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Night sky luminance under clear sky conditions: Theory vs. experiment

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ABSTRACT

Sky glow is caused by both natural phenomena and factors of anthropogenic origin, and of the latter ground-based light sources are the most important contributors for they emit the spatially linked spectral radiant intensity distribution of artificial light sources, which are further modulated by local atmospheric optics and perceived as the diffuse light of a night sky. In other words, sky glow is closely related to a city's shape and pattern of luminaire distribution, in practical effect an almost arbitrary deployment of random orientation of heterogeneous electrical light sources. Thus the luminance gradation function measured in a suburban zone or near the edges of a city is linked to the City Pattern or vice versa.

It is shown that clear sky luminance/radiance data recorded in an urban area can be used to retrieve the bulk luminous/radiant intensity distribution if some *a-priori* information on atmospheric aerosols is available. For instance, the single scattering albedo of aerosol particles is required under low turbidity conditions, as demonstrated on a targeted experiment in the city of Frýdek-Mistek. One of the main advantages of the retrieval method presented in this paper is that the single scattering approximation is satisfactorily accurate in characterizing the light field near the ground because the dominant contribution to the sky glow has originated from beams propagated along short optical paths.

1. Introduction

The requirement of night lighting may preclude astronomical observations at many sites because of necessarily increased sky glow. However, in principle, sky glow depends on many factors, including spectra of ground-based light sources [1,2], angular behavior of upwardly directed urban beams [3] and, the turbidity (or optical thickness) of an atmospheric environment [4,5]. It is well recognized that the amount of downwelling diffuse radiation typically increases as aerosol optical depth grows [6]. Although this process is associated with enhanced scattering and attenuation efficiencies, the scattering processes usually dominate under low or medium turbidity conditions. Nevertheless, the situation may change if light beams are propagating through long optical paths or in an optically thick environment. Most commonly this is relevant to a hazy or cloudy atmosphere, for as the concentration of atmospheric pollutants increases, the intensity of electromagnetic radiation decays more rapidly and the objectionable brightness of the surrounding environment becomes discomforting. A by-product of this effect is an intensified disability glare, with its obviously negative consequences for visibility [7].

The optical behavior of the atmosphere can also alter with the microphysical properties of aerosol particles, such as size, shape, or composition. Small particles scatter equally in forward and backward directions. However, this is not true for large particles (large compared to wavelength) where they asymmetrically scatter preferentially to the forward direction where the dominant peak is observed [8]. The backscatter is even more suppressed if particles become irregularly shaped [9]. It is also obvious

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that non-absorbing and strongly absorbing particles will scatter in a completely different manner.

Therefore, the optical behavior of the night sky can rarely be predicted by means of empirical methods, even if cloudless conditions are considered exclusively. Many prediction methods have no theoretical foundation and notoriously lack any consideration of the physical characteristics of the ambient environment. Nevertheless, tools are urgently needed to simulate the night sky radiances accurately. A reasonable estimation of sky glow is highly important to many scientists from astronomers, through biologists to environmental designers [10,11], city and suburban planners together with their funding and political responsibilities.

One most common anthropogenic factor is outdoor lighting which is increasingly complex. Hence, it is becoming a standard practice to require an environmental impact statement to accompany any proposal to change, redesign or reconstruct illumination systems that change the light environment. Without a theoretically sound environmental impact model it is implausible to expect the effects of luminaire renovations on the sky brightness to be predetermined.

Note that light emitted from statistically deployed heterogeneous sources is directed partly upwards and partly downwards. The latter signals interact with inhomogeneous surroundings (buildings, trees, obstacles) which consequently redirect the light beams in all directions. Upwardly directed signals form so called bulk emission function of a city. In addition to street lighting, advertisement boards distributed irregularly in the space, and emissions from building interiors contribute to the overall light field, which is characterized by the suppressed azimuthal pattern due to heterogeneity previously discussed. Basically, this emission function can be interpreted as an azimuthally weighted radiant/luminous intensity distribution, averaged over a bounded area or over a statistically relevant set of pixels. The total emission of a city can then be computed as an integral of an intensity function over the city pattern. There is an urgent need for a direct, or indirect method which could be used to identify emission patterns routinely. Hence, one such retrieval concept, based on measured sky radiance data, is introduced in [12]. This theory was applied to the experimental data collected during the targeted field campaign in the city of Frýdek-Místek. However, the main intention was not only to verify and validate the theoretical model, but also to analyze the effects of both the city pattern and the single scattering approximation on sky radiance/luminance in an urban area.

2. Theoretical night sky luminance

The propagation of visible radiation in an inhomogeneous atmosphere is, in general, a complex problem which requires a non-trivial mathematical treatment. Even if the atmosphere is considered to be a plane-parallel stratified medium, the short distances to the light sources make the theoretical solution difficult. For sparsely distributed ground-based light sources the concept of 3D radiative transfer has to be used to determine spectral sky radiances under varying meteorological conditions [13]. Following this approach, the altitude-dependent intensity of scattered radiation can be computed as the integral of the source function at a given optical depth [14]. Unfortunately, the integration is not a straightforward procedure since the source function in turn depends on the emergent intensity. The problem is then formulated in terms of an integro-differential radiative transfer equation (RTE) which can be solved iteratively under certain circumstances. However, this procedure is time-consuming and unattractive for routine use in design or assessment practice or when solving the inverse problems of the atmospheric optics. The advantage of the RTE concept is that it accounts for multiple scattering effects implicitly.

If the measurements are made in an urban area or in its vicinity, the light beams forming the light field near the ground typically propagate at short distances (Fig. 1), thus implying that the multiple scattering would play a marginal role. However, there is no doubt that beams traveling over long trajectories can undergo multiple scattering processes, but the intensity of such radiation recorded near the ground-based light source is low compared to the single scattering component.

The single scattering approximation (SSA) is an advantageous concept since it simplifies the computational scheme significantly. Accepting that luminaires are located in an urban area with surface S, then the theoretical spectral sky radiance under clear sky conditions is

$$L_\lambda(z_O, a_O) = M(z_O) \int_S \int_{h=0}^{H} B_\lambda\left[z_E(h)\right] \cos^2 z_E(h) \times \frac{t_\lambda(h, z_E) t_\lambda(h, z_O)}{h^2} \Gamma_\lambda(h, \theta) dh ds \tag{1}$$

which corresponds to the second term at the right hand side of Eq. (27) published in [15]. The term $\cos^{-1}(z_O)$ introduced in [15] is replaced by the optical air mass $M(z_O)$ to make Eq. (1) well suited for light beams traveling over long distances, being subjected to atmospheric refraction. In Eq. (1) z_O and a_O are observational zenith and azimuth angles; λ is the wavelength, $B_\lambda(z_E)$, the cosine weighted radiant intensity function for beams emitted from an elementary pixel with area ds toward the zenith angle z_E; $t_\lambda(h, z')$ is the transmission

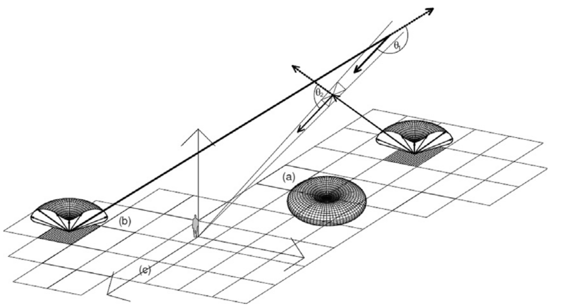

Fig. 1. The sky luminance in an urban area is mostly due to single scattering in a lower atmosphere. The pixel (a) is for the front-scatter case (in front of the observer), the pixel (b) is for the side-scatter case and (c) is for the back-scatter case. The light signals emitted from city pixels that are situated in the front of an observer are dominant due to scattering to low angles. The light emissions from other pixels are less important because of side-scatter or back-scatter that is generally weaker than near-forward scatter efficiencies.