Sky Glow from Cities: The Army Illumination Model v2

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Outline

Purpose
Objective
LP Models
Army Illumination Model v2
V&V
To provide urban illumination levels for use in/for

- Simulations
  - IWARS
- Target Acquisition
  - TAWS
- Night Vision Devices
Night Illumination

Light Sources
Atmosphere
Cloud Cover
Land Surface

starlight
moonlight
twilight airglow
absorption/scattering
cultural light
Urban Lighting

Why?

• Affects target acquisition
  • differing contrasts for differing lighting levels and types

• Reflected light can provide significant illumination
  • clouds
  • buildings

• Can Occasionally “Outshine” the Moon
Objective

• A quick running model that accurately portrays both broadband and spectral illumination received from urban sources by an arbitrarily placed observer
  • point source
    • observer > 2 x city radius
  • extended source
    • observer < 2 x city radius
    • internal to the city

• Easily obtainable inputs

• Atmospheric variables
  • aerosols
  • clouds

\[ E_e = \pi L'R^2 / (R^2 + D^2) \]
\[ E_p = \pi L'R^2 / D^2 \]
\[ \varepsilon = D^2/R^2 \]
\[ D \geq R \varepsilon^{-1/2} \ (\varepsilon \approx 20\% \ \Rightarrow \ D \geq 2.25 \ R) \]

E: irradiance
L': radiance
\varepsilon: acceptable error
D: distance to source
R: radius of source
In 1973 Walker, after consulting with city utility companies, found that the city Luminosity, \( L \), was directionally proportional to the population: \( L \propto P \).
He then took sky brightness measurements of various cities to determine the distance where the artificial sky brightness was $\leq 0.1$ mag at the zenith. From this he constructed the Population-Distance relation.

Garstang reformulated Walker’s P-D relation as $B = CPD^{-2.5}$. Known as Walker’s law, it is the simplest model for light pollution.

C does not depend on P and D, but depends on factors such as the light emission per head of the population and the reflectivity of the ground.
About the same time Treanor proposed a simple model for scattering along the direct beam (TZ) by restricting scattering to a small angle $\phi_m$. This restricts scattering to the particles which are contained within the figure of revolution generated by rotating the arc TQZ about TZ.

This scattered light then undergoes a final scattering at Z into the observer’s LOS.
Garstang’s Model

Assumptions for Garstang’s model are:

- Flat Earth
- All downward-directed light from fixtures does not undergo scattering or absorption
- No interaction with buildings or vegetation
- Aerosol scattering is predominantly in the forward direction
Garstang’s Model

Garstang further modified Treanor’s model by introducing an exponential atmosphere and directly relating the atmospheric molecular content to the aerosol content:

$$N_a \sigma_a = 11.11 \ N_m \ \sigma_m \ K \ e^{-cH}$$

where $K$ is Garstang’s “clarity factor”, and by adding a city emission function:

$$I^\uparrow = \frac{LP}{2\pi} \{2G \ (1-F) \ \cos \psi + 0.554 \ F \ \psi^4\}$$

where $I^\uparrow$ is the upward intensity, $F$ is the fraction of light that “escapes” the luminaries shielding in an upward direction, and $G$ is the surface albedo.
“Double Scattering”

\[ SAA = N_m \sigma_m \left( 11.778 K \frac{1 - e^{-a s \cos \psi}}{a} + \gamma \frac{1 - e^{-c s \cos \psi}}{c} \right) \cos^{-1} \psi \]
Finally the Broadband Brightness in Garstang’s model is represented by

\[
b = \pi N_m \sigma_R \exp(-cH) \int \int (dx dy / \pi R^2) \int_0^\infty du \times I_{up} s^{-2} (EF)_{XQ} (EF)_{QO} (DS) \\
\times \{ \exp(-ch)3(l + \cos^2[\theta + \phi])/(16\pi) \\
+ \exp(-ah)11.11 Kf(\theta + \phi) \} .
\]
• **Original model tenets maintained**
  • brightness $\sim$ population

• **City population data base included**

• **Cloud effects added**
  • 8 cloud types
  • reflection

• **Lighting data base added**

• **Airglow included**
• City data base provided
  • 315 world wide cities
  • metropolitan population used when available

• Input
  • city name
  • allows for user input
    • optional inclusion in data base

• Output
  • city population
  • latitude and longitude
In the absence of moonlight and artificial light, the night sky still is not “dark”.

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Surface brightness $V$ ($S_{10}$ units)</th>
<th>Typical $V_{zenith}$ (sunspot minimum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airglow</td>
<td>$\approx 145 + 130(S_\odot - 0.8)/1.2$</td>
<td>145</td>
</tr>
<tr>
<td>Aurora</td>
<td>negligible at $</td>
<td>\text{latitude}</td>
</tr>
<tr>
<td>Zodiacal light</td>
<td>$\approx 140 - 90\sin(</td>
<td>\beta</td>
</tr>
<tr>
<td></td>
<td>$\approx 60$ ($</td>
<td>\beta</td>
</tr>
<tr>
<td>Stars ($V &gt; 20$, integ. light)</td>
<td></td>
<td>$&lt; 5$</td>
</tr>
<tr>
<td>Starlight scattered by interstellar dust</td>
<td>$\approx 100 \exp(-(</td>
<td>b</td>
</tr>
<tr>
<td>Extragalactic light</td>
<td></td>
<td>$\sim 1$</td>
</tr>
<tr>
<td>Light pollution</td>
<td>$&lt; 20$ at a ‘dark’ site (Smith 1979)</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>220</td>
</tr>
</tbody>
</table>

$S_{10}$ is a bizarre astronomical unit of surface brightness corresponding to one 10th-magnitude star per square degree.
In general:

\[ B_{\text{nsb}} = 27.78 - 2.5 \times \log_{10}(B_{\text{airglow}} + B_{\text{zodiacal}} + B_{\text{starlight}}), \]

where \( B_{\text{airglow}}, B_{\text{zodiacal}}, \) and \( B_{\text{starlight}} \) are functions of the solar sunspot cycle, the ecliptic latitude, and the galactic latitude respectively.

It was deemed reasonable to set the value of \( B_{\text{nsb}} = 17.6 \) nL rather than carry out additional computations for only a small additional contribution to the total night sky brightness.

For Denver at a distance of \( \sim 70 \) km the model predicts that the brightness is \( \sim 18 \) nL.
Cloud Effects

• Transmission through clouds determined using ILLUMA
  • 8 cloud types in 3 layers
    • High - clear, thin and thick Ci/Cs
    • Medium - clear, As/Ac
    • Low - clear, clear (f/k), Cu/Cb or St/Sc
  • allowance for partial cloudiness

• Cloud reflection
  • cloud and angle dependent reflectivity taken from Shapiro
  • simple attenuation in upward and downward paths
  • from lowest layer only
Broadband illumination is broken into spectral components dependant on the City’s light types and amounts

Approach

Determine

1) Light types
2) Percent contribution
3) Spectral radiance values for each light type
**Light Types and their default percentages**

<table>
<thead>
<tr>
<th>Light Type</th>
<th>Default Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Mercury</td>
<td>20.2</td>
</tr>
<tr>
<td>Low Pressure Sodium</td>
<td>0</td>
</tr>
<tr>
<td>High Pressure Sodium</td>
<td>77.9</td>
</tr>
<tr>
<td>Metal Halide</td>
<td>1.9</td>
</tr>
<tr>
<td>white LED</td>
<td>0</td>
</tr>
<tr>
<td>Standard Fluorescent</td>
<td>0</td>
</tr>
<tr>
<td>Incandescent</td>
<td>0</td>
</tr>
<tr>
<td>Liquid Kerosene</td>
<td>0</td>
</tr>
<tr>
<td>Pressurized Propane</td>
<td>0</td>
</tr>
</tbody>
</table>
Light Type Spectra
(1 nm resolution)
For Light Type $i$

1) Identify total contribution over wavelength band $S_1$ to $S_2$

$$L_{total} = \sum_{\lambda=S_1}^{S_2} L_{\lambda} \Delta \lambda$$

2) Bin contribution

$$L_{Jth \ bin} = \sum_{\lambda=J}^{J+1} L_{\lambda} \Delta \lambda$$
3) Fractional radiance

\[ L_i = \frac{L_{bin}}{L_{total}} \times P_i \]

4) Final spectral radiance

- summation over light type

\[ B_\lambda = B \times \sum_{i=1}^{N} L_{i\lambda} \]
AIM Input

- city name, city radius, city altitude, lumens/head
- distance from observer to source, observer altitude, zenith angle, azimuth angle
- clarity factor, surface albedo, fraction of light in upward direction
- month, day, year, UTC
- beginning, ending wavelength
- light type percents
- cloud switch, diagnostic/plot switch
- cloud type & cloud amount for layer i, i = 1,3
Clear Skies

Sky brightness due to Denver as a function of zenith angle at a distance of 40 k

Sky brightness due to Denver as a function of distance for a zenith angle of zero
Brightness Distribution

Denver
8.6 km from city center
Zenith = 0°
Brightness Distribution

Boulder
Zenith = 65°
Azimuth = 180°
Distance = 0 km

Boulder
Zenith = 65°
Azimuth = 0°
Distance = 0 km

Boulder
Zenith = 65°
Azimuth = 45°
Distance = 0 km

Boulder
Zenith = 65°
Azimuth = 45°
Distance = 2 km

X marks observer position
Contributed Brightness along the LOS as a function of position
Spectral Radiance

Spectrum of Los Angeles
Zenith view

Courtesy of Dr. Martin Aubé
http://lightpollution.no-ip.org/~lightpol/data_usage.html
10% Clear Mercury
5% LPS
55% HPS
20% Metal Halide
10% Incandescent

SAB + Airglow
• Variable turbid atmosphere
  • add assortment of aerosol types
• Inclusion of horizontal single scattering effects
  • zenith angles > 80° produce dubious results
• City reflection from partially cloudy skies
  • reflection only allowed from lowest layer
• Terrain/Vegetation blocking
• Nighttime Illumination Test Evaluation
  • underway at NASA space harbor
upward city radiation
City
Zenith
observer
X
Y
β
ε
Z