Light pollution models and detection method take account of heterogeneous environments

Martin Aubé

Major improvements have been made to light pollution modeling and detection capabilities for a heterogeneous environment. These innovations give rise to new applications such as the development of a method for remotely sensing aerosols at night and the assessment of night sky quality for present and future astronomical sites. Other possibilities include the implementation of new tools to perform intelligent design of low-light-pollution lighting devices and the optimization of lighting conversion scenarios in order to reduce light pollution for a specific site and/or a given application.

Since the 1980s, very few improvements have been made to light pollution models. Most studies have been made with first-generation models such as Garstang’s well-known model, and have been considered accurate enough to achieve night-sky quality assurance of astronomical sites. However, first-generation models used simplified approaches such as considering a city as a perfect circle of constant luminosity and constant ground reflectance. They also neglected the effect of topography, which could introduce shadowing effects. Most of the simplifying assumptions were driven by the limited power of computers. Moreover, validation of models was relatively limited because very few attempts have been made to monitor, accurately, the spectral behaviour of light pollution in space and time. Hyperspectral light-pollution remote sensing is, in fact, a major issue, since most sources contributing to light pollution emit line spectra (e.g. high-pressure-sodium or metal-halide lamps). Without spectral discrimination, it remains difficult to separate the artificial and natural contribution to the observed night sky brightness.

The rapid development of personal computers now allows high-performance computing tasks to be carried out at a low cost. Because of this, we decided to implement a heterogeneous light pollution model in which a city may take any shape, can have a variable distribution of light sources, and can have local variations in topography and ground reflectance. This second-generation, 3D model is called ILLUMINA.

ILLUMINA allows the simulation of real situations as long as all the relevant information is available (e.g. geographical distribution of light, spectral luminosity and angular emission patterns, ground spectral-reflectance variability, topography, and atmospheric aerosol content). ILLUMINA was designed to simulate the light scattered back to a spectrometer, so the model does not allow the simulation of direct observation of the ground or any direct sight toward a lighting device. So far, the model only simulates the contribution of artificial light to the night-sky glow. Contributions from moonlight, auroras, stars, and any other celestial objects have not yet been implemented.

Following on from our enhanced modeling capabilities, we have designed a spectrometer that is dedicated to the remote sensing of light pollution. This instrument may be used to validate model results or simply to monitor the temporal evolution of light pollution for some specific sites.

The total spectral flux $\Phi$ (Watt/nm) entering the simulated spectrometer is given by:

$$\Phi = \sum_n I_n \Omega_n \frac{\Omega_m}{\Omega_{FOV}}$$

Here $I_n$ is the light spectral intensity (W/str/nm) scattered toward the spectrometer by a model cell crossed by the spectrometer line of sight; $\Omega_n$ is the solid angle subtended by the spectrometer entrance as seen from scattering cell $n$ (see Figure 1); $\Omega_m$ is the solid angle subtended by cell $n$ as seen from the spectrometer position; $\Omega_{FOV}$ is the solid angle of the spectrometer field of view (FOV). The model takes the sum over $n$ to integrate the light scattered along the spectrometer line of sight.

We assume that $I_n$ may be mainly explained by the combination of the first-order scattering $I_1$ and $I_2$, (with and without reflection on the ground) and the second-order scattering $I_3$ and $I_4$. Second-order scattering terms consume the most computer time.

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since there are many first-order scattering cells $m$ that contribute significantly to the flux crossing the cell $n$ for the second-order scattering process.

Light extinction arising during various light paths between the light source and the spectrometer is computed. To enable this computation, we assume that the vertical profiles of the molecular and aerosol concentrations follow exponentially decreasing functions. We also assume that aerosol and molecular concentration profiles are uniform over the modeling domain. For simplicity, we restricted ILLUMINA applications to some visible and near-infrared spectral bands that were carefully chosen to exclude carbon-dioxide and water-vapour molecular absorption.

Ground reflectance is assumed to be Lambertian. We allow the computation of the reflected light up to a maximum reflective radius (MRR) centered on each lighting ground cell. MRR represents the free light path towards the ground, which is determined by the presence of obstacles, such as trees, buildings or topography.

ILLUMINA may be seen as a tool for resolving complex questions related to light-pollution behaviour. Without this kind of model, it is difficult to draw conclusions about the importance of a given parameter on light-pollution levels in real conditions. ILLUMINA is a significant improvement on previous models. One of the most important innovations is the implementation of the heterogeneous and complex nature of real environments.

However, much evaluation and validation work remains to be done. We are presently conducting a sensitivity study to estimate the impact of particular lighting parameters that are reputed to have significant influence on light pollution. For example, we are evaluating the importance of light-source angular geometry, the impact of snow cover for northern regions, and the influence of the temporal variability of aerosol optical depth. We are also working on a comparative study with previous models and, in spring 2006, we plan to do an intensive field study in Flagstaff, AZ, to acquire a real-case light pollution validation dataset.

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Martin Aubé got his Ph.D. in remote sensing from Université de Sherbrooke (Canada). He also completed a M.Sc. in astrophysics at Université Laval. He founded the Applied Physics research at the CÉGEP de Sherbrooke, is the scientific director at the MEMO Environnement company, and is an adjunct researcher of the Centre Observatoire du Mont Mégantic. In addition, he has written three papers for SPIE proceedings.
References
