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DAYLIGHT AVAILABILITY AS A FUNCTION
OF ATMOSPHERIC CONDITIONS

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Abstract

This paper reviews the differences between thermal and daylighting considerations for building design and their implications for using illuminance and irradiance data. Old and new mathematical models for luminance distribution and illuminance calculation are explained. Overcast, clear, and average sky conditions are discussed and their dependence on atmospheric factors is examined. We focus in particular on the turbidity of the clear atmosphere and the luminance at the zenith. We conclude that more measured daylighting data are required for validating the equations that have been developed separately in various parts of the world.

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1. INTRODUCTION

It is commonly believed that daylight, the visible portion of solar radiation, can be readily derived from measurements of direct, diffuse, or total radiation. Conversion factors in lumens per watt, called the luminous efficacy of solar radiation, have been suggested by researchers for converting irradiance to illuminance.

The fact that measurements of solar radiation have been carried out much more extensively than those of daylight give this procedure a tremendous advantage. On the other hand, other considerations make the method unattractive for the design of energy-efficient buildings. We should bear in mind that daylight in buildings is not used in the same way as thermal radiation. The major source of heat gain in a building is obviously direct solar radiation, while the diffuse component adds 8-9% of the total solar irradiance on a very clear day and much higher levels on hazy days. On the other hand, the major source for daylighting buildings is the sky and, to some extent, the light reflected from external surfaces. Direct sunlight is almost always too bright and produces direct or reflected glare. For this reason, the luminance (brightness) pattern of the sky, with its orientational variation, is essential for calculating daylight, particularly that which comes through vertical windows.

Furthermore, the cumulative effect of solar radiation on the thermal balance makes it useful for long-term averaging of energy savings. This is not the case with daylighting, where there is no cumulative effect; the response is instantaneous. This characteristic is particularly important for effective integration of daylight with electric light to maintain the specified minimum illuminance, because no time-delayed behavior analogous to thermal time constants is expected.

Efficient daylight management is much more sensitive to the direction of the sun than is the overall heat gain. With flexible shading controls, sky light can be fully utilized, and even direct beam sunlight may be admitted indoors and diffused when and where it is not likely to create thermal or glare discomfort.

Illuminance data required for analyzing design effects will be different from seasonal or annual data that might be used to estimate energy savings.

We can clearly see that daylighting management depends not only on general knowledge of diffuse or global values, but also on knowledge of sky luminance distribution. The structure of clouds, their layers, thickness, and height are usually not of great importance to daylight availability considerations. Consequently, the overall transmittance of the atmosphere is investigated.

2. SKY LUMINANCE PATTERNS

2.1 Basic Equation for Calculating Illuminance from the Sky

Considering the light from the sky as the primary source for indoor daylighting, we can write the basic equation that relates the luminance of the sky to the illuminance on a given point in a building:

$$E_v = \int L \cdot d\Omega \quad (1)$$

E_v = the illuminance at a point on the surface under consideration (lux),²
 L = the luminance of a sky element (cd/m²),
 Ω = the solid angle subtended by the sky seen from the point under consideration (steradian),
 $d\Omega$ = the elementary solid angle subtended by a sky element.

2.2 Uniform Sky

The simplest luminance distribution, i.e., the uniform sky, was the first proposed for daylighting calculations. It was defined by the following relationship:

$$L_p = L = \text{constant} \quad (2)$$

where:

L_p = the luminance of the sky element p under consideration (see Fig. 1),
 L = the uniform luminance of the whole sky.

This sky pattern was adopted primarily because it is mathematically simple. However, such a distribution does not occur often in reality, so calculations are inevitably inaccurate.

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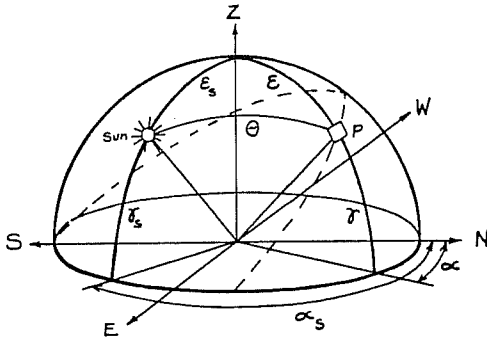


Figure 1: Angles of the sun and point p on the sky vault.

2.3 Overcast Sky

A more realistic sky pattern was proposed by Moon and Spencer and later adopted by the Commission International de L'Eclairage (CIE) [1]. They described the luminance distribution of the overcast sky by the following equation:

$$L_p = L_z \left[\frac{1+2\sin\gamma}{3} \right] \quad (3)$$

where:

L_z = luminance at the zenith (cd/m^2),
 γ = the angle of the sky element above the horizon (degrees) (see Fig. 1).

It should be stressed that with the overcast sky, the cloud cover is thick enough to entirely obscure the sun. This means that a fully cloudy sky is not always considered overcast. Although the location of the sun does not affect the luminance distribution of the overcast sky, the absolute luminance values depend on solar altitude. Krochmann [2] proposed the following empirical formula, which is suitable for temperate zones:

$$E_{\text{och}}(\gamma_s) = 300 + 21,000 \sin \gamma_s \quad (4)$$

where:

E_{och} = the illuminance on a horizontal surface (lux),
 γ_s = the angle of the sun above the horizon; solar altitude (degrees).

For indoor lighting calculations, the major features of the overcast sky are, first, that the sky is brighter at higher angles above the horizon. It can be seen from Eq. (3) that the luminance at the zenith is three times greater than luminance at the horizon. The second major feature of overcast skies is that the distribution is independent of azimuth direction. This means that all similar vertical windows will be equally illuminated regardless of orientation.

2.4 Clear Sky

Daylight under clear conditions is the sum of direct sunlight, sky light, and externally reflected light. With a clear sky, daylight levels depend on the location of the sun and the clarity of the atmosphere. The luminance distribution of the clear sky was defined by Kittler and later approved by the CIE [3]:

$$L_p = L_z x \quad (5)$$

$$x = \frac{(1 - e^{-0.32 \sec \epsilon})(0.91 + 10e^{-3\theta} + 0.45 \cos^2 \theta)}{0.27385 (0.91 + 10e^{-3\epsilon_s} + 0.45 \cos^2 \epsilon_s)}$$

where:

ϵ = angle of the sky element p from the zenith (see Fig. 1),
 ϵ_s = angle of the sun from the zenith, and
 θ^s = angle of the sky element p from the sun (all angles in radians).

The illuminance from the sky on any surface can then be calculated directly by integration of Equation 5 over the appropriate fraction of the sky vault visible from the surface.

The direct solar illuminance on a horizontal surface can be calculated (see Aydinli [4]):

$$E_{\text{vh}}(\gamma_s, T) = E_{\text{vo}} e^{-a_R m T} \sin \gamma_s \quad (6)$$

where:

E_{vh} = illuminance from direct sun on a horizontal surface, klux
 E_{vo} = illuminance solar constant - 128.4 klux ($E_{\text{vo}} = 1370 \text{ W}/\text{m}^2$),
 a_R = mean extinction coefficient (function of m),
 m = optical air mass,
 T = turbidity factor according to Linke (see below).

We can see from Eq. (5) that the illuminance received on vertical surfaces depends strongly on orientation and varies according to the location of the sun in the sky. As a result, all windows that face southerly orientations will generally admit more light than windows facing north.

2.5 Intermediate Sky

The abovementioned sky patterns describe the two extreme atmospheric conditions, overcast sky and clear sky. Standard intermediate conditions, such as partly cloudy, hazy, or foggy skies, which occur everywhere in various proportions, have not been defined. It is recognized that partly cloudy conditions may provide maximum sky luminance levels (e.g., white clouds reflecting sunlight). This lack of definition derives from the complexity and variability of these unstable conditions and from an uncertainty as to how such definition, if established, could contribute to design strategies for buildings. However, in spite of these doubts, a new generation of sky luminance patterns has emerged due primarily to the improved calculation capabilities brought about by the increased use of computers.

3. AVERAGE SKY MODELS

In recent years, the energy crisis has generated a much greater interest in the energy-saving potential of daylight. As a result, new efforts have been made to develop mathematical models for calculating sky light

which will average all the existing sky conditions. Because of space limitations we shall describe here only two models and mention some other investigators who have been working on such models.

3.1 Average Sky Illuminance

One of the models was proposed by S. Aydinli of the Lichttechnik Institut of the Technical University in Berlin, for the monthly mean of hourly values of irradiance or illuminance [4]. The average sky condition is derived from data on the extreme conditions of overcast and clear sky and the local sunshine probability. The average irradiance or illuminance on a horizontal surface is given by:

$$E_{avh} = \left[E_{sh} \frac{\sigma_h}{100} R_s + \left(E_{clh} \frac{\sigma_h}{100} + E_{och} \left(1 - \frac{\sigma_h}{100} \right) \right) R_h \right] \quad (7)$$

All irradiances (or illuminances) are monthly means of hourly values on a horizontal surface, (all irradiances in cd/m^2 and illuminances in lux), where:

- E_{avh} = average sky irradiance or illuminance
- E_{sh} = direct beam solar irradiance or illuminance,
- E_{clh} = clear sky diffuse irradiance or illuminance,
- E_{och} = overcast sky diffuse irradiance or illuminance,
- σ_h = monthly mean of hourly values of sunshine probability (%),
- R_s = correction function for direct solar radiation (dimensionless),
- R_h = correction function for sky radiation.

R_s and R_h are calculated from the following series:

$$R_s, R_h = \sum_{i=0}^{i=3} a_i \sigma_h^i \quad (8)$$

where:

	a_0	a_1	a_2	a_3^4
R_s	1.48	-4.066×10^{-2}	6.92×10^{-4}	-3.34×10^{-6}
R_h	1.00	2.54×10^{-2}	-2.98×10^{-4}	4.44×10^{-7}

A similar expression for the irradiance or illuminance on inclined surfaces has been developed. It requires data on only overcast and clear sky conditions, which are more available than data on unstable partly cloudy conditions.

It is worth mentioning that the evaluation of the average sky luminance distribution model has been bypassed using the easily obtainable values of direct sunshine and sky radiation or illumination data.

For energy estimation purposes, statistical data on daylight availability (e.g., frequency of occurrence, probability that criti-

cal values are exceeded) are often required. This can be determined empirically by long-term measurement (see samples in Ref. 8) or by use of the illuminance equations for instantaneous values, assuming that adequate climatological data are available to drive the model.

3.2 Average Sky Luminance Distribution

A mathematical model for the luminance distribution of the average of a succession of real skies has been proposed by P. Littlefair of the Building Research Establishment in England [5]. This model is based on the assumption that the luminance distribution of the sky can be described as a sum of two components: the luminance of the circumsolar region and a uniform luminance for the rest of the sky vault. The direct sunlight component is considered separately. The mathematical expression for the average sky luminance distribution as a function of solar altitude is given by the following equation:

$$L_p = a(\gamma_s) e^{-b\theta} + c(\gamma_s) \quad (9)$$

where:

- L_p = luminance of the considered sky element (kcd/m^2),
- γ_s = solar altitude--angle of the sun above the horizon (degrees),
- a = a function of solar altitude (kcd/m^2),
- b = calculated as $b = 0.025$,
- θ = angle between the sun and the considered element p (degrees),
- c = the uniform sky luminance.

The values of coefficients a and c must be evaluated from measured data for a typical climatic pattern. The author based his fits on a limited amount of data, i.e., from Kew in England and Berlin in Germany. More validation seems necessary before this model can be considered for design application.

3.3 Other Sky Models

In addition to the average sky models mentioned above, other investigators in various countries have proposed, or are developing, models for calculating the availability of daylight outdoors and indoors. A few of these investigators are mentioned here: W. Pierpoint, C. Robbins, G. Gillette, S. Treado, A. McCluney, and others in the United States; R. Dogniaux in Belgium; H. Nakamura and M. Oki in Japan; N. Ruck in Australia, etc.

4. ATMOSPHERIC FACTORS

If we go through the sky luminance equations given above, we see that they cannot be applied unless we obtain values characterizing the atmospheric conditions. This is also true for many of the more detailed computer models of heat transfer in the atmosphere. While they appear to model atmospheres well, the input data required to drive the models are not commonly available.

The effect of atmospheric clarity (in terms of turbidity and the luminance at the zenith) on daylight availability has been studied by the Windows and Daylighting Group at

Lawrence Berkeley Laboratory (LBL), University of California, Berkeley, and reported in a series of papers to the International Daylighting Conference in Phoenix, Arizona, in February of 1983 [6,7,8].

These studies attempted to discover common atmospheric factors that can characterize the "daylighting climate" of a region. If validated, the knowledge of such factors will enable the calculation of daylight without the need for long-term measurements of daylight availability. The analysis is based on measurements that have been carried out for about four years on top of a high-rise building (the Pacific Gas & Electric Company) in downtown San Francisco, California (Lat. 38°N, Long. 123° West). Measurements of horizontal global and diffuse irradiance and illuminance, as well as illuminance on four vertical surfaces facing north, east, south, and west are automatically recorded every 15 minutes. Another sensor measures zenith luminance [8].

Two distinct sky conditions already have been discussed, i.e., overcast and clear skies. These two conditions are well understood, although it has not been easy to define the border between them. For a long time the sky has been considered clear as long as the direct beam component was intense enough to scorch the paper strip of the Campbell-Stokes Sunshine Recorder. With the introduction of automated electronic data recorders, the World Meteorological Organization (WMO) adopted an equivalent by specifying that the atmosphere should be considered clear if the direct solar irradiance exceeds 200 W/m². When the direct component falls below this value the sky is considered cloudy, foggy, or heavily polluted.

This specification can be adequate for high solar altitudes, but at lower altitudes the intensity drops below the value of 200 W/m² even with a clear atmosphere. However, these short periods of time early in the morning and late in the evening can be ignored for most design applications.

5. TURBIDITY OF THE ATMOSPHERE

The "clarity" of the clear sky is often defined by turbidity factor. Before reaching the ground, the direct beam solar radiation is attenuated by the atmosphere. This is caused by scattering due to air molecules (Rayleigh scattering), scattering absorption by aerosols, and absorption by atmospheric gases and water vapor.

5.1 Radiation Turbidity

Several definitions of atmospheric turbidity have been proposed. For daylighting calculations, the turbidity factor defined by Linke has been adopted. It can be evaluated in several ways.

Wherever long-term recorded data on solar radiation are available, the Linke turbidity factor (T_L) can be calculated from Eq. (6) above. By modifying the equation for normal incidence ($\sin \gamma_s = 1$), we get:

$$T_L = \frac{\ln E_{eo} - \ln E_{esn}}{a_R \cdot m} \quad (10)$$

where:

- E_{eo} = solar constant (extra-terrestrial irradiance) = 1370 W/m²,
- E_{esn} = direct beam solar irradiance on a surface normal to the sun (W/m²),
- a_R = mean extinction coefficient for dry and clean air (Rayleigh scattering),
- m = relative air mass.

If radiation data are not available, the turbidity factor can be estimated with data on the water vapor content in the atmosphere (w) and the aerosol content defined by the turbidity coefficient according to Angström (β). Several equations exist for such a calculation. One of the best-known expressions was proposed by Dogniaux [9]:

$$T_L = \left[\frac{\gamma_s + 85}{39.5e^{-w} + 47.4} + 0.1 \right] + [16 - 0.22w] \beta \quad (11)$$

where:

- γ_s = solar altitude (degrees),
- w = water vapor in the atmosphere (cm), and
- β = Angström turbidity coefficient.

Figure 2 shows hourly averaged values of Linke's turbidity factor based on LBL's four years of measured data from San Francisco. The graph represents all readings of direct normal components above 200 W/m². The high turbidities in the morning hours are explained in part by the typical San Francisco weather, which has morning fog that burns off later in the day. Average hourly values on a monthly and seasonal basis have also been calculated.

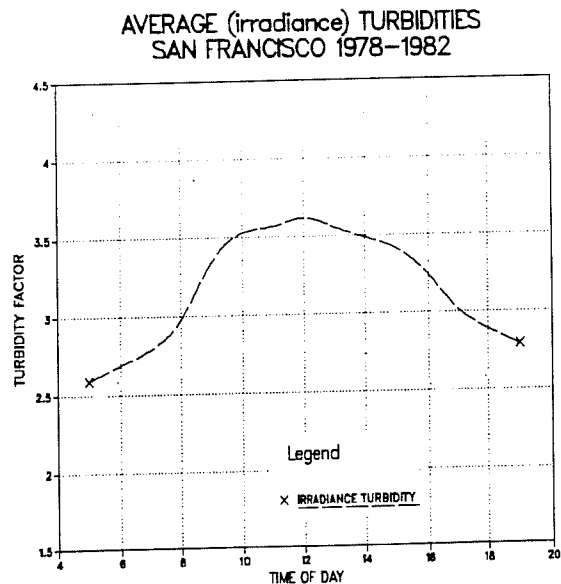


Figure 2: Linke's turbidity factor: average hourly values for a period of four years. Based on measurements from San Francisco. (Ref. 7)

5.2 Illuminance Turbidity

To determine illuminance, for daylighting applications, we first use the appropriate value of T_L from Eq. 11 and Eq. (6) to calculate the irradiances.

Then we multiply the irradiance values by the luminous efficacy, K . However, K is a function of solar altitude and atmospheric parameters that are not normally available. As the water vapor absorption affects primarily the infrared part of the spectrum, a significant source of error can be eliminated by calculating an "Illuminance Turbidity Factor" [7]. This turbidity factor is limited to the visible solar spectrum and can be evaluated from measured illuminance data, centered on 550 nm.

The concept of illuminance turbidity is being validated by measured data, and may enable us to use fewer data for calculating daylight availability in a given location.

6. ZENITH LUMINANCE

The luminance at the zenith is used in many mathematical models for the sky luminance distribution. Many equations have been proposed for calculating zenith luminance (see [9] and [10]). Most of these equations were developed in northern Europe, where the solar altitude (which strongly affects the zenith luminance under both cloudy and clear conditions) is limited to 65° degrees above the horizon.

An equation applicable to solar altitudes up to 75° above the horizon was proposed by LBL [6], based on the data collected in San Francisco.

$$L_z = (1.376T_L - 1.81) \tan \gamma_s + 0.38 \quad (12)$$

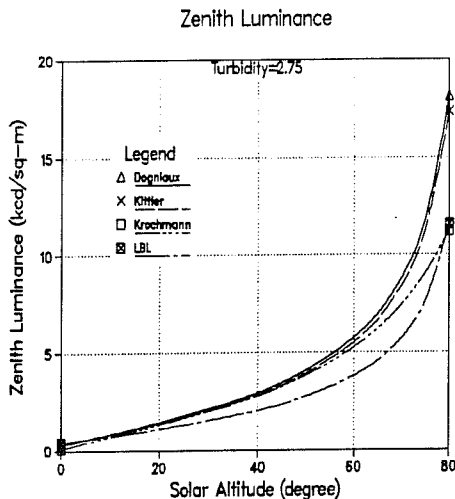


Figure 3: Zenith luminance as a function of solar altitude for Linke's turbidity factor of 2.75 (fairly clear atmosphere).

The limitations are: $2^\circ \leq \gamma_s \leq 75^\circ$, $1.5 \leq T_L \leq 8.5$.

In Fig. 3, four curves represent the dependence of zenith luminance on solar altitude for fairly clear atmosphere ($T_L = 2.75$). The equations were developed by Dogniaux in Belgium, Kittler in Czechoslovakia, Krochmann in Germany, and LBL in the U.S.A. It should be noted that all the curves except the LBL curve are limited to solar altitudes of 65°; they are extrapolated in Fig. 3 only for comparison with the LBL curve.

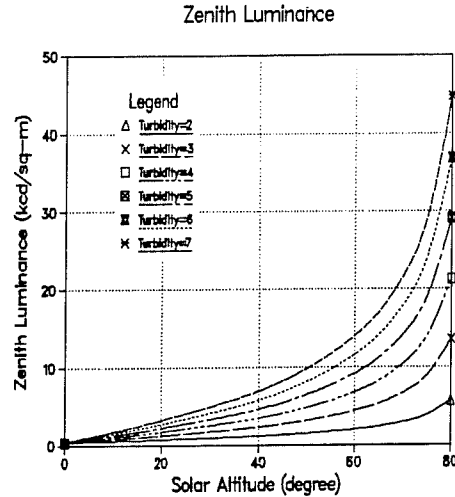


Figure 4: Zenith luminance as a function of solar altitude calculated for turbidity factors of 2 to 7.

Figure 4 demonstrates the dependence of zenith luminance on the turbidity of the clear sky. The LBL Eq. (12) has been used to plot zenith luminances for $T_L = 2$ to 7. The more turbid (polluted) the atmosphere, the higher the zenith luminance, and consequently the higher the luminance of the whole sky. This will result in higher sky illuminances on the one hand and a weakened direct beam illuminance on the other. It should be noted that the averages do not show the variations in individual readings. When calculations are performed during short time intervals, the rapid fluctuations in turbidity should be taken into consideration.

7. SUMMARY

Our dependence on the light from the sky as the major source for indoor daylighting requires a thorough knowledge of hourly data on vertical surface illuminance and sky luminance distribution and their dependence on atmospheric factors. These data have not been historically available in the solar radiation field to building science researchers. They have therefore been developed somewhat independently from the solar field by the daylighting illumination research community. We suggest it will be useful to create further links between those working on related radiation and illumination problems.

More data are needed from different climatic regions to develop and validate models for zones for which no data are yet available. Microclimate effects, particularly in urban areas, are likely to be significant. The algorithms and relationships widely used in the international community (CIE) must be checked and, if appropriate, altered to reflect characteristic U.S. climates. New daylight illuminance data must be developed in a manner that is sympathetic to the needs of the daylight research and design community.

8. ACKNOWLEDGEMENT

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