Light Pollution Modelling and Detection in a Heterogeneous Environment: Toward a Night Time Aerosol Optical Depth Retrieval Method

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ABSTRACT

Tracking the Aerosol Optical Depth (AOD) is of particular importance in monitoring aerosol contributions to global radiative forcing. Until now, the two standard techniques used for retrieving AOD were; (i) sun photometry, and (ii) satellite-based approaches, such as based DDV (Dense Dark Vegetation) inversion algorithms. These methods are only available for use during daylight time since they are based on direct or indirect observation of sunlight. Few attempts have been made to measure AOD behaviour at night. One such method uses spectrally-calibrated stars as reference targets but the number of available stars is limited. This is especially true for urban sites where artificial lighting hides most of these stars. In this research, we attempt to provide an alternate method, one which exploits artificial sky glow or light pollution. This methodology links a 3D light pollution model with in situ light pollution measurements. The basic idea is to adjust an AOD value into the model in order to fit measured light pollution. This method requires an accurate model that includes spatial heterogeneity in lighting angular geometry, in lighting spectral dependence, in ground spectral reflectance and in topography. This model, named ILLUMINA, computes 1\textsuperscript{st} and 2\textsuperscript{nd} order molecular and aerosol scattering, as well as aerosol absorption. These model features represent major improvements to previous light pollution models. Therefore, new possibilities for light pollution studies will arise, many of which are of particular interest to the astronomical community. In this paper we will present a first sensitive study applied to the ILLUMINA model.

Keywords: aerosol optical depth, remote sensing, light pollution, artificial sky glow

1. INTRODUCTION

The AOD, which represents total aerosol optical attenuation at a given wavelength, is a key parameter in the monitoring of aerosol optical properties. This monitoring is particularly useful in estimating aerosol contribution to global radiative forcing. Many techniques have been developed in order to monitor the spatio-temporal variability of the AOD. A well-established method consists in observing direct solar radiation using ground based sunphotometer networks such as AERONET (AErosol Robotic NETwork).\textsuperscript{1} A second important technique is based on inversion algorithms, which exploits the atmospherically dominant signal present over dark target pixels in remotely-sensed satellite images. This technique has been successfully applied over dense dark vegetation (DDV) and ocean pixels using satellite-based sensors such as AVHRR (Advanced Very High Resolution Radiometer)\textsuperscript{2} and MODIS (Moderate Resolution Imaging Spectro-radiometer).\textsuperscript{3} These two techniques are somewhat complementary, since sunphotometers give good temporal sampling but are limited to a few sites, and satellite inversion algorithms give better spatial sampling but low temporal data coverage, but they do not allow AOD retrieval at night time. Recently, starphotometers have been designed to overcome this drawback. Starphotometers use spectrally calibrated stars as reference targets to give an estimate of the atmospheric extinction. However, the number of available bright stars is limited, particularly in urban sites where most are hidden by light pollution.
We intend to provide a new complementary method that will fill the night gaps in spatio-temporal AOD measurements. This method links spectral measurements of artificial night sky glow and the predictions of a light pollution model. The model, named ILLUMINA, computes 1st and 2nd order molecular and aerosol scattering, as well as aerosol absorption onto a 3D grid. The model account for spatial heterogeneity in lighting angular geometry, in lighting spectral dependance, in ground spectral reflectance and in topography (including the computation of shadows). These model features represent major improvements to previous light pollution models. For example, the well-known Garstang's 4 model idealized a city as a circular light emitting disk with a constant luminosity per unit of ground surface. The level of luminosity is computed from the empirical relationship found between luminosity and the population of a city. Inside the city, the model assumes that angular light emission functions as long as ground reflectance values are homogeneous. This model was unable to account for shadows effects arising when any obstacles are present inside the modelling domain. Our important improvement to light pollution modelling capabilities, allow new possibilities for more detailed light pollution studies. These studies may be of particular interest to the astronomical community and for nature park services who both wish to preserve the quality of night skies.

In this paper we will focus on a description of ILLUMINA's capabilities and features. We will also present our preliminary results from an ongoing sensitive study applied to the ILLUMINA model.

2. BASIC AOD RETRIEVAL METHOD

Our methodology relies on a combination of enhanced 3D light pollution modelling capabilities and spectral measurements of night sky brightness. The basic idea is to simulate the measurement of a given light pollution spectral detector pointed toward the sky in any position and orientation. We may adjust, in an iterative way, the aerosol optical depth value into the light pollution model in order to obtain the best possible fit between the model and the observation. We then assume that this optical depth is our best estimate of the atmospheric AOD. Figure 1. gives a graphical representation of that methodology.

![Diagram of AOD retrieval method](image)

Figure 1: Graphical representation of our night time AOD measurement technique

Light pollution spectral measurement is done with the Spectrophotometer for Aerosol Night Detection (SAND) which is a non-imaging long slit diffraction grating-based instrument. SAND was developed by the Groupe de Recherche et d'Application en PHYsique au Collège de Sherbrooke (GRAPHYCS). The instrument was recently used for the 2005 Intensive Light Pollution Spectral Monitoring Experiment, in California-Arizona-Utah. The measuring method focused

Important note: An error in equation 1 have been corrected since the publication.
on the discrimination of some key spectral lines which are representative of specific kinds of lighting devices frequently used for street and commercial lighting applications (high pressure sodium, metal halide, low pressure sodium). With this instrument, it is relatively easy to separate total light pollution into its major contributing sources. Natural contribution to sky brightness (aurora, moonlight, stars, etc) are easily removed from the detected signal.

3. MODEL SUMMARY

ILLUMINA was designed to simulate light scattered back to a spectrometer, so that the model not allow the simulation of direct observation of the ground or any direct sight toward a lighting device. The model only simulates the contribution of artificial light to the night sky glow. Contributions from moonlight, auroras, stars, and any other celestial objects are not yet implemented.

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

\[
\Phi_m = \sum_n I_{no} \Omega_{no} \frac{\Omega_{FOV}}{\Omega_{on}}
\]

Where \( I_{no} \) is the light spectral intensity (W/str/nm) scattered toward the spectrometer by a model cell crossed by the spectrometer line of sight. \( \Omega_{no} \) is the solid angle subtended by the spectrometer entrance as seen from scattering cell \( n \) (see figure 2). \( \Omega_{on} \) is the solid angle subtended by cell \( n \) as seen from the spectrometer position \( o \). \( \Omega_{FOV} \) is the solid angle of the spectrometer field of view (FOV). The ratio \( \Omega_{on}/\Omega_{FOV} \) gives the ratio of light coming from a given cell \( n \) which will in fact enter the instrument. In some cases, the spectrometer will see more than the cell \( (\Omega_{FOV}/\Omega_{on}>1) \) and sometimes less \( (\Omega_{FOV}/\Omega_{on}<1) \). The model takes the sum over \( n \) to integrate the light scattered along the spectrometer line of sight.

Figure 2: Modelling geometry and most important contribution to the received flux by a spectrometer in position \( o \).
We assume that $I_{no}$ may be mainly explained by the combination of the first order scattering (with and without reflection on the ground) and the second order scattering (again with and without reflection on the ground). Consequently, we can write

$$I_{no} \approx I_1 + I_{r1} + I_2 + I_{r2}. \quad (2)$$

$I_1$ is the single scattered intensity, $I_{r1}$ is the first scattered intensity after reflection on the ground, $I_2$ is the second order scattering intensity, and $I_{r2}$ is the second order scattering intensity after reflection on the ground. The two last terms of equation 2 are the most computer-time consuming since there is a lot of first order scattering cells $m$ which contribute significantly to the flux crossing the cell $n$ for the second order scattering process.

Extinction arising during various light paths between the light source and the spectrometer is computed. This extinction is a multiplicative combination of molecular extinction and aerosol extinction transmittances. To enable this computation, we assume that the molecular and aerosol concentration vertical profiles follow exponential decreasing functions. We set the decreasing scale height to $H_a=2\text{km}$ for aerosols and $H_{mol}=8\text{km}$ for molecules. We also make the assumption that aerosol and molecular concentration profiles are uniform over the modelling domain.

For simplicity, we restricted ILLUMINA applications to some spectral bands which are a subset of the visible (VIS) and near-infrared (NIR) spectral regions. These bands have been carefully chosen to exclude parts of the spectrum affected by carbon dioxide and water vapour molecular absorption. These two gases are highly variable in space and time so that their precise modelling represents a task too difficult for the scope of our study. Figure 3 shows the spectral bands accessible to ILLUMINA. Only the highlighted parts of the spectrum are considered by the model. This figure was obtained from a MODTRAN simulation of the atmospheric transmittance for mid-latitudes. The slow increasing trend of the curve corresponds to extinction from molecular scattering, but high frequency patterns are made by molecular absorption.

![Figure 3: MODTRAN simulation of the VIS and NIR spectral transmittance of the earth’s atmosphere for mid-latitudes.](image-url)

**A-Computation of $I_1$**

The first term of equation 2 is given by
\[ I_1 = L_0 T_{no} E(\theta_{sn}) \Omega_{sn} T_{sn} P_{sn} f(\theta_{sn}, \theta_{no}) \]  

(3)

where \( L_0 \) stands for the total source spectral luminosity (Watts/nm), \( T_{sn} \) is the transmittance from source to scattering cell \( n \), \( E(\theta_{sn}) \) is the horizontally averaged angular emission function for a given lighting device, and \( \theta_{sn} \) is the zenithal angle of the light path from source \( s \) to the scattering cell \( n \). \( P_{sn} \) is the scattering probability of the cell \( n \), this probability relies on the cell molecular and aerosol content along with \( s-n \) light path orientation. \( \Omega_{sn} \) is the solid angle subtended by the scattering cell \( n \) as seen from the source \( s \). \( T_{sn} \) is the atmospheric transmittance from scattering cell \( n \) to spectrometer \( o \), and \( \theta_{no} \) is the zenithal angle of the cell \( n \) to spectrometer \( o \) path. Finally, \( f(\theta_{sn}, \theta_{no}) \) is the scattering phase function which is normalized so that the integral of that function over every solid angle of the sphere is equal to 1. This function is pre-computed using the Mie or Rayleigh theory depending if we are to consider respectively aerosol or molecular contributions to \( I_1 \). To determine the atmospheric transmittance, we assume that the total transmittance is given by

\[ T = T_a T_{mol} \]  

(4)

where \( T_a \) is the aerosol transmittance and \( T_{mol} \) the molecular transmittance. \( T_a \) is calculated with the value of the total aerosol transmittance \( T_{a,\infty} \) which is estimated with the total aerosol optical depth \( \tau_a \), corrected for the air mass \( M_\infty \).

\[ T_{a,\infty} = \exp(-M_\infty \tau_a) \]  

(5)

The air mass \( M_\infty \) is computed from a first order geometric correction (assuming plane parallel atmosphere). We will remove this approximation in a future version of the model.

\[ M_\infty \approx \frac{1}{\cos \theta} \]  

(6)

As long as we assume an exponential vertical profile for aerosol atmospheric content, we can show that the effective aerosol transmittance for an air slice starting at altitude \( z_1 \) to altitude \( z_2 \) is given by

\[ T_a = T_{a,\infty} \left( \exp \left( \frac{z_1}{H_a} \right) - \exp \left( \frac{z_2}{H_a} \right) \right). \]  

(7)

According to Kneizys et al.\(^{10} \), the total molecular transmittance may be written as

\[ T_{mol,\infty} = \exp \left( \frac{-M'_\infty}{\lambda^4 \left( 115.6406 - \frac{1.335}{\lambda^2} \right)} \right). \]  

(8)

where we have corrected the air mass for ground level atmospheric pressure variations

\[ M'_\infty = M_\infty \frac{P_0'}{p_0} \]  

(9)

Important note: An error in equation 1 have been corrected since the publication.
\( p_0' \) is the actual ground level atmospheric pressure and \( p_0 \) is the standard sea level atmospheric pressure.

Like for the aerosol case (equation 7), we can write the effective molecular transmittance for an air slice starting from altitude \( z_1 \) to altitude \( z_2 \).

\[
T_{\text{mol}} = T_{\text{mol} \infty} \left( \exp\left(-\frac{z_1}{H_{\text{mol}}}\right) - \exp\left(-\frac{z_2}{H_{\text{mol}}}\right) \right) \tag{10}
\]

The effect of molecular absorption may be vanished by a proper choice of working wavelength (see figure 3) so that the molecular scattering probability of a given cell is computed according to the cell intrinsic transmittance \( T_{\text{mol}} \).

\[
P_{\text{mol}} = 1 - T_{\text{mol}} \tag{11}
\]

For aerosols, the transmittance may be explained by a combination of absorption and scattering effects. If the air transmittance associated to a cell is large enough \( (T_a \approx 1) \), we can write

\[
T_a = e^{-d\tau_{ae}} \approx 1 - d\tau_{ae} \tag{12}
\]

where \( d\tau_{ae} \) is the intrinsic extinction aerosol optical depth of the cell.

The probability of any interaction (scattering or absorption) between the radiation and the aerosol may be written as

\[
P_a = 1 - T_a \approx d\tau_{ae} \tag{13}
\]

by definition \( d\tau_{ae} \) is proportional to the aerosol extinction cross section \( \sigma_E \)

\[
d\tau_{ae} \propto \sigma_E \tag{14}
\]

Similarly, we can write the intrinsic scattering aerosol optical depth of the cell \( d\tau_{as} \) as a function of the scattering cross section \( \sigma_S \)

\[
d\tau_{as} \propto \sigma_S \tag{15}
\]

The proportionality constant is the same for Equations 14 and 15. Consequently, we can formulate the cell scattering optical depth \( d\tau_{as} \) as a function of \( d\tau_{ae} \) and a proper combination of the cross sections.

\[
d\tau_{as} = \frac{\sigma_S}{\sigma_E} d\tau_{ae} \tag{16}
\]

We then obtain the approximate formulation of the aerosol scattering probability of the cell

\[
P_{as} \approx \frac{\sigma_S}{\sigma_E} P_a \tag{17}
\]
The first order scattering after reflection is given by

\[ I_{r1} = \frac{L_0}{2\pi} T_{no} \sum_r E(\theta_{sr}) \Omega_{sr} T_{sr} \rho_r \cos(\theta_r + \varepsilon) \Omega_r P_r f(\theta_r, \theta_{no}) T_r , \tag{18} \]

where \( \theta_{sr} \) is the zenithal angle of source \( s \) to the ground surface \( r \) light path, \( \theta_r \) is the zenithal angle for the ground surface \( r \) to scattering cell \( n \), and \( \varepsilon \) is the tilt angle of the ground surface. \( \Omega_{sr} \) is the solid angle subtended by the ground cell as seen from the source and \( \Omega_r \) is the solid angle subtended by the scattering cell as seen from the ground cell. \( \rho_r \) is the reflectance of the ground cell. This reflectance is assumed to be lambertian. Since our model allows ground reflectance variations from one grid point to the other, we used a cosine function to compute the real contribution of each size-limited reflecting surface. This time we defined \( P_n \), as the scattering probability of cell \( n \) giving the direction from ground cell \( r \) to cell \( n \). The sum over \( r \) allows the computation of the total reflected light contribution for the case of a maximum reflective radius (MRR) greater than the horizontal cell size. The MRR account for the fact that in typical environments, the free light path toward the ground is generally limited to a certain radius, which is determined by the presence of obstacles on the ground, such as trees, buildings and topography.

The second order scattering contribution is computed by adding a large number of light paths between the source (or the reflecting surface) and the scattering cell \( n \). To restrict computing time, we defined a maximum scattering radius (MSR). This radius defines a volume of cells around the \( s - n \) path (or the \( r - n \) path). This volume of cells is represented by the grey squares on Figure 2 (a). To account for the second order scattering, we have to sum a number of \( m \) first order scattering contributions, which act as sources for the \( 2^{rd} \) order scattering cell \( n \). This process is described by Equation 18.

\[ I_2 = L_0 T_{no} \sum_m T_{sm} E(\theta_{sm}) \Omega_{sm} P_{sm} f(\theta_{sm}, \theta_{mn}) T_{mn} \Omega_{mn} P_{mn} f(\theta_{mn}, \theta_{no}) \tag{19} \]

\( \theta_{sm} \) is the zenithal angle for source \( s \) to first scattering cell \( m \) light path, \( \theta_{mn} \) is the zenithal angle for the light path starting at a first scattering cell \( m \) and ending at the second scattering cell \( n \). \( \Omega_{sm} \) and \( \Omega_{mn} \) are respectively the solid angle of cell \( m \) as seen from source \( s \) and the solid angle of cell \( n \) as seen from cell \( m \).

As in Equation 18, we can add the source to ground light path to write the second order scattering after reflection.

\[ I_{r2} = \frac{L_0}{2\pi} T_{no} \sum_r \left( E(\theta_{sr}) \Omega_{sr} T_{sr} \rho_r \sum_m \cos(\theta_r + \varepsilon) \Omega_r P_r f(\theta_r, \theta_{mn}) T_r T_{mn} \Omega_{mn} P_{mn} f(\theta_{mn}, \theta_{no}) \right) \tag{20} \]

4. MODEL INPUTS

As a first step, ILLUMINA users must define the relevant horizontal resolution to use for the requirements of specific modelling experiments. Given that ILLUMINA does not account for horizontal anisotropy in the angular emission function of lighting devices, a typical cell in the urban environment may contain more than one device per lamp model.
The angular emission function could be computed from a photometric file stored in the Illuminating Engineering Society of North America (IESNA) standard format. This file could be tilted to reflect possible tilts in light fixture installations. We assume that the result of their statistical horizontal orientation is equivalent to an horizontal averaging of the function. The resolution may also be determined according to the scale of the study (regional to local). In fact, in order to limit computer memory needs, we restricted the number of horizontal cells to a maximum of 1024 by 1024 cells so that the horizontal resolution is necessarily lower or equal to the domain size divided by 1024. On the vertical axis, ILLUMINA splits the study zone into voxels with predefined variable vertical cell thickness. The vertical axis is divided into 50 levels with logarithmic increasing thickness along altitude. The first level is very thin (25 cm) compared to the 50th level (2.5 km). The maximum vertical height ends at around 15 km above the lowest altitude found in the modelling geographical domain. This scale allows for better modelling of the most contributing cells of the atmosphere. In fact, light intensity and atmospheric content are greater near ground level. Ground level atmospheric pressure is used to determine the molecular content of the atmosphere. Other key input parameters are (i) the wavelength used, (ii) a first guess total aerosol optical depth at that given wavelength, and (iii) a map of the ground reflectance at the same wavelength. Ground reflectance for various soil types and wavelengths may be found in the Advance Spaceborne Thermal Emission and Reflection Radiometer (ASTER) database. ASTER is part of NASA’s Earth Observing System (EOS). The user must also choose a aerosol model (urban, rural) to define the optical properties of the aerosol content, such as absorption and scattering cross sections along with the scattering phase function. These optical properties are characteristic of a given aerosol type mixture and size distribution. Default aerosol models used by ILLUMINA have been computed using a Mie theory code with Shettle and Fenn refractive index tables and typical lognormal particle size distributions for a relative humidity of 70%. It is easy to calculate aerosol optical properties for any other relative humidity. The user must also provide a digital terrain model, and up to 9 maps of artificial light distribution (one map per lamp model). The maps must specify for each horizontal grid point and for each type of light the angular emission function, the light spectral luminosity (W/nm) and the light height above the ground level below. The maximum reflective radius (MRR), the maximum scattering radius (MSR) and the simulated spectrometer position, orientation along with its optical properties must also be defined by the user.

3. PRELIMINARY RESULTS FROM THE SENSITIVE STUDY

As a first experiment, we tried to estimate the relative importance of computing 2nd order scattering. To perform this experiment, we used a modelling domain of 201 x 201 horizontal cells. The cell size was set to 200m. Right in the centre of the modelling domain, we defined an idealized circular city with a uniform light luminosity per cell. The city radius was set arbitrarily to 4900 m. Inside that radius, we set the reflectance at 0.085, a good estimate for typical combination of artificial (e.g. roofs and streets) and natural surfaces (vegetation) at 550 nm. For the countryside, we set the reflectance at 0.11, which is representative of typical vegetation cover at the same wavelength. We assumed that the ground topography was flat. We set the MRR to 50 m which means that only the cell right under a lighting device would reflect the light. The aerosol optical depth was set at 0.07, a typical value for clean air conditions. The ground level atmospheric pressure was supposed to be equal to the normal sea level value. Finally, we assumed that there was only one lighting device model in the city. We chose an isotropic angular output light pattern. This kind of lighting fixture is probably the worst for light pollution since it emits 50% of the light upward. Our simulated spectrometer was directed toward the zenith at two distinct positions. The first position was situated in the center of the city (urban case) and the second one was set to a remote site at 9800m from the city center (remote case). This distance is twice the city radius. In the urban case, our simulation shows that, the 2nd scattering contribution to the artificial zenithal sky brightness is roughly 7% of the single scattering contribution. This result indicates that 2nd scattering could not be neglected even for observing sites situated near light sources. For the remote case, we obtained a 2nd to 1st order scattering ratio very close to 2 (2nd order scattering is roughly 200% of the single scattering contribution). Our result for the remote case is very important since it highlights the importance of accounting for 2nd scattering in light pollution studies. This is particularly true for astronomical sites which are generally far from city lights. We also tried to estimate the best choice of the MSR value, and our results show that MSR must encompass most city lights. In our particular
case, we found an optimal MSR of ~40 km. Of course, this radius could be greater than that value, but no significant improvement to the flux estimate was obtained with rapidly increased computing time.

6. CONCLUSION

Preliminary results derived from this study indicate the potential of ILLUMINA as a tool for resolving complex questions associated to light pollution behaviour. Without this kind of modeling tool, it is difficult and tricky to draw conclusions on the importance of a given parameter on real condition light pollution level. ILLUMINA is a significant innovation compared to previous light pollution models elaborated during the 1980s. One of the most important innovations relies on the implementation of the heterogenous and complex nature of real environments. A lot of validation works remains to be done, but will be realized soon. We are presently conducting a sensitive study to estimate the real effect of some particular lighting parameters generally reputed to have significant incidences on light pollution. For example, we are trying to verify the importance of near-horizon light emissions. We will also estimate the impact of snow cover for northern regions. Another experiment will be conducted to determine the influence of realistic aerosol optical depth temporal variability on net light pollution variability. Finally, we are presently working on inter-comparison with previous models to ensure that our model is able to simulate simpler ones. An inter-comparison with the 1986 Garstang's modelling of light pollution behaviour around Denver Colorado is in progress.

According to our ultimate goal, the final evaluation will be to use ILLUMINA as a night time aerosol optical depth measuring tool. It will be interesting to verify the temporal continuity between day and night measurements by taking night time measurements near an AERONET sunphotometer. An inter-comparison with starphotometers will also be a major issue.

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