LIGHT POLLUTION MODELING AND DETECTION IN A HETEROGENEOUS ENVIRONMENT

MARTIN AUBÉ
GRAPHYCS, CÉGEP DE SHERBROOKE, QUÉBEC, CANADA.
CARTEL, UNIVERSITÉ DE SHERBROOKE, QUÉBEC, CANADA
MEMO ENVIRONNEMENT, QUÉBEC, CANADA

Few attempts have been made to measure aerosol optical depth (AOD) behaviour during the night. One such method uses spectrally calibrated stars as reference targets but the available number of stars is limited. This is especially true for urban sites where artificial lighting hide most of these stars. In our research we attempt to provide an alternate method one which exploits the artificial sky glow generated by light pollution. To achieve that goal, we designed a new methodology which links a 3D light pollution model with in situ light pollution spectral measurements obtained with our detector called Spectrometer for aerosol night detection (SAND). The basic idea was to adjust an AOD value into the model in order to fit the measured artificial sky brightness. 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 along with a detailed definition of the vertical atmospheric profile. This model, named ILLUMINA, computes 1st and 2nd order molecular and aerosol scattering as well as aerosol absorption. A correction for sub grid obstacles is also included. 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 model and detector features and some of the first results derived from ILLUMINA model. We will also present our web based spatio-temporal Sky spectral luminance measurements database project.

Introduction

This paper summarizes major improvements to remote sensing and modeling of artificial sky brightness. The original goal of that research was to provide a new methodology to enable Aerosol Optical Depth (AOD) retrieval. AOD represents the extinction of light passing true an aerosol cloud. This parameter is sensitive to wavelength. The spectral dependence of AOD generally follows a lambda^{-1} law. The exponent may differ slightly from unity depending of the size distribution of the aerosol population. This exponent is often referred as the angstrom coefficient. Smaller particles raise the absolute value of the exponent. As an extreme case, for tinny particles like atmospheric molecules the angstrom coefficient is of the order of 4. For that case we define the molecular optical depth (MOD). MOD is quite easy to model because the molecular composition of the atmosphere is stable (except for H_2O, CO_2 and ozone). AOD is more difficult to model because of its high spatial and temporal variability.

AOD is an important parameter in studying climate changes because it plays an important role in the atmospheric radiative forcing. Some remote sensing techniques allow the follow up of AOD during daytime. The most often used are sunphotometry and inversion of dark targets pixels on satellite imagery. Daytime techniques rely on the direct or indirect observation of sunlight. A problem occurs when we want to track AOD during the night. In that case, lidar and starphotometry may be used. The later technique is more powerful since starphotometers are cheaper than lidars. But starphotometry requires direct observation of calibrated stars. It becomes a difficulty for urban sites were artificial light increase the sky brightness. Most of the calibrated stars are hidden by urban sky brightness. In order to overcome this drawback, we suggested using sky brightness as a reference target instead of calibrated stars.

Model description

Using sky brightness as a reference target may only be possible if we are able to determine its value on the basis of very accurate modeling techniques. A few artificial sky brightness model have been implemented in the past (e.g. Garstang1) but they are clearly not enough accurate for our needs. These models did not account for the heterogeneity of the environment like the spatial variations of the ground reflectance, the topography, the non uniform distribution of light fixture luminosity, the variation of the angular light output pattern with geographical position along with vertical variations in atmospheric optical properties. No attempts have been made to account for sub grid obstacles shadowing effects (trees, buildings, etc.).

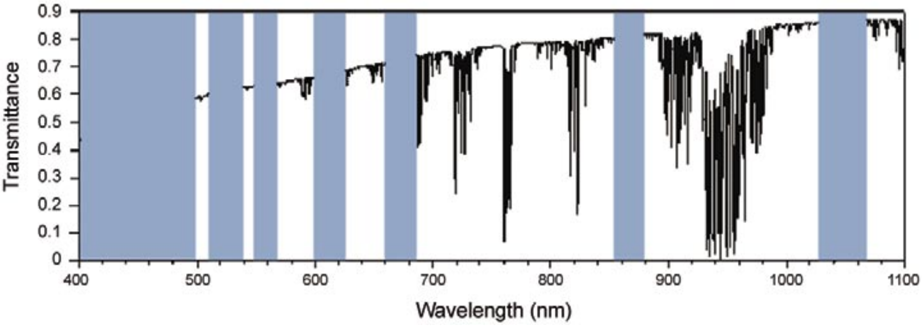

Figure 1: Set of wavelength available in ILLUMINA (blue sections).

We design from scratch a new model having all these features plus the integration of their spectral dependences. This model called ILLUMINA[2,3,4] resolve the radiative transfer budget in a given observation direction on a 3D grid. Computations include first and second order aerosol and molecular scattering. Aerosol extinction (scattering and absorption) and molecular extinction (scattering only) is also calculated along every light paths. The fact that we don't account for molecular absorption means that we cannot uses ILLUMINA in the H_2O and CO_2 absorbing bands. Figure 1 show the remaining available wavelengths which are highlighted in blue.

ILLUMINA computes four different light paths which may enter the Field Of View (FOV) of the simulated observer. We are computing the first order scattered light (I_1, see figure 2), the first order scattered light after a reflection on the ground (I_{r1}). These two fluxes are also used to generate the first order light dome. This dome is considered as a new set of sources to compute the second order scattering (I_2 and I_{r2}). Since the first scattering dome correspond to a volume which is defined by a large amount of model voxels, the computation of second order contributions to the simulated luminance becomes rapidly a crucial problem in term of computation time. This may requires access to high performance computing facilities. Université de Sherbrooke own this kind of facility, which is a supercomputer called Mammouth. Mammouth is a large linux cluster made of more than 1500 pc. ILLUMINA may of course be used on a single pc but computation time in that case may take several days. To restrict computation time, there is a possibility to restrict the size of the first scattering dome considered in the computation by setting a maximum second scattering radius (MSR). The user is also asked to set the maximum reflection radius (MRR) and the mean obstacle height. The maximum reflection radius represents the light mean free path toward the ground. The mean obstacle height represents typical sub grid structure size. These structures are typically trees and buildings. Figure 2 shows a representation of the main computed fluxes in ILLUMINA.

ILLUMINA requires a light fixtures inventory as accurate as possible. The accuracy of this inventory is especially important for light fixtures located near the simulated observer. The inventory has to define the total luminance of a maximum of 9 kind of source per grid cell. Each kind of source may differ by their angular output pattern, their spectrum, or their height. It is also important to define each ground cell elevation to allow the computation of shadowing effects.

The model vertical scale has been chosen in order to get a more accurate computation near the ground where light intensity and atmospheric concentrations are higher. The prescribed scale is divided into 50 vertical levels where the first level is 50 cm thick and the 50th is about 5km thick. The 50th level end at an elevation of 30 km above the lowest ground cell.

As of now ILLUMINA do not account for azimuthal variation in the light fixture output pattern. This limitation requires that the horizontal grid size have to be chosen in a way that a few light fixtures are contained in the cell (of the order of 10 fixtures per cell). Since the orientation of each light fixture is variable, the presence of some light fixtures is equivalent to having a horizontally averaged light output pattern. Typical resolutions are of the order of 100 m. The maximum horizontal model dimension is 1024x1024. This led to a typical maximum modeling domain of about 100km x 100 km.

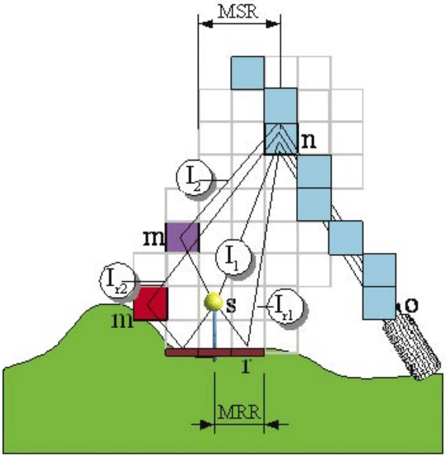

Figure 2: Light paths computed by ILLUMINA

Figure 3: The SAND spectrometer

Spectrometer description

The determination of the sky luminance with our modeling technique is not sufficient to track AOD. We also need to compare model prediction with in situ measurements. To achieve that task, we designed a portable and automated spectrometer. This instrument, called Spectrometer for Aerosol Night Detection (SAND[5]), is basically a long slit spectrometer combined with a cooled CCD detector. Along with the spectrometer, the system is complemented by a set of environmental sensors (luminosity, temperature, humidity) and by a remotely controlled web cam. To benefit all the SAND features, the system has to be connected to the internet. In that case the user can take the control of the system remotely for manual operation or to program an automated observing sequence. The instrument FOV is 14 deg. which allow a relatively good sensitivity while allowing the monitoring of light pollution multi-angular behaviour. Integration time in urban environment is of the order of a few minutes but it increases up to 2h in astronomical dark sites. Figure 3 show an image of the opto-mechanical part of SAND. Detailed instrument specifications are given in table 1.

SAND is protected from rain and snow for permanent outdoor use. There is also a UPS to protect the instrument from electrical problems and form short term power failure. Fans and heating system allow maintaining proper operating temperature. A webcam is also installed in the system in order to monitor remotely the state of the system, which is a great advantage for maintenance means. SAND is now constructed by MEMO Environnement[6] and therefore some more information about this instrument could be found on their web site.

Table 1: Technical specifications of the SAND spectrometer.

Feature	Value
Field of view without extension tube	14°
Slit width	100 microns
Focal length of collimation lens	50 mm
Collimator diameter	25 mm
Diffraction grating grooves per mm	600 lines/mm
Focal length imaging lens	28 mm
Imaging lens diameter	10 mm
CCD chip	Kodak KAF-0402ME
Chip size	510 x 765
Pixel size	9 x 9 microns
CCD camera	-10 °C
Main computer	AMD Sempron 2600+ minimum
Network interface	1 x 10/100Mbps minimum
Ports	1 USB-2 port and 1 serial port minimum
RAM	256 MB minimum
Hard disk	80 GB IDE minimum
Router	4 ports
Mount	LXD-75 with autostar
Maximum electric power without fans and heating	80 W
Battery backup	APC Back-UPS ES 500
Typical duration of a direction change	60 sec
Time to flush ghost image	270 sec
Spectral band	400 nm – 700 nm

Modeling experiments

As a first step we tried to conduct a sensitive study with ILLUMINA. We assumed a circular city with constant light fixture luminosity per unit of ground surface. We did not put any topography but we set obstacles height to 7 meters and MRR to 150 meters. We also put a constant reflectance of 0.15 all over the domain. Light fixtures were supposed to be semi-cutoff, like cobraheads fixtures. Our first experiment was to estimate the importance of the 2nd order scattering compared to the first order scattering contribution to the total sky spectral luminance. This was done by setting MSR to its maximum value (equal to the modeling domain size) and then by setting MSR to zero. When MSR is set to zero, only the first scattering is computed. The difference MSR - MSR0 gives the contribution of the second order scattering to the total spectral luminance. The results of that experiment for a zenithal line of sight showed big differences depending on the position of the observer. For an observer located right inside the city, 2nd order scattering contributes to about 10% of the total luminance. This clearly indicates that 2nd order scattering cannot be neglected for light pollution modeling. But the most striking result was obtained for the case of a countryside observer. We found that the 2nd order contribution rises with distance from city limits and may rises up to 66% of the total luminance for very remote sites. This result is in contradiction with previous results obtained with simpler models. According to previous models the sky luminance for remote sites was supposed to be dominated by light emitted near the horizon[7]. In fact this is not the case because those light paths are rapidly stopped by sub grid obstacles like trees and buildings. Another important factor which may explain this discrepancy is the fact that the first order dome is a non point like source, it is expected that its contribution decrease less rapidly with the distance in comparison with first order scattering.

Figure 4: Numerical model of the luminary's inventory for Scotstown Canada.

We also conducted an experiment to investigate an optimal value for the MSR. MSR_0 is directly related to the computational time. It is then very important in a technical point of view to restrict its size so that the associated error remains small (under 1% of the total luminance). Our experiment showed that it is achieved when MSR include all city lights (i.e. the distance from city centre plus the city radius).We also used ILLUMINA in order to conduct a public light conversion scenario. This experiment was conducted in the framework of a large light conversion plan around the Mont Mégantic observatory[8] in Quebec Canada. The experiment was applied to the city of Scotstown. The scenario was to reduce overall light luminosity by a factor of 2 along with replacing existent cobrahead fixtures (6% upward flux) by cutoff fixtures (Helios, 0% upward flux). A numerical model of Scotstown lighting facilities (figure 4) have been made at a nominal horizontal resolution of 150 m. Grey levels on figure 4 are proportional to the total luminosity

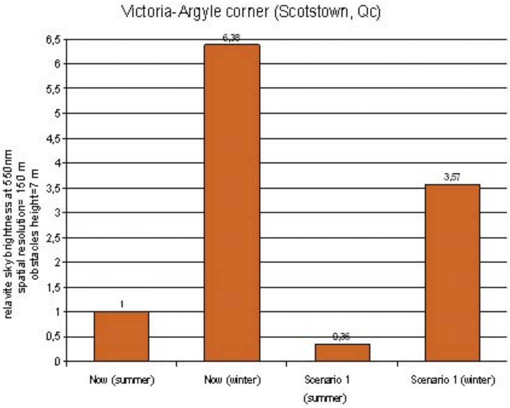

Figure 5: Results from the Scotstown lighting conversion scenario simulation.

per cell. For that experiment, we evaluated zenithal sky luminance in downtown (yellow dot on fig. 4) for four cases. The two first cases correspond to the present situation for summer (reflectance of 0.085 inside the city and 0.11 outside) and for winter (reflectance of 0.98 everywhere). The experiment was done for a wavelength of 550 nm. The two remaining cases correspond to the conversion scenario described above again for summer and winter. The results are shown on figure 5. Excluding the fact that the overall luminosity has been reduced by a factor of 2 we can conclude that for the summer case, the effect of converting cobraheads to cutoff reduced the sky luminance by 28 percent of its initial value. For the winter case the effect of changing light output geometry increase the total luminance by 12 percent from its initial value.

We also tested the spectral behaviour of the light pollution. For that experiment we used the numerical model of Scotstown before conversion. We changed the wavelength while assuming a constant spectral flux of light fixtures. We assumed an aerosol angstrom coefficient of 1.3 which is typical of clear continental atmospheric conditions. Figure 6 shows the result of that last experiment. It is interesting to notice that in the blue region the spectral dependence is dominated by molecular extinction (lambda^{-4} law) while in the red region, it is dominated by aerosols (~lambda^{-1}). But an interesting feature may be observed around 550nm where there is a small bump on the curve. This bump was generated by the green reflection peak of the vegetation. In fact, inside the city, the reflectance has been determined by a mixing of 35% of the vegetation reflectance and of 65% of the asphalt reflectance. We also made a crude estimation of the relative contribution of mercury lamps versus sodium lamps for a constant luminosity (constant lumen). We assumed that mercury light is equally produced by two main spectral lines (436.8nm and 546.1nm) while the light of sodium is mainly generated at 589 nm. This gives that mercury lamps generates 2.5 times more light pollution than sodium for a constant number of lumen.

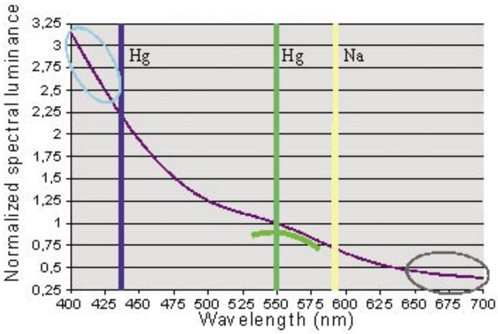

Figure 6: Effect of wavelength for a constant spectral flux under clean atmosphere (AOD_550nm = 0.07) cobrahead fixtures.

Artificial sky spectral luminance experiments

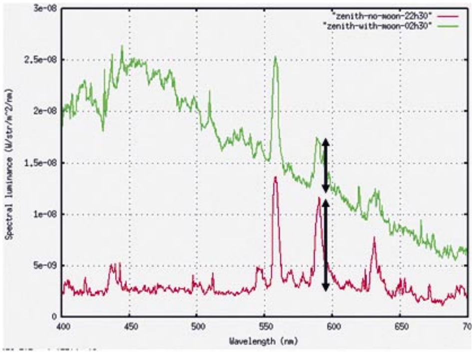

Figure 7: Effect of moonlight and of San Diego and Riverside Counties lighting code on sky spectral luminance observed with SAND from Mount Palomar Observatory in May 2005.

The SAND spectrometer was used in a variety of conditions. The first and ongoing experiment is to monitor light pollution temporal evolution at Mont Mégantic observatory while the conversion project is in progress. We also conducted an intensive light pollution monitoring experiment in South-West USA during spring 2005. During this experiment we acquired data at Los Angeles, Palomar Observatory, Ajo National Monument, Kitt Peak National Observatory (KPNO), Lowell Observatory (Mars Hill, Anderson Mesa, and Happy Jack), and at US Naval Observatory near Flagstaff Arizona. The main goal of this experiment was to test the reliability of the instrument over a long term experiment (21 nights). Figure 7 gives a sample of that database. On that figure we can clearly see the impact of moon rise which increased the continuum part of the spectrum (especially in the blue region). An other interesting feature is that we can clearly see the impact of the San Diego and Riverside Counties lighting code which requires Class II & III lights turned off after 11pm. Finally we returned to Flagstaff in spring 2006 to acquire detailed multi-angular data at US Naval Observatory. The later experiment goal is to validate the multi-angular behaviour of ILLUMINA. We choose this site because the lighting inventory of Flagstaff is relatively well known. By the way we returned back shortly to KPNO and we also acquired some data at Fred Lawrence Whipple Observatory (mount Hopkins). As long as the data are processed, they are placed on a free accessed web database[9]. Interested user has to read and conform to data usage.

Conclusion

A lot of work remains to be done like improving the bi-directional reflectance function (BRDF) which is considered as lambertian for now. But before doing any other changes to the model we will concentrate our efforts toward two real condition validation experiments. The first one will exploit the data acquired in May 2006 to validate the multi-angular behaviour of the model and the second experiment will be to validate the decreasing function along distance from a source. For that case we had chosen a well isolated site near Baie-Comeau (Northern Canada) to be sure that no other cities may contaminate our data. This experiment will take place during June 2007. A graduate student will use the two dataset in the framework of his M.Sc. thesis.

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