Journal of Quantitative Spectroscopy & Radiative Transfer 139 (2014) 35–42

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Modeling the night-sky radiances and inversion of multi-angle and multi-spectral radiance data

Miroslav Kocifaj [a,b,*]

[a] ICA, Slovak Academy of Sciences, Dúbravská Road 9, 845 03 Bratislava, Slovakia
[b] Faculty of Mathematics, Physics, and Informatics, Comenius University, Mlynská dolina, 842 48 Bratislava, Slovakia

ARTICLE INFO

Article history:
Received 15 May 2013
Received in revised form
17 November 2013
Accepted 2 December 2013
Available online 10 December 2013

Keywords:
Sky-glow
Light pollution
Aerosols
Light scattering
Inverse problems

ABSTRACT

Information on a city's emission pattern is crucial for any reasonable predictions of night sky radiances. Unfortunately, the bulk radiant intensity distribution as a function of zenith angle is scarcely available for any city throughout the world. Even if the spatial arrangements of urban light fixtures and lamp specifications are known, the cumulative effect on upwardly directed beams is difficult to determine; due to heterogeneity of the ambient environment, reflectance from ground surfaces, arbitrarily scattered obstacles, orography of terrain and many other site specific factors.

The present paper develops a theoretical model and a numerical technique applicable to the retrieval of a City Emission Function (CEF) from the spectral sky radiances measured under clear sky conditions. Mathematically it is an inverse problem that is solved using a regularization algorithm in which the minimization routines penalize non-smooth solutions and the radiant intensity pattern is found subject to regularizing constraints.

When spectral sky radiances are measured at a set of discrete wavelengths or at a set of discrete distances from the monitored light source, both the aerosol optical properties and the CEF can be determined concurrently. One great advantage of this approach is that no a-priori assumptions need to be made concerning aerosol properties, such as aerosol optical depth.

The numerical experiment on synthetically generated city emissions' patterns has proven the functionality of the method presented.

1. Introduction

The propagation of electromagnetic radiation through disperse media illuminated by an external light source belongs to the class of radiative transfer problems that can be solved subject to boundary conditions. In atmospheric optics, sunbeams are considered to interact with a very heterogeneous environment that is responsible for a complex transformation of the electromagnetic field vector. It is well-known that clouds are the greatest modulators of ground impacting radiation [13,29] but under cloudless conditions aerosol particles are a most important atmospheric variable influencing downwelling radiation. The intensity field at any altitude is closely related to the aerosol microphysics [32], especially to particle size- and shape-distributions [30], chemistry [37], or internal topology [23]. The scattering domains that are small compared to wavelength scatter in accordance with Rayleigh's law and thus the ratio of forward to backward scattering efficiencies quickly approaches unity. However, the particulates with sizes below 0.1 μm (nucleation mode) are usually short-lived and grow rapidly into larger objects which have a longer residence time in the atmosphere [25]. These objects

* Corresponding author at: ICA, Slovak Academy of Sciences, Dúbravská Road 9, 845 03 Bratislava, Slovakia. Tel.: +421 2 5930 9293; fax: +421 2 5477 3548.
E-mail address: kocifaj@savba.sk

0022-4073/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jqsrt.2013.12.002

can be formed into composite (possibly solid-phase) aggregates showing a large variability in angular scattering patterns [6,31]. Basically, particles of different origin can coexist in heterogeneous polydisperse systems for which the bulk extinction or scattering coefficients change with location, altitude, and many other parameters. The vertical stratifications of aerosols and other atmospheric constituents typically differ, implying that light field characteristics would change with both the altitude and total concentration of aerosol particles. Typically, the aerosol content is related to the aerosol optical depth (AOD) that is employed in many optical models [40] and radiative transfer theories [15]. The concept of optical depth is also applied to water vapor, ozone, or other gaseous constituents to distinguish their distinct effects on the intensity of electromagnetic radiation propagated through the atmosphere.

In principle, the spectrum of a light source predetermines the spectrum recorded by a measuring device installed at ground level. However, the original spectrum can undergo a significant distortion in an Earth's atmosphere contaminated by aerosol particles with different sizes, shapes, and compositions. It is a straightforward procedure to determine the spectral radiance or flux density of electromagnetic radiation if the characteristics of both the light source and the atmospheric constituents are known. Nevertheless, this precondition is seldom true and rather than being fulfilled one or more of the required inputs is uncertain, for instance, if the light source properties or the optical characteristics of the atmosphere are only partly known, or are completely unknown.

The spectral properties of solar radiation play a pivotal role in modeling daylight behavior under different turbidity conditions. Dubovik et al. [7] have shown that daytime radiances contain the required information on atmospheric characteristics for interpretation in terms of aerosol and molecular optics. Basically, the physics of light propagation through the daytime and nighttime atmospheres is the same, with only some exceptions: in the nighttime regime the light sources are situated at ground level, with distances to these sources usually small enough for geometrical relationships to become important. This makes the radiative transfer equation difficult to solve for ground-based light sources because of their 3D geometry.

However, modeling of the light field in nighttime is of great interest to astronomers, who are interested in noise free light near their observatories (e.g. [39]). Illumination engineers who deal with public lighting systems, must also recognize the potentially adverse effects of night lighting characteristics on the environment [8]. In recognition of these needs and imperatives legislation to control the level of diffuse nightlight has been implemented in some countries with the aim of eliminating excess and inappropriately configured lighting. This goal may be partially achieved simply by retrofitting inappropriate luminaire installations.

Yet it is extremely difficult to predict luminance and illuminance levels accurately using only information on spatial distribution of individual lamps. That is because the radiant intensity distribution for upwardly directed urban beams depends on the physical deployment of these lamps in an heterogeneous urban environment, on the orography and reflectance of surrounding terrain and on many other locality-specific parameters [3]. All these effects coalesce, resulting in a specific City Emission Function (CEF), which plays a decisive role in forming the sky radiance/luminance patterns under arbitrary meteorological conditions. Because the diffuse light of a night sky can influence the ground-based photometric or radiometric measurements, and the processing of recorded astronomical data, astronomers need CEF data to estimate the effects of artificial light on observed sky brightness [26].

Many professional observations are made by narrowband and broadband filters with different widths and shapes of transmission curves. There is no doubt that without well-founded theories no reasonable prediction of light noise could be made and modelers would not be able to differentiate data derived theoretically from data recorded from observations in nature. However, in order to make the numerical simulation of light noise possible, the optical characteristics of both the atmospheric environment and artificial light-sources have to be known or determined indirectly under well controlled conditions. Retrieval of either of these two functions from observed sky brightness (or other optical data, such as irradiances) belongs to the class of ill-posed problems that are notoriously difficult to solve because of the instability or ambiguity of the solution function, especially if no a-priori information on the search function is available. This paper shows that mapping between theoretical sky brightness and CEF is possible through an integral operator. Similarly, the interrelation between observational data and atmospheric optical properties can be formulated in terms of an integral equation for which the approximate solution exists. Retrieval possibilities for some atmospheric and light-source characteristics are analyzed theoretically using multi-angle and multi-spectral radiance data.

2. Theoretical radiance

If a beam of monochromatic radiation with wavelength λ propagates through an atmospheric layer containing the aerosol particles, the intensity decays in accord with the Bouger–Lambert–Beer law

$$J_\lambda(\tau_\lambda, z_E) = J_\lambda(0, z_E)\exp\left\{-\frac{\tau_\lambda}{\cos z_E}\right\}, \tag{1}$$

where τ_λ is the optical depth of the layer that extends from the ground level to the altitude $h = h(\tau_\lambda)$. Since $d\tau_\lambda = k_{ext,\lambda} dh$, the optical depth τ_λ and the altitude h can be interrelated through the integral form $\tau_\lambda = \int_0^h k_{ext,\lambda}\, dh$, where $k_{ext,\lambda}$ is the volume extinction coefficient (this quantity is traditionally used in modeling the optical properties of a stratified atmosphere, see e.g. [38]). Assuming that z_E is the zenith angle of a light beam propagating through the plane-parallel atmosphere and $J_\lambda(0, z_E)$ is the spectral radiance of an elementary surface, then $J_\lambda(\tau_\lambda, z_E)$ represents the fraction of radiation that reaches the level of τ_λ and was originally emitted from a ground-based light source.

Following the convention introduced above we can define the transmission coefficient $t_\lambda(h, z_E) = \exp(-\tau_\lambda/\cos z_E)$ between the ground level and level of scattering event.