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# Unified model of radiance patterns under arbitrary sky conditions

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**Abstract**

The radiance/luminance patterns that simulate more realistic skies are urgently needed in lighting engineering applications to model daylight availability in exterior and interior spaces. Undoubtedly, the angular behavior of sky radiance/luminance is a key factor determining the daylight conditions in rooms with variable orientations and window sizes. Therefore, much effort is currently expended in search of a universal, scalable daylight model that accepts actual meteorological situations.

The natural sky radiances are neither monotonic nor smooth functions of zenith/azimuth angle, primarily due to the presence of broken cloud arrays or single clouds scattered over the whole sky vault. In this paper we show how we have addressed the phenomena and developed a universal sky radiance model for a turbid, cloudy atmosphere. This model accommodates higher scattering orders, aerosol optics, surface albedo, and the statistically relevant contributions of single clouds. The radiance at ground depends on the bulk characteristics of cloud fields, such as spectral optical thickness, spectral reflectance, altitude, positions on the sky, sizes, and shapes. We have shown that single scattering approximation fails to reproduce the radiance in the circumsolar region when clouds block the direct solar beams. The single scattering concept also overestimates reflection by individual clouds. Incorporation of double scattering into a computational model generally makes the radiance patterns smooth and less steep at the edges of clouds as commonly occur in nature. The numerical demonstrations are based on UniSky Simulator (Kocifaj and Fecko, 2014) which allows for modeling of various cloud configurations and is available for public use.


*Keywords:* Sky radiance patterns; Stochastic cloud coverage; Aerosols; Light scattering

## 1. Introduction

Modeling the sky radiance under different meteorological conditions is a convenient tool for predicting ground-reaching radiation. In addition, the spectral sky radiance computed at different altitudes can be used in simulating the radiative balance for any atmospheric layer, or in determining the radiation budget of the atmosphere across the solar spectrum. It is evident that the spectral sky radiances form a basis for computing the diffuse-component of photosynthetically active radiation (PHaR), which is a source of energy for plants (Grant et al., 1996). PHaR apart, the radiance pattern predetermines the efficiencies of photovoltaic systems or solar concentrators that profit from enhanced forward scattering in the circumsolar region (Gueymard, 2001). In general, the radiance distribution reflects the physical state of the atmosphere, especially its composition, turbidity, humidity and cloud cover – which is by far the greatest modulator of downwelling radiation at the surface (Marshak and

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**Nomenclature**

| | |
|---|---|
| $a_C$ | albedo of a cloud |
| $a_E$ | earth's albedo |
| $A$ | observational azimuth angle |
| $A'$ | any azimuth angle |
| $A_S$ | azimuth angle of the sun disk |
| $B$ | special ancillary function |
| $C_F$ | cloud fraction |
| $F_0$ | flux density of solar radiation |
| $g$ | asymmetry parameter of aerosol particles |
| $g'$ | any asymmetry parameter scaling the Henyey–Greenstein function |
| $h, h_1$ | altitude |
| $h_C$ | average altitude of a cloudy array |
| $h_a$ | aerosol scale height |
| $H$ | the Heaviside function |
| $H_S$ | the scale height of a turbid atmosphere |
| $I^+_{p1}$ | scattering phase function integrated over azimuth angle |
| $I^+_{p2}$ | product of scattering phase functions integrated over azimuth angle |
| $k$ | angular scattering coefficient of an elementary atmospheric volume |
| $L^+_{1,R}$ | 1st scattering order radiance originated from diffuse reflection by a cloud |
| $L^+_{1,S,b}$ | undercloud radiance in 1st scattering order approximation |
| $L^+_{1,S,a}$ | 1st scattering order radiance above cloud level |
| $L^+_{2,S}$ | undercloud radiance in 2nd scattering order approximation |
| $L^+_{1,T}$ | downward radiance of a cloud in the first scattering order approximation |
| $M_Z, M_S$ | optical air mass |
| $p_a$ | aerosol scattering phase function |
| $p_m$ | molecular scattering phase function |
| $P$ | probability function characterizing the relative portion of electromagnetic energy that penetrates through windows in a cloud array |
| $\bar{P}_0$ | single-lobed Henyey–Greenstein scattering phase function |
| $\bar{r}_F$ | reflectance factor |
| $R$ | radius of a spherical cloud |
| $S_e$ | special ancillary function |
| $T$ | transmission function |
| $z$ | observational zenith angle |
| $z'$ | any zenith angle |
| $z_S$ | solar zenith angle |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | any scattering angle |
| $\beta$ | characterizes the cloud geometry and typically varies from 0.75 to 2.5 |
| $\delta$ | delta function |
| $\tilde{\omega}^a$ | single scattering albedo of aerosol particles |
| $\theta, \theta', \varphi''_1, \varphi''_2$ | scattering angles |
| $\tau^m_0$ | molecular optical thickness |
| $\tau^a_0$ | aerosol optical depth |
| $\tau_0$ | total optical depth |
| $\tau_C$ | cloud optical depth |

Davis, 2005). Apart from clouds, the wave front of electromagnetic radiation is constantly distorted by aerosol particles that are ubiquitous in the atmosphere. Aerosol optics depend significantly on the microphysical characteristics of size- and shape-distributions, composition, spatial concentration and vertical stratification of the particulate matter (Mishchenko et al., 2002). Due to these reasons the solution of the radiative transfer equation in a turbid atmosphere is a non-trivial task which requires a complex mathematical treatment (Thomas and Stamnes, 1999; Zdunkowski et al., 2007). On the other hand, the spectral sky radiance is a valuable source of information on aerosols, especially when acquired together with other optical data like aerosol optical depth (Dubovik et al., 2000).

There is no doubt that radiance distribution is commonly related to energetic quantities, while illumination engineering applications require information on luminance maps. For instance, the luminance distribution is necessary for modeling daylight availability and variability in building interiors or urban spaces in order to make the building design and use of daylight more efficient (Reinhart and Walkenhorst, 2001). Basically, luminance is integrated radiance, however, different wavelengths evoke different sensations in humans, showing a peak in the middle of the visible spectrum (Bohren and Clothiaux, 2006). The spectral response of a human eye can be simulated by the so-called luminous efficiency curve for photopic vision. Therefore, the luminance can be computed as an integral product of spectral sky radiance and luminous efficiency. In order to avoid these computations, some authors suggest use of the same formula for simulating the angular behaviors of both luminance and radiance. The radiance/luminance conversion is then a base for the all-sky (Igawa et al., 2004) or all-weather (Perez et al., 1993) models. In principle, the conversion is not always straightforward due to spectral averaging and also because the radiative transfer theory is strictly only valid for monochromatic radiation (Korb and Zdunkowski, 1970).

Independently of conversion tool, the difficulties with modeling the realistic radiance or luminance distributions remain the same under cloudy conditions. That is because the clouds are notoriously large sources of uncertainty and irregularity of radiance/luminance patterns. Cloud fields are often formed into non-static arrays with random geometries for which stochastic radiative transfer theory is soundly applicable, however CPU intensive (Zuev and