A Technical Discussion of DOE's Sky Glow Study, Modeling Methods, and Key Variables

Tess Perrin
Pacific Northwest National Laboratory

Solid-State Lighting Program Webinar
August 3, 2017
Recap: The Impact of LED Street Lighting on Sky Glow

AMA Adopts Guidance to Reduce Harm from High Intensity Street Lights

For immediate release: Jun 14, 2016

Photo Credit: Dan Duriscoe, NPS

Photo Credit: Acuity

Chicago area, 2012
Photo credit: Nathan Rupert

Los Angeles, 2017

Photo Credit: Nathan Rupert

OMERAD - Strong arguments exist for overhauling the lighting systems on U.S. roadways with light emitting diode (LED) but concerns for improper LED technology on have adverse consequences. In response, physicians at the Annual Meeting of the American Medical Association (AMA) today adopted guidance for communities on selecting among LED lighting options to minimize potential harmful human and environmental effects.
Miroslav Kocifaj, PhD
Institute of Construction and Architecture, Slovak Academy of Sciences

http://unisky.sav.sk/?lang=en&page=aplikacia&subpage=glow
SkyGlow Simulator: An Illustration
SkyGlow Simulator

Distribution of Radiance/Luminance Values

- **azimuth (angle along circle)**
- **zenith (angle measured from center to margin of polar plot)**

- Diffuse irradiance or scotopic illuminance on horizontal surface
- Ratio of zenith radiance/luminance to diffuse horizontal irradiance/illuminance
SkyGlow Simulator

Verification

Measurements
(zenith-normalized luminance)

Reconstructed data
(zenith-normalized luminance)

Indices and positions of measurements

Night sky luminance under clear sky conditions: Theory vs. experiment (Journal of Quantitative Spectroscopy & Radiative Transfer, 139, 43-51, 2014)
Based on predominant contribution factors to sky glow

215,160 runs total
City and Observer

City size and lighting density

<table>
<thead>
<tr>
<th>City</th>
<th>Radius (km)</th>
<th>City Area (km²)</th>
<th>No. Fixtures</th>
<th>Lighting Density (fixtures per km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>City1</td>
<td>1.4</td>
<td>7</td>
<td>342</td>
<td>52</td>
</tr>
<tr>
<td>City2</td>
<td>7.2</td>
<td>164</td>
<td>3,500</td>
<td>21</td>
</tr>
<tr>
<td>City3</td>
<td>8.6</td>
<td>232</td>
<td>39,884</td>
<td>172</td>
</tr>
</tbody>
</table>

Observer’s location relative to city center:
‘Near’ – at perimeter
‘Distant’ – 40 km (~25 mi) from center

Photo Credit: NPS Natural Sounds and Night Skies Division
### Atmosphere

#### Aerosol Robotic Network (AERONET):

https://aeronet.gsfc.nasa.gov/

<table>
<thead>
<tr>
<th>Atmospheric conditions</th>
<th>ATM1</th>
<th>ATM2</th>
<th>ATM3</th>
<th>ATM4</th>
<th>ATM5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Clouds</strong></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Details</strong></td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Cloud</strong></td>
<td>Altitude of the cloud base (km)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Details</strong></td>
<td>Spectral albedo (select data file)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Aerosols</strong></td>
<td>Reference aerosol optical thickness at 500 nm</td>
<td>0.1</td>
<td>0.1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Details</strong></td>
<td>Angstrom exponent</td>
<td>0.3</td>
<td>1.5</td>
<td>0.3</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Aerosols</strong></td>
<td>Scale height for the molecular atmosphere (km)</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td><strong>Details</strong></td>
<td>Vertical gradient of the aerosol concentration (1/km)</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td><strong>Data files</strong></td>
<td>single scattering albedo</td>
<td></td>
<td></td>
<td></td>
<td>constant_background.ssa</td>
</tr>
<tr>
<td><strong>for</strong></td>
<td>asymmetry parameter</td>
<td></td>
<td></td>
<td></td>
<td>constant_background.ssa</td>
</tr>
<tr>
<td><strong>Horizon</strong></td>
<td>No light blocking objects near horizon</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Emission Function + Percent Uplight

- Fraction of light emitted downward and isotropically reflected (assuming a 15% ground reflectance)
  - 0%: “full cut-off” fixtures
  - 2% and 5%: typical and relatively poor drop-lens cobra heads
  - 10%: good quality acorn top, assumed in other sky glow models

- Fraction of light radiated directly upward, proportional to $\psi^4$ (above 90°)
  - 0%: “full cut-off” fixtures

- Combined product of downward-reflected and upward-emitted quantities

**Garstang’s City Emission function:**

$$B(Q, q, z_0) = 2Q(1 - q) \cos z_0 + 0.554qz_0^4$$

©CB Luginbuhl et al. 2009
# Luminaire Characteristics: Spectral Content

## Input SPDs (normalized to maximum output of 1)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Equal Energy)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Specifications and Calculated Metrics/Values

<table>
<thead>
<tr>
<th>Source type</th>
<th>SPD1</th>
<th>SPD2</th>
<th>SPD3</th>
<th>SPD4</th>
<th>SPD5</th>
<th>SPD6</th>
<th>SPD7</th>
<th>SPD8</th>
<th>SPD9</th>
<th>SPD10</th>
<th>SPD11</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCT (K)</td>
<td>N/A</td>
<td>2041</td>
<td>1778</td>
<td>3924</td>
<td>1872</td>
<td>2704</td>
<td>2981</td>
<td>3940</td>
<td>4101</td>
<td>5197</td>
<td>6101</td>
</tr>
<tr>
<td>photopic lux</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>scotopic lux</td>
<td>2265</td>
<td>629</td>
<td>218</td>
<td>1381</td>
<td>445</td>
<td>1173</td>
<td>1188</td>
<td>1345</td>
<td>1650</td>
<td>1797</td>
<td>1970</td>
</tr>
<tr>
<td>S/P ratio</td>
<td>3.60</td>
<td>1.00</td>
<td>0.35</td>
<td>2.19</td>
<td>0.71</td>
<td>1.86</td>
<td>1.89</td>
<td>2.14</td>
<td>2.62</td>
<td>2.85</td>
<td>3.13</td>
</tr>
</tbody>
</table>

A Equal Energy  
B Metal Halide  
C PC Amber LED
Additional Variables

Unweighted: irradiance (W/m²)
Weighted: scotopic illuminance (cd/[m²sr])

SPD Full: 380 to 780 nm
SPD Increments: 5 nm bands

Lumen output 1: 100%
Lumen output 2: 50%
Individual Impacts
Atmosphere: Near Observer

- Cloudy condition: decrease uplight → increase sky glow
- Cloudless: decrease uplight → decrease sky glow
- Cloudy condition: decrease uplight → increase sky glow

Clouds act as amplifiers
Atmosphere: Distant Observer

observers only receive light at low elevation angles

decrease uplight  \rightarrow  decrease sky glow
The relationship between lumen output and sky glow is linear.
For near observers under clear conditions, reducing uplight reduces sky glow.

The **only circumstance** under which reducing the percent uplight increases sky glow is under cloudy conditions for the near observer.

For distant observers, sky glow is *virtually eliminated* at 0% uplight.
the greater the amount of short wavelength energy, the greater the range in impact

scotopic weighting further emphasizes these impacts
Atmosphere & Uplight

Clear conditions: greater short wavelengths relative to longer wavelengths

Cloudy conditions: less of a difference in short and long wavelength propagation $\rightarrow$ sky glow SPD is more similar to source SPD

Both effects are less pronounced for observer outside of city as shorter wavelengths are attenuated
TOP CHARTS show the effect of replacing the baseline HPS SPD with the various LED SPDs.
MIDDLE CHARTS add the effect of reducing luminaire lumen output by half compared to the baseline HPS.
Overall

**BOTTOM CHARTS** further add the impact of eliminating uplight from the luminaires, assuming a typical HPS baseline value of 2%. This is a typical U.S. conversion.
Overall

Short wavelength content does contribute towards increased sky glow but CCT is not always a reliable predictor of impact.

Much of the current public discussion reflects this comparison of SPD in isolation of the other factors.

When scotopically weighted, some LED products reduce sky glow while others increase it.

Reduction in uplight from 2% (primarily emitted at low elevation angles) to 0% increases the range of impacts.

In a typical U.S. conversion, all unweighted results show reduced sky glow for all LEDs.
Overall

Greater variability compared to near observer due to impact of different atmospheric effects.

Much of the current public discussion reflects this comparison of SPD in isolation of the other factors.

When scotopically weighted, some LED products reduce sky glow while others increase it.

Reducing 2% uplight to 0% virtually eliminated sky glow (by 95+) for all LEDs, when unweighted and scotopically weighted.
If you’re looking for more...


http://unisky.sav.sk/?lang=en&page=aplikacia&subpage=glow
Questions?

Thank you for your participation!

Tess Perrin
Pacific Northwest National Laboratory
Tess.Perrin@pnnl.gov

Related resources:
https://energy.gov/eere/ssl/street-lighting-and-blue-light
• Webinar: The Impact of LED Street Lighting on Sky Glow
• Sky Glow Investigation Report
• Frequently Asked Questions: Street Lighting and Blue Light
• Webinar: Get the Facts on LED Street Lighting
• SSL Posting: Getting the Facts Straight About LED Street Lighting