Modelling the night sky brightness and light pollution sources of Montsec protected area

Hector Linares\textsuperscript{a,b}, Eduard Masana\textsuperscript{b}, Salvador J. Riba\textsuperscript{a,b}, Manuel Garcia - Gil\textsuperscript{c}, Martin Aubé\textsuperscript{d}, Alexandre Simoneau\textsuperscript{e}

\textsuperscript{a} Parc Astronòmic Montsec
\textsuperscript{b} Institut de Ciències del Cosmos (ICC-UB-IEEC)
\textsuperscript{c} Servei de Prevenció de la Contaminació Acústica i Lumínica, Generalitat de Catalunya
\textsuperscript{d} Département de physique, Cégep de Sherbrooke
\textsuperscript{e} Université de Sherbrooke
PAM

Parc Astronòmic del Montsec (COU and OAdM) is ideal for astronomic purposes:
- Low pluviometry and humidity
- Elevation 1600m
- High ratio of clear nights
- LP protected area

Purposes

1. Model the night sky over Montsec Observatory:
   - Natural sky brightness
   - Any LP in a range of 50km
   - Special treatment for Lleida, Tremp and Balaguer.
2. Test our method: all sky maps (ASTMON)
3. Compare the emission received from Lleida before and after a lighting system update

Model

1. ILLUMINA (Martin Aubé et al)
2. Post processing for NSB and astronomic magnitudes
PAM
Parc Astronòmic del Montsec (COU and OAdM) is ideal for astronomic purposes:
- Low pluviometry and humidity
- High ratio of clear nights
- Elevation 1600m
- LP protected area

Purposes
1. Model the night sky over Montsec Observatory:
   - Natural sky brightness
   - Any LP in a range of 50km
   - Special treatment for Lleida, Tremp and Balaguer.
2. Test our method: all sky maps (ASTMON)
3. Compare the emission received from Lleida before and after a lighting system update

Model
1. ILLUMINA (Martin Aubé et al)
2. Post processing for NSB and astronomic magnitudes
PAM

Parc Astronòmic del Montsec (COU and OAdM) is ideal for astronomic purposes:
- Low pluviometry and humidity
- Elevation 1600m
- High ratio of clear nights
- LP protected area

Purposes

1. Model the night sky over Montsec Observatory:
   - Natural sky brightness
   - Any LP in a range of 50km
   - Special treatment for Lleida, Tremp and Balaguer.
2. Test our method: all sky maps (ASTMON)
3. Compare the emission received from Lleida before and after a lighting system update

Model

1. ILLUMINA (Martin Aubé et al)
2. Post processing for NSB and astronomic magnitudes

Image obtained using PyASB
“Absolute photometry and Night Sky Brightness with all-sky cameras-UCM”,
ILLUMINA (Aubé et. al.)  
(DOI: 10.1016/j.jqsrt.2018.02.033)  

**Light path**  
- First and second order (aerosol and molecular)  
- Ground reflectance: MODIS  

**Input parameters**  
- Light emittance: VIIRS  
- Topography: SRTM  
- Atmospheric parameters: AoD, AC, pressure, humidity  
- LP zones definition  
- Observer position  
- Lines of sight  
- Wavelength range and subdivision  

**Output data**  
Sky radiance (W/str/m²) in any direction.  
Contribution of each point to the total sky radiance.
ILLUMINA  
(DOI: 10.1016/j.jqsrt.2018.02.033)

Light path
- First and second order (aerosol and molecular)
- Ground reflectance: MODIS

Input parameters
- Light emittance: VIIRS
- Topography: SRTM
- Atmospheric parameters: AoD, AC, pressure, humidity
- LP zones definition
- Observer position
- Lines of sight
- Wavelength range and subdivision

Output data
Sky radiance (W/str/m²) in any direction.
Contribution of each point to the total sky radiance.
ILLUMINA
(DOI: 10.1016/j.jqsrt.2018.02.033)

Light path
- First and second order (aerosol and molecular)
- Ground reflectance: MODIS

Input parameters
- Light emittance: VIIRS
- Topography: SRTM
- Atmospheric parameters: AoD, AC, pressure, humidity
- LP zones definition
- Observer position
- Lines of sight
- Wavelength range and subdivision

Output data
Sky radiance (W/str/m²) in any direction.
Contribution of each point to the total sky radiance.
ILLUMINA

VIIRS sensitivity correction

VIIRS does not detect all the light emitted. If not corrected we are underestimating the LP produced.

\[ \Phi_e = \int_{\lambda} R(\lambda) T(\lambda) \left( \frac{1}{2} \rho(\lambda) F_{90-180}(\lambda) + \langle G \rangle_{0-56}(\lambda) \right) d\lambda \]

<table>
<thead>
<tr>
<th>Technology</th>
<th>%Light detected by VIIRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP Sodium</td>
<td>79</td>
</tr>
<tr>
<td>LED 4000k</td>
<td>66</td>
</tr>
<tr>
<td>Mercury</td>
<td>59</td>
</tr>
<tr>
<td>Metal Hallide</td>
<td>62</td>
</tr>
</tbody>
</table>
POST-PROCESSING

Mission

Convert the output of ILLUMINA to astronomical magnitudes in the visible B-V-R Johnson’s Filters taking into account the natural brightness of night sky.

Apparent magnitudes

\[ F_{NNS} = F_{Vega} \times 10^{(0.4 \times (m_{Vega} - m_{NNS}))} \]

\[ m_{obs} = m_{Vega} - 2.5 \times \log_{10} \left( \frac{F_{LP} + F_{NNS}}{F_{Vega}} \right) \]

<table>
<thead>
<tr>
<th>Johnson Filter</th>
<th>Vega (mag)</th>
<th>Natural Sky (mag/arcsec^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>-0.023</td>
<td>22.7</td>
</tr>
<tr>
<td>V</td>
<td>-0.023</td>
<td>21.8</td>
</tr>
<tr>
<td>R</td>
<td>-0.023</td>
<td>20.9</td>
</tr>
</tbody>
</table>
Parameters
- WL: 350-830nm (16x30nm) - LoS: 1225 (az5xel5)
- Atm pressure: 101.3 kPa - No clouds, sky clear
- Relative humidity 70% - AoD: AERONET 0.090
- Angstrom coefficient: AERONET 0.996

LP sources
- Lleida: 140,000 inhabitants, 50km from PAM (190⁰)
- Balaguer: 16,000 inhabitants, 35km from PAM (165⁰)
- Tremp: 6,000 inhabitants, 20km from PAM (45⁰)

<table>
<thead>
<tr>
<th></th>
<th>HPS</th>
<th>MH</th>
<th>LED</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>LL</td>
<td>%#</td>
<td>49</td>
<td>13</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>%F</td>
<td>72</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>BLG</td>
<td>%#</td>
<td>77</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>%F</td>
<td>78</td>
<td>17</td>
<td>5</td>
</tr>
<tr>
<td>TR</td>
<td>%#</td>
<td>100</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>%F</td>
<td>100</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GNRL</td>
<td>%#</td>
<td>80</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>%F</td>
<td>90</td>
<td>10</td>
<td>-</td>
</tr>
</tbody>
</table>
All-sky maps (B)

- Cities well modeled
- Good correlation above 15° (zenith)

- Complete model too bright in low elevation angles
- Model has clear NNS vs MW presence in measurements
All-sky maps (V)

- Cities well modeled
- Good correlation above 15° (zenith)
- Model 3 or 4 LP directions, measurements 5 (Barcelona)

- Complete model too bright in low elevation angles
- Model has clear NNS vs MW presence in measurements
All-sky maps (R)

- Cities well modeled
- Good correlation above 15° (zenith)
- Model 3 or 4 LP directions, measurements 5 (Barcelona)

- Complete model too bright in low elevation angles
- Model has clear NNS vs MW presence in measurements
Brightness-Distance function

NSB: B=22.7, V=21.8, R=20.9
Brightness-Distance function

NSB: B=22.7, V=21.8, R=20.9
Brightness-Distance function

NSB: B=22.7, V=21.8, R=20.9
Brightness-Distance function

NSB: B=22.7, V=21.8, R=20.9
Brightness-Distance function

NSB: B=22.7, V=21.8, R=20.9
Change of lights in Lleida 2014

140,000 inhabitants, 50km south from PAM (190°)
2014 update of lighting system
- Removal of Mercury lamps
- Installation of LED 4000 K
- Lowering the power of HPS
- 36% reduction in power consumed (W)
- 30% reduction in luminous flux (lm)

<table>
<thead>
<tr>
<th></th>
<th>HPSV</th>
<th>MH</th>
<th>LED 4k</th>
<th>MV</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>% #</td>
<td>71</td>
<td>19</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>% F</td>
<td>84</td>
<td>13</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>2015</td>
<td>% #</td>
<td>49</td>
<td>13</td>
<td>33</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>% F</td>
<td>72</td>
<td>13</td>
<td>15</td>
<td>-</td>
</tr>
</tbody>
</table>
COMPARING USING VIIRS

VIIRS images show fluctuation:
- Aerosol content
- Angle of vision

Reference point -> Balaguer

No changes in the lighting system
No change in the LP measured from the PAM

Fluctuations up to 25% in any direction and w/
Spectral flux comparison

\[ C = \frac{F_{2018} - F_{2013}}{F_{2013}} \]

- Huge reduction at very low \( \lambda_l \) (>60%)

Modelling the night sky brightness and light pollution sources of Montsec protected area | Hector Linares | 14th November 2018
Spectral flux comparison

\[ C = \frac{F_{2018} - F_{2013}}{F_{2013}} \]

- Huge reduction at very low wavelength (>60%)
- Persistent reduction above 550 nm (~30%)
Spectral flux comparison

\[ C = \frac{F_{2018} - F_{2013}}{F_{2013}} \]

- Huge reduction at very low wl (>60%)
- Persistent reduction above 550 nm (~30%)
- No reduction, even increase at 440-530nm
Astronomic magnitudes

Direct filter comparison

Brightness subtraction (After-Before)
B: max 0.03 mag
V: max 0.3 mag, ≥0.1 mag 35° wide
R: max 0.27 mag, ≥0.1 mag 25° wide

Color images

Brightness subtraction between filters (B-V, V-R)
Brightness subtraction (2015-2013)
B-V: 2015 bluer sky
V-R: very small difference
Astronomic magnitudes

Direct filter comparison

Brightness subtraction (After-Before)
B: max 0.03 mag
V: max 0.3 mag, ≥0.1 mag 35° wide
R: max 0.27 mag, ≥0.1 mag 25° wide

Color images

Brightness subtraction between filters (B-V, V-R)
Brightness subtraction (After-Before)
B-V: bluer sky
V-R: very small difference
Modelling the night sky brightness and light pollution sources of Montsec protected area | Hector Linares | 14th November 2018

Introduction

Model

Montsec Case

F(B,D)

Lleida Case

Summary

Hypothesis (PC AMBER LED)

<table>
<thead>
<tr>
<th>HPSV</th>
<th>MH</th>
<th>PC LED</th>
<th>MV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>84</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>Hyp.</td>
<td>72</td>
<td>13</td>
<td>15</td>
</tr>
</tbody>
</table>

\[ C = \frac{F_H - F_{2013}}{F_{2013}} \]
Hypothesis (PC AMBER LED)

\[ C = \frac{F_H - F_{2018}}{F_{2018}} \]

<table>
<thead>
<tr>
<th></th>
<th>HPSV</th>
<th>MH</th>
<th>LED 4k</th>
<th>PC LED</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>72</td>
<td>13</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Hyp.</td>
<td>72</td>
<td>13</td>
<td></td>
<td>15</td>
</tr>
</tbody>
</table>
Summary

1. The methodology has been validated by measurements, especially for well described cities.
2. The sky over the PAM is polluted only in low elevation angles.
3. The change of lights in Lleida reduced light emission unevenly among the filters. Sky is bluer now than in 2013.
4. A reduction in emission does not necessarily means a reduction in LP in all the spectrum.

Progress

1. Define the methodology  ✔️
2. Study Lleida and its light system update  ✔️
3. Add Balaguer and Tremp in the PAM model  ✔️
4. Describe a population-distance function, to know the range of affectation of any town.
5. Complete PAM night sky model
6. Valle del Roncal (Navarra) and Pic du Midi (Haute Pyrénées) cases
Modelling the night sky brightness and light pollution sources of Montsec protected area

Hector Linares\textsuperscript{a,b}, Eduard Masana\textsuperscript{b}, Salvador J. Ribas\textsuperscript{a,b}, Manuel Garcia - Gil\textsuperscript{c}, Martin Aubé\textsuperscript{d}, Alexandre Simoneau\textsuperscript{e}

\textsuperscript{a} Parc Astronòmic Montsec
\textsuperscript{b} Institut de Ciències del Cosmos (ICC-UB-IEEC)
\textsuperscript{c} Servei de Prevenció de la Contaminació Acústica i Lumínica, Generalitat de Catalunya
\textsuperscript{d} Département de physique, Cégep de Sherbrooke
\textsuperscript{e} Université de Sherbrooke