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On the feasibility of inversion methods based on models of urban sky glow

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ABSTRACT

Multi-wavelength imaging luminance photometry of sky glow provides a huge amount of information on light pollution. However, the understanding of the measured data involves the combination of different processes and data of radiation transfer, atmospheric physics and atmospheric constitution. State-of-the-art numerical radiation transfer models provide the possibility to define an inverse problem to obtain information on the emission intensity distribution of a city and perhaps the physical properties of the atmosphere. We provide numerical tests on the solvability and feasibility of such procedures.

1. Introduction

The Hungarian protected area network (national parks, wildlife reserves) almost overlaps with the dark sky areas. This fact indicates their mission in protecting dark skies, as nature conservation is deeply interrelated with protecting the nocturnal landscape. Our goal was to identify those areas, which could be suitable for the nomination to be dark sky parks. In Europe it is hard to find really dark places. Even far from large cities and local settlements there is an increased level of sky brightness due to excessive sources hundreds of kilometres away from that location. Therefore, night sky quality monitoring becomes an important part of nature conservation. We performed imaging sky luminance measurements at different locations in the country as part of the designation of natural park areas for International Dark Sky Parks (IDSP) recognised by the International Dark Sky Association (IDA). As a result of our work the Zselic Landscape Protection Area and the Hortobágy National Park were recognised as IDSP in 2009 and 2011.

A possible method to qualify the light pollution (sky glow) over a large area is to make maps of night sky brightness in and around a protected area. A possible way to generate such maps is to measure the (average) luminance of a portion of the night sky by a luminance meter (e.g. Sky Quality Meter). If such measurements are made on a dense enough geographic grid, the sky glow of the territory can be mapped. However, significantly more information can be gathered by imaging photometry of the sky. In addition, recent techniques to survey light pollution (e.g. [1,2]) provide the spatial distribution of artificial sky luminance as a function of different parameters (wavelength, sky position, etc.). Recent Digital Single Lens Reflex (DSLR) cameras provide a new opportunity to monitor the quality of the night sky and light pollution. Cameras that are able to save images in an unaltered raw format can be calibrated to get measurements of the luminance of the sky on a physical scale. Then, the photo of the night sky can be converted to false colour images, which represents the distribution of sky

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brightness [2]. Such calibrated images of the light domes over cities provide enough information to interpolate or even extrapolate them to a larger area if the measurements are combined with numerical radiation transfer modelling.

The general procedure of light pollution modelling uses the spatial distribution and the characteristic properties of light sources and the physical parameters of the atmosphere as an input for the calculations, and then the distribution of the luminance of sky glow is provided as a result. The basic elements of these methods can be found e.g. in [3,4] and references therein. The output of the models then can be compared with measurements to verify the physical ingredients and input parameters of the numerical calculations. These models are based on numerical integration of the radiation transfer equations. Another possible way is to perform Monte-Carlo simulation of photon packets (see e.g. [5]). For the tests in this paper we used the second method.

The combination of models and observations gives the possibility to invert the procedure and to use light pollution models to predict the quantities of the emission sources from observations. Details of this inversion method are provided in the paper.

2. Models

To interpret the sky brightness measurements and to provide models of the light pollution, we have developed a Monte-Carlo radiation transfer code. In clear air (no clouds), the propagation of light is determined by the Rayleigh scattering for molecules and by the Mie scattering for aerosols. For most of the calculations of this paper, absorption was neglected for simplicity. The mean free path of photons in terrestrial atmosphere is several tens of kilometres, depending on the aerosol content and elevation. It gives a natural choice to use Monte-Carlo simulation of the light propagation since the observed photometric quantities are statistical averages of photon packets. For detailed description of Monte-Carlo radiation transfer calculations see e.g. [5]. Here we summarise only the major ingredients of the code: the Mie scattering is approximated by the Henyey–Greenstein phase function (see e.g. in [5]). This makes some approximation in our calculations, but the use of different phase functions does not alter our main conclusions. Multiple scattering is calculated, the code follows the photon packets until they leave the atmosphere at the outer boundary or absorbed on the ground. Both forward and reverse (the photon packets are initiated at the detector) calculation is possible. The efficiency of the Monte-Carlo simulation is greatly increased by the peel-off technique [6].

The spatial distribution of sky glow is determined by spatial distribution of the total flux radiated to the atmosphere and the upward-directed angular luminous (or radiant) intensity distribution $I(\psi)$ of the light polluting sources. Note that in this paper we simply use intensity to denote luminous intensity. But in most of the circumstances the results are valid for radiant quantities as well. In all the tests we calculated radiation transfer for a set of wavelengths (between 380 nm and 780 nm in 5 nm steps) and integrated the monochromatic results with the CIE 1931 photopic visibility function ($V(\lambda)$) [7] to get the luminous quantities. We note that the calculations can be performed with the scotopic visibility function ($V'(\lambda)$) as well. In our study the intensity distribution is approximated by a series of spherical harmonics. If we concentrate on the axial symmetric distribution, then the series is reduced to the associated Legendre polynomials $P_{lm}(\cos\psi)$ with $m=0$. To avoid negative intensities in the calculations, the elementary intensity distributions are slightly modified: $F_0 = P_{00}$, $F_1 = P_{10}$, $F_2 = P_{20} + \frac{1}{2}P_{00}$, $F_3 = P_{30} + \frac{1}{2}P_{00}$, $F_4 = P_{40} + \frac{1}{2}P_{00}$.

To demonstrate the effectiveness of this series, the fit of the generally used Garstang's distribution [8] is displayed in Fig. 1. The conclusions of this paper do not depend on the intensity scale. However, for this figure and for all the other polar diagrams in the paper we used an arbitrary scale that gives the luminous intensity assuming that the total luminous flux of the source is 100 units (e.g. a flux of 100 lumens gives the intensity in candelas). Garstang's standard upward intensity distribution is a sum of the Lambertian reflection (identical to $F_1 = P_{10}(\cos\psi)$) and a distribution defined by the fourth power of the zenith angle (ψ^4). A fit with the first three polynomials (F_0, F_1, F_2) gives a sufficient result. A fifth order fit (used for the tests discussed in this paper) is almost undistinguishable from the original upward angular light distribution.

2.1. Model components

A grid of models with different atmospheric conditions is calculated by our Monte-Carlo radiation transfer code. To test the effect of humidity and aerosol content in the atmosphere, a two parameter model of aerosol distribution is used. The aerosol optical thickness at 500 nm (τ_a) is varied from 0 to 0.4 (for a fixed grid of τ_a=0.0, 0.02, 0.05,

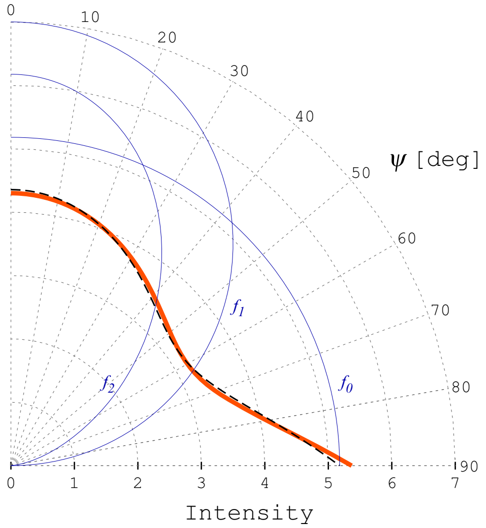

Fig. 1. Garstang's upward angular intensity distribution function (thick solid line). The fit with the first three F_l polynomials is shown by a thin solid curve. The weighted polynomials $f_k = c_k F_k$, constrained by $f_1 - f_2 + f_3 = \text{fit}$, are displayed by thin dashed curves. The intensity scale is arbitrary (see the text for more details).