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Urban artificial light emission function determined experimentally using night sky images

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ABSTRACT

To date, diverse approximations have been developed to interpret the radiance of a night sky due to light emissions from ground-based light sources. The radiant intensity distribution as a function of zenith angle is one of the most unknown properties because of the collective effects of all artificial, private and public lights. The emission function (EF) is, however, a key property in modeling the skyglow under arbitrary conditions, and thus it is equally required by modelers, light pollution researchers, and also experimentalists who are using specialized devices to study the diffuse light of a night sky.

In this paper, we present the second generation of a dedicated measuring system intended for routine monitoring of a night sky in any region. The experimental technology we have developed is used to interpret clear sky radiance data recorded at a set of discrete distances from a town (or city) with the aim to infer the fraction of upwardly emitted light (F), that is a parameter scaling the bulk EF. The retrieval of the direct upward emissions has been improved by introducing a weighting factor that is used to eliminate imperfections of experimental data and thus to make the computation of F more stable when processing the radiance data taken at two adjacent measuring points. The field experiments made in three Mexican cities are analyzed and the differences found are discussed.

1. Introduction

Upwardly emitted artificial light is usually a cause of skyglow (diffuse light) that is an environmental problem with serious consequences for the night environment. The downward diffuse radiation is mostly due to the interaction of the artificial light at night with atmospheric constituents, specifically air molecules and aerosols distributed in the lower troposphere. Such a luminous flux emitted into the upper hemisphere undergoes absorption and scattering processes. As a consequence, skyglow is strongly related to the optical properties of an atmospheric environment. The problem has a deleterious effect on astronomy because it creates a glow that reduces the contrast of a night sky making the observation of astronomical objects difficult. The first studies on this topic date back to Walker [43], Hoag [15], Bertiau et al. [4], Berry [3] and Pike [36].

The artificial light at night has other implications as well. For example, the disturbance of natural night cycles produced by light pollution creates serious ecological imbalances for life on the earth [33]; including effects on animals and plants [29,42], on insects [12], and on humans [1,6]. Skyglow could also have distinct effects on the

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natural biological processes of some living organisms [32]. Such negative consequences can be correlated to the type of lighting technology [39].

The night sky radiance distribution can change with aerosol microphysics as demonstrated by Garstang [14], Joseph et al. [16], Aube et al. [2], Kocifaj [18], and Kocifaj and Solano Lamphar [20]. However, aerosols and air molecules only act as modulators of emission patterns that, in turn, have relation to the characteristics of the urban lighting system. The emission function (EF) is an important feature of a light source and plays a significant role in the consequent skyglow. Among other approaches, Garstang's emission function (GEF) has been the primary technique used by light pollution researchers [13,17,24,30,7]. At present, GEF is still in use because of lack of convenient analytical functions that are controlled by one or more parameters each having physical significance. Basically, there is no specific reason to prefer Garstang's model, especially because this function ignores obstacle blocking and thus simulate near horizon emissions inaccurately. However, any mathematical representation of EF is required to simulate different optical effects: from a diffuse reflection to the emissions exclusively directed upwards, including intermediate states that combine weighted contributions of both up-light emission and diffuse reflection. Otherwise, the retrieval methodology described in this paper will not work properly.

In general, when no assumption is made on the form of EF, the retrieval becomes an extremely difficult (ill-posed) problem that may fail to satisfy at least one of the following conditions: (a) the existence of a solution, (b) the uniqueness of the solution, and/or (c) the continuity of the data function solution. Therefore, a simplified parametrized formula for EF is preferred if intended to be used in routine inversion of radiance data. GEF might not be the best tool as indicated earlier, but it benefits from an easy analytical formula that can be used in simulating the radiant intensity as a function of two well-justified parameters, F and G. In this case, the inversion procedure will be reduced to a minimization of discrepancies between theoretically predicted and experimentally measured radiance data, while searching for optimum values of F and/or G. Here the reflectance (G) characterizes the fraction of the light that is isotropically reflected from the ground, while uplight (F) is the fraction of the light radiated directly into the upward hemisphere.

Experimental determination of both parameters is of great interest in the light pollution community. It has been shown recently that uplight can be retrieved from zenith radiance and horizontal irradiance when measured concurrently [23]. However, it is necessary to record optical data at different measuring points, typically up to several radii from the city edge. In the present work, we propose an experimental system with the intention of enhancing the possibilities offered by DSLR cameras that were used before in retrieval of the EF. The proposed system consists of a steady and inexpensive platform that is easy to prepare and control, operating by means of an automated data acquisition system. The approach we are following is advantageous due to its clear theoretical base, easy algorithm and straightforward numerical implementation.

2. A critical review of advantages and shortcomings of the model selected

The EF is largely unknown for many cities worldwide. This is because of different lighting installations, urban design, orography, etc. Attempts to estimate EF using the information on up-to-date inventory of public light sources is a nontrivial task and even if successfully completed this procedure may lead to conclusions that might not be substantiated. The bulk emission function of a city is due collective effects of many sources embedded into various environments (city parks, streets, industrial zones, etc.), while a considerable portion of light emissions can even originate from automobile lighting, sports lighting, industry, advertisement boards, but also from private households. For instance, Novák et al. [35] have conducted an extensive experiment in Liberec district, Czech Republic, comparing the illumination levels before and after switching off public lighting and concluded that share of street lighting in total illuminance might be as low as 50%, or even less [34]. Therefore a simple approximation based on the photometry of dominant lights (e.g. cobrahead luminaire for roadway lighting) combined with lambertian reflectance is not what is perceived as a bulk emission function.

No doubt that EF is a city-specific property and a systematic retrieval of bulk emissions from various regions is needed to build a good database in order to come with a reasonable classification of EFs. Direct monitoring of EF is difficult, expensive, and still very rare. For instance, a lens-equipped optical device has been developed only recently [28] and mounted on an aerial platform of low-flying aircraft. However, the distance between a camera system and light emitting pixels is comparable to the characteristic size of a city, so the signals recorded this way account for a collective effect of many emission angles. In addition, the optical signals undergo different distortion due to different atmospheric extinctions at inclined trajectories. Another source of information on ground-based emission could be a nighttime satellite imagery, that however allows only for monitoring EF at zenith angles. In addition, the radiance obtained this way fluctuate due to spatial and temporal heterogeneity of atmospheric environment, specifically due to cloud motion.

Another possibility is to infer EF from indirect methods that interrelate the theoretical radiance of a night sky with light emissions upwards. The methods to obtain EF from measured characteristics of the diffuse light field belong to ill-posed inverse problems that are difficult to solve, partly because small changes in the data function tend to produce large changes in solutions sought, and partly because of incomplete data sets. Solution of the ill-posed problem may suffer from continuity, uniqueness or physical meaning (e.g. negative values or oscillatory behavior of EF can be found). A general solution of the inverse problem for EF is introduced in [19] where the quadratic minimization principle is customarily combined with a quadratic constraint showing that ill-conditioned problem reduces to a well-posed problem if quadratic forms are positive and one of them is non-degenerated. Inversion that is independent of *a-priori* information on the EF