1)(\sin\gamma_s)^C}{(\cos\gamma_s)^D} + 0.04\,Tv$$

where $A = A1\,Tv + A2$

i.e. for typical turbidity Tv=4, A=3.62

with standard parameters

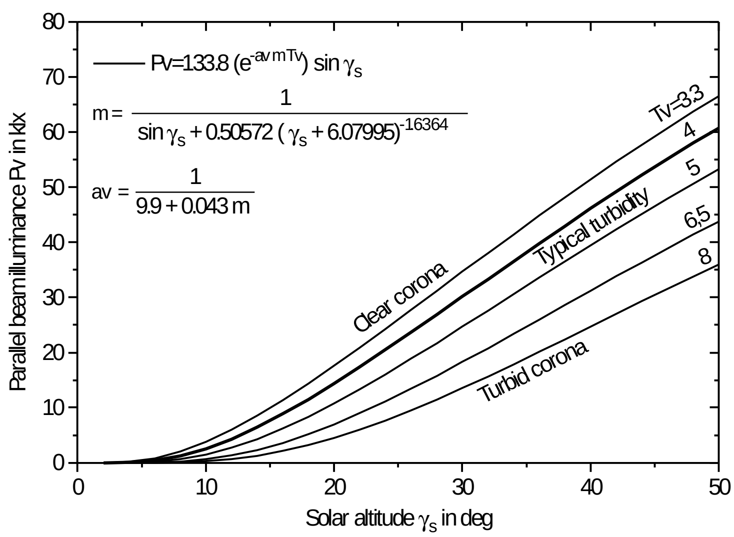
A1	A2	B	C	D	E
0.418	1.95	28.08	4.13	0.79	13.0



Diffuse horizontal illuminance Dv after a general formula :

$$Dv = 133.8\,\frac{Dv}{Ev}\sin\gamma_s$$

is equal to Dv calculated by integration of the luminace pattern



Probable direct solar horizontal illuminance Pv under this sky standard

List of Appendices

Figure A.1 - A.3: Isoline sky luminance patterns after measured scanning data
Figure B.1 - B.6: Measured relative indicatrices and their fit functions
Figure C: Gradation on clear skies at Berkeley, Tokyo and Sydney
Figure D: Interconnected variations of Pv/Ev, Dv/Ev and Lz/Dv ratios

App. I. Defining Standard Overcast Sky conditions using Dv/Ev and Lz/Dv ratios
Figure 1 - 13

App. J. Sky luminance and illuminance under clear and intermediate sky standards
Figure 1 - 26 plus two tables

App. K. Frequency distribution of the fifteen standard skies detected in monthly and yearly Bratislava data

App. L. A user´s friendly computer program calculating and presenting any standard sky pattern in relative or absolute terms with resulting horizontal sky illuminance

Due to the bulk of 235 pages comprising all appendices, this bookled contains the first main part of the text of the final report and only this list of appendices