Sky Glow from Cities :
The Army Illumination Model v2

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ITEA T&E of System-of-Systems Conference
24 – 27 Jan 2012

Outline

Purpose

Objective

LP Models

Army Illumination Model v2

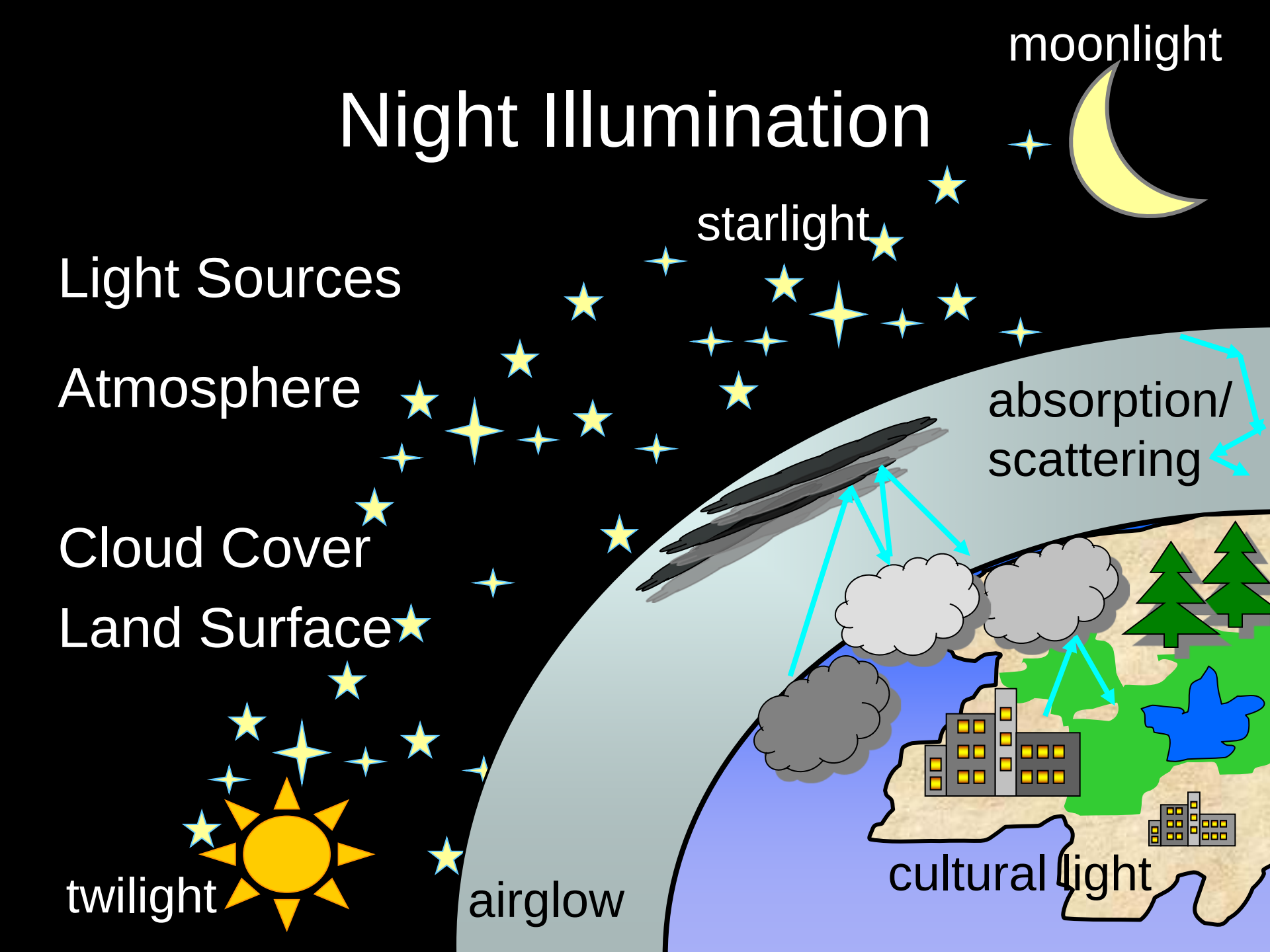
V&V

Purpose

To provide urban illumination levels for use in/for

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

Night Illumination



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**

$$E_e = \pi L' R^2 / (R^2 + D^2)$$

$$E_p = \pi L' R^2 / D^2$$

$$\varepsilon = D^2/R^2$$

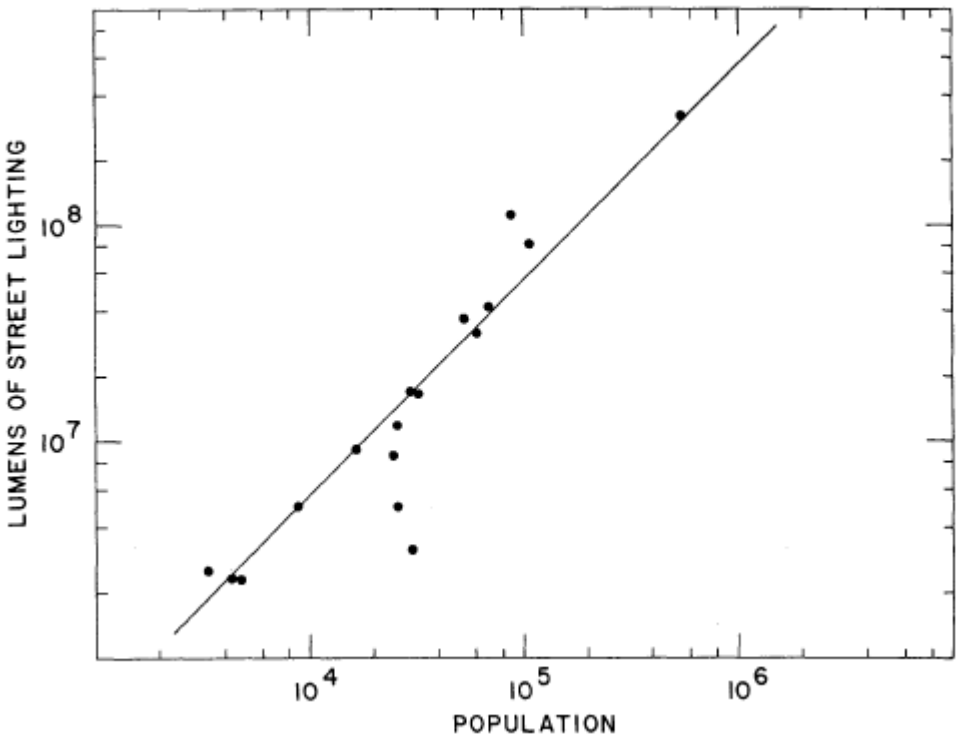
$$D \geq R\, \varepsilon^{-1/2} \quad (\varepsilon \approx 20\% \rightarrow D \geq 2.25\, R)$$

E: irradiance
L′: radiance

ε: acceptable error
D: distance to source
R: radius of source

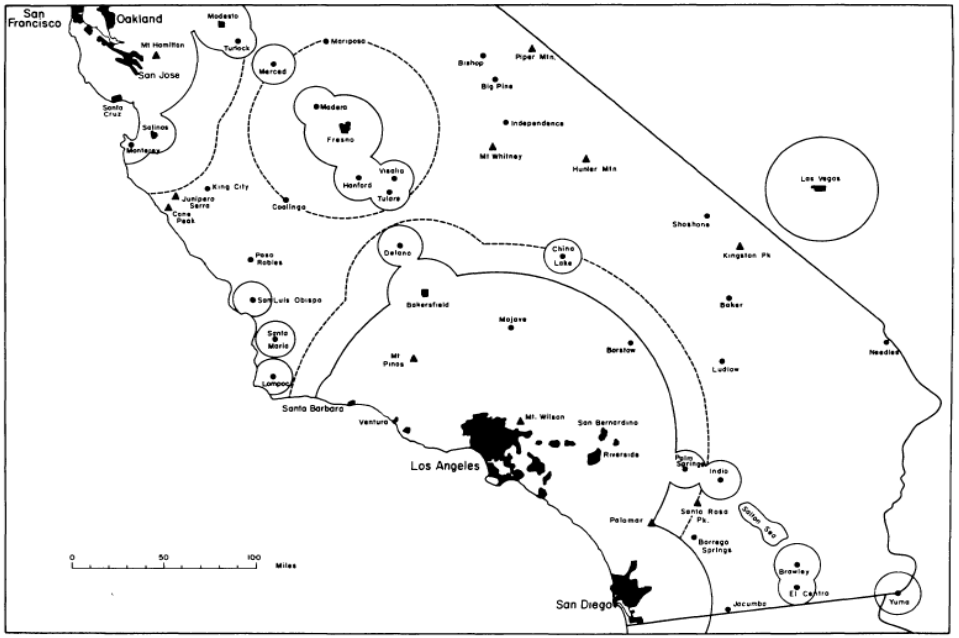
Walker's Model

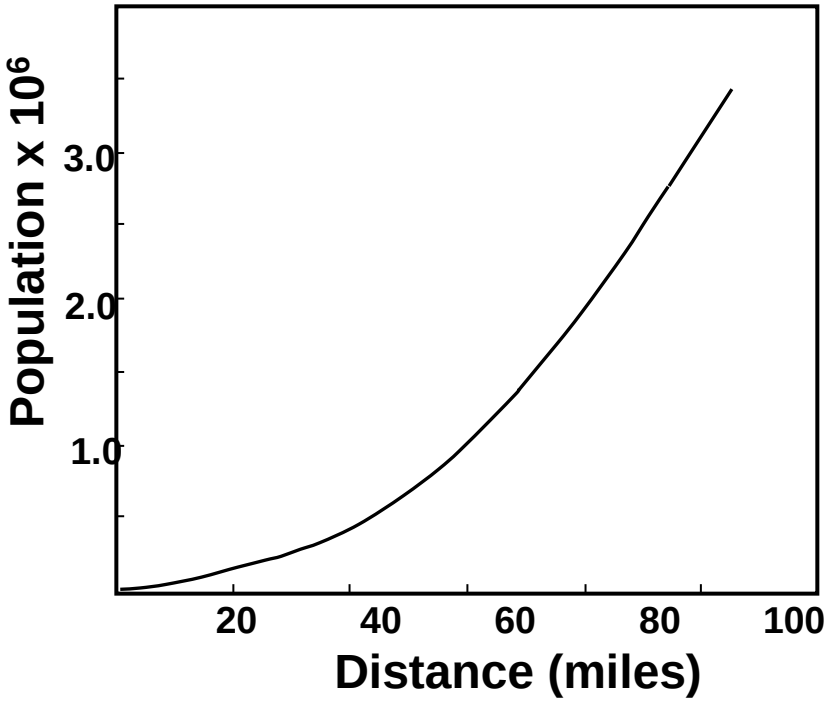
In 1973 Walker, after consulting with city utility companies, found that the city Luminosity, L, was directionally proportional to the population: L ∝ P.



Walker's Model

He then took sky brightness measurements of various cities to determine the distance where the artificial sky brightness was ≤ 0.1 mag at the zenith. From this he constructed the Population-Distance relation.





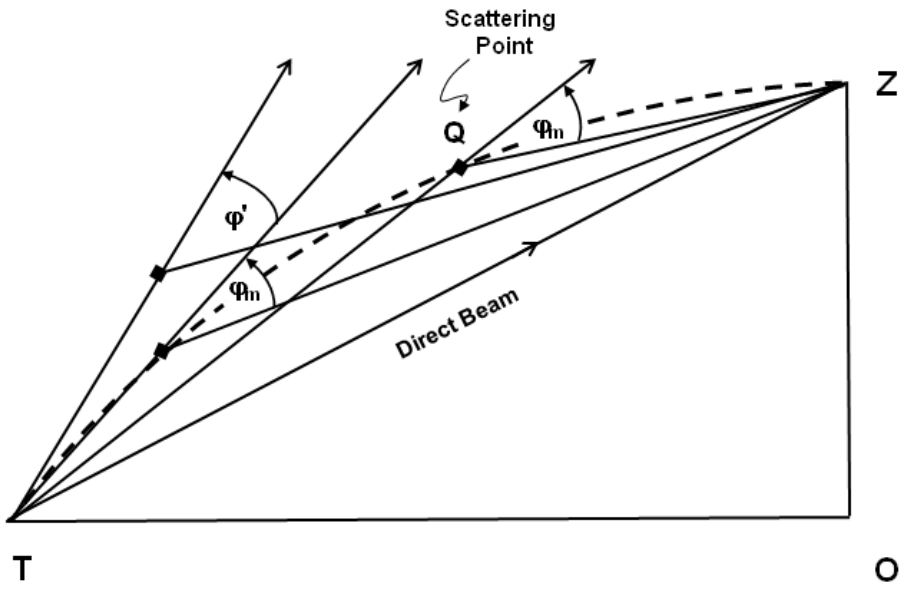
Garstang reformulated Walker's P-D relation as $B = CPD^{-2.5}$.
Known as Walker's law, *it is the simplest model for light pollution.*

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

Treanor's Model

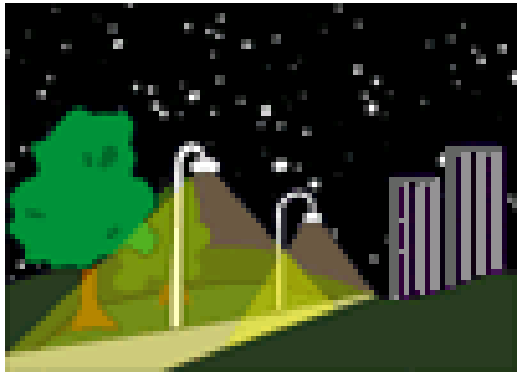
About the same time Treanor proposed a simple model for scattering along the direct beam (TZ) by restricting scattering to a small angle ϕ_m. This restricts scattering to the particles which are contained within the figure of revolution generated by rotating the arc TQZ about TZ.

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



Garstang's Model

Assumptions for Garstang's model are:



© International Dark-Sky Association

- 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

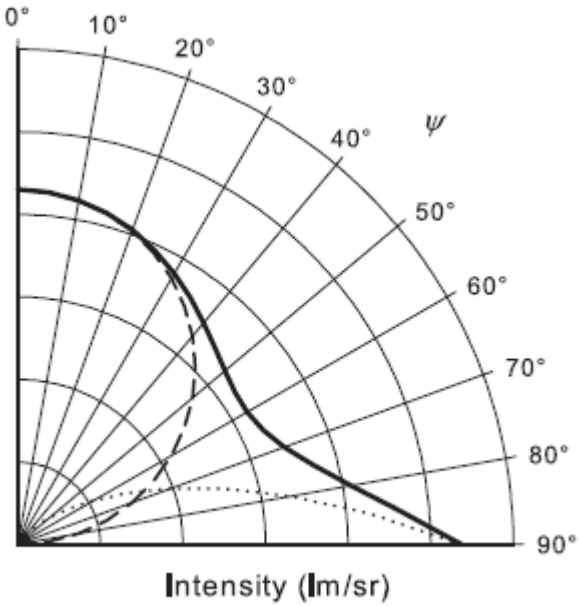
$$N_a \sigma_a = 11.11 N_m \sigma_m K e^{-cH}$$

where K is Garstang's "clarity factor", and by adding a city emission function

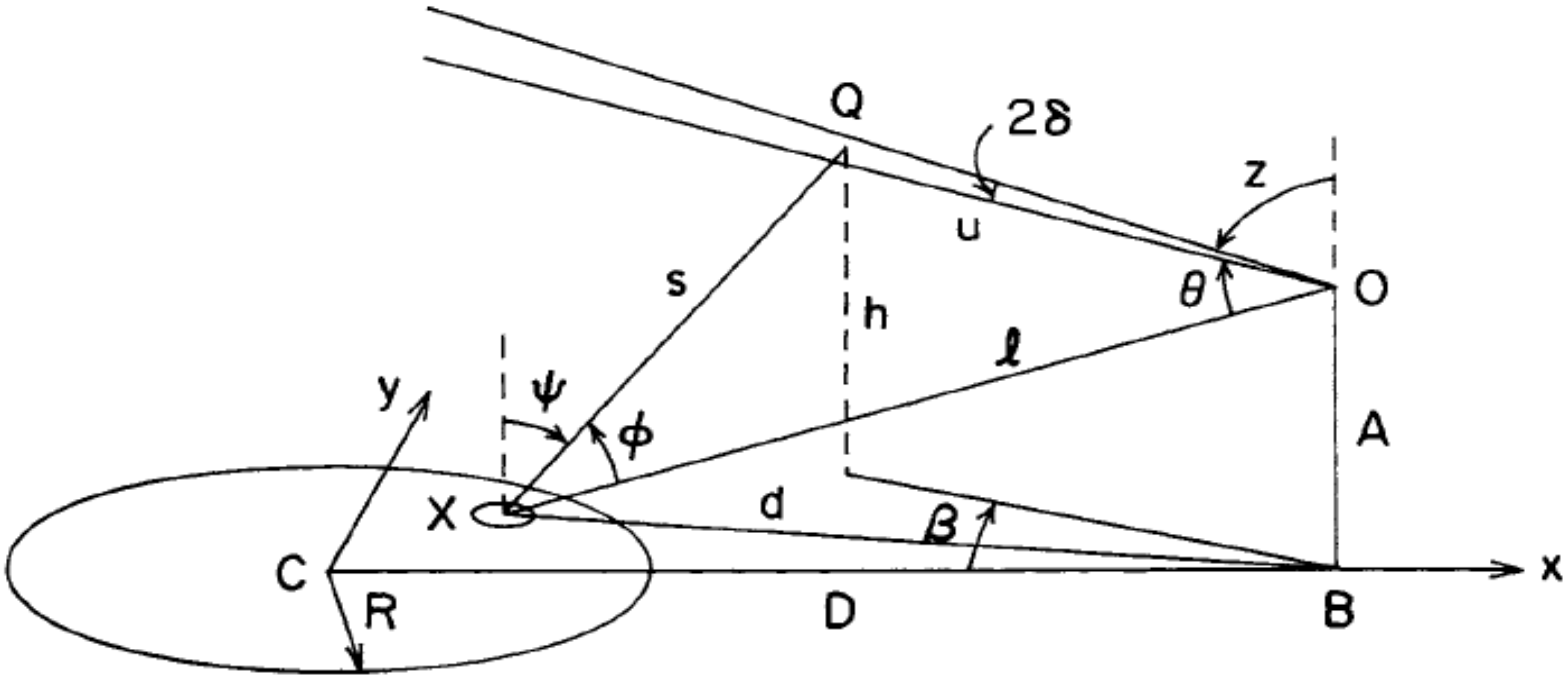
$$I^{\uparrow} = LP/2\pi \{2G (1-F) \cos \psi + 0.554 F \psi^4\}$$

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.

City Emission Function



"Double Scattering"



$$SAA = N_m \sigma_m \left(11.778\, K \frac{\{1 - e^{-a\, s\, cos\psi}\}}{a} + \gamma \frac{\{1 - e^{-c\, s\, cos\psi}\}}{c} \right) \cos^{-1}\psi$$

Garstang's Model

Finally the Broadband Brightness in Garstang's model is represented by

$$
\begin{aligned}
b = \pi N_m \sigma_R \exp(-cH) \iint (dxdy/\pi R^2) \int_0^\infty du \\
\times I_{up}\, s^{-2} (EF)_{XQ}\, (EF)_{QO}\, (DS) \\
\times \{\exp(-ch) 3(1 + \cos^2[\theta + \phi])/(16\pi) \\
+ \exp(-ah)\, 11.11\, Kf(\theta + \phi)\} \ .
\end{aligned}
$$

AIM v2

- **Original model tenets maintained**
  - brightness ~ population
- **City population data base included**
- **Cloud effects added**
  - 8 cloud types
  - reflection
- **Lighting data base added**
- **Airglow included**

City Populations

- 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

Natural Background Radiation

In the absence of moonlight and artificial light, the night sky still is not “dark”.

Contribution	Surface brightness V (S_{10} units)	Typical V_{zenith} (sunspot minimum)
Airglow	$\approx 145 + 130(S_{\odot} - 0.8)/1.2$	145
Aurora	negligible at |latitude| $< 40^o$	0
Zodiacal light	$\approx 140 - 90sin(\|\beta\|)$ ($\|\beta\| < 60^o$)	60
	≈ 60 ($\|\beta\| > 60^o$)	
	(when $> 90^o$ from the sun)	
Stars ($V > 20$, integ. light)		< 5
Starlight scattered by interstellar dust	$\approx 100 \exp(-(\|b\|/10^o))$	10
Extragalactic light		~ 1
Light pollution	< 20 at a ‘dark’ site (Smith 1979)	
		—
Total		220

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

Natural Background Radiation

In general:

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

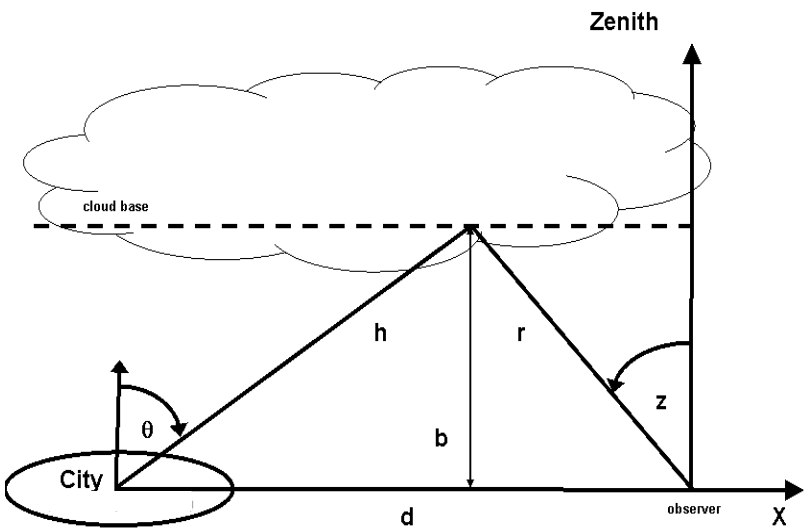
where $B_{airglow}$, $B_{zodiacal}$, and $B_{starlight}$ are functions of the solar sunspot cycle, the ecliptic latitude, and the galactic latitude respectively.

It was deemed reasonable to set the value of B_{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 ~70 km the model predicts that the brightness is ~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 Shaprio
  - simple attenuation in upward and downward paths
  - from lowest layer only

Spectral Radiant Energy

Broadband illumination is broken into spectral components dependant on the City's light types and amounts

Approach

Determine

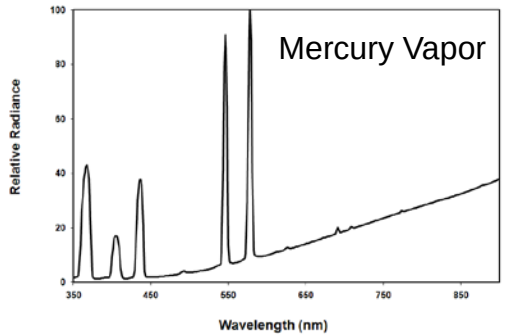
1) **Light types**
2) **Percent contribution**
3) **Spectral radiance values for each light type**

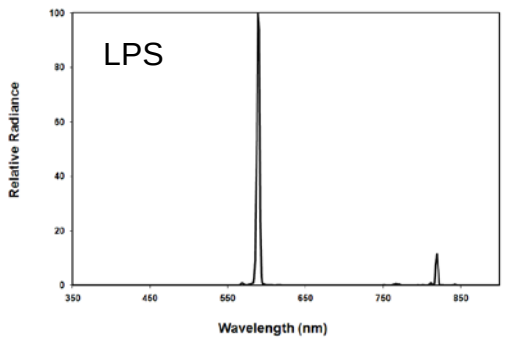
Spectral Radiant Energy

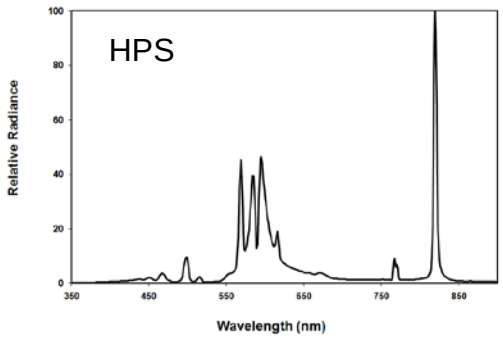
Light Types and their default percentages

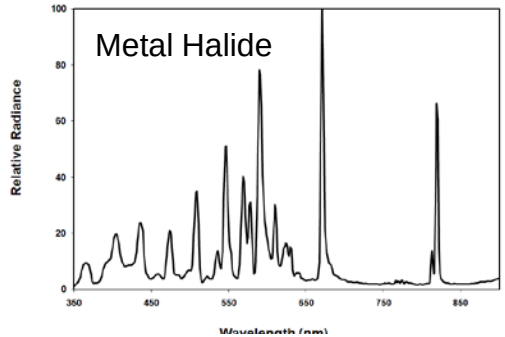
Light Type	Default Value (%) P_i
Clear Mercury	20.2
Low Pressure Sodium	0
High Pressure Sodium	77.9
Metal Halide	1.9
white LED	0
Standard Fluorescent	0
Incandescent	0
Liquid Kerosene	0
Pressurized Propane	0

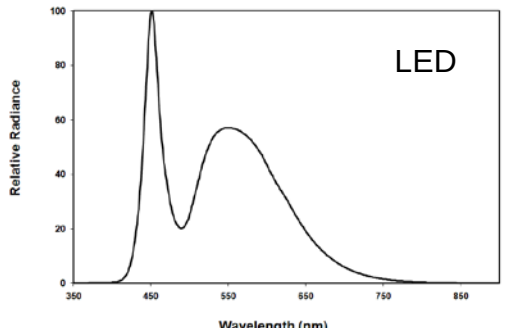
Light Type Spectra
(1 nm resolution)

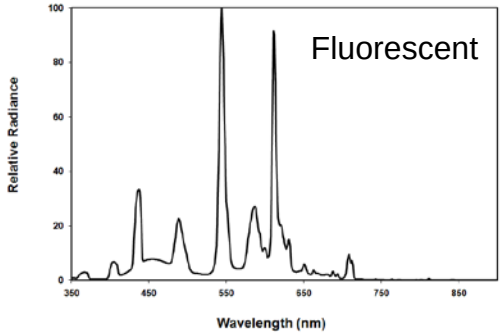


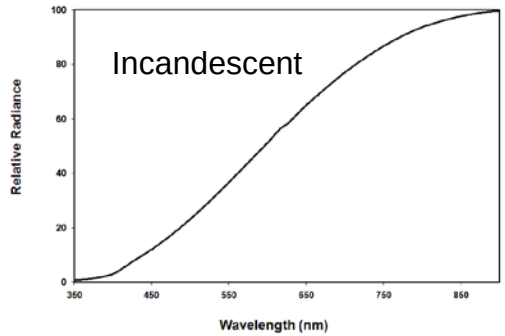


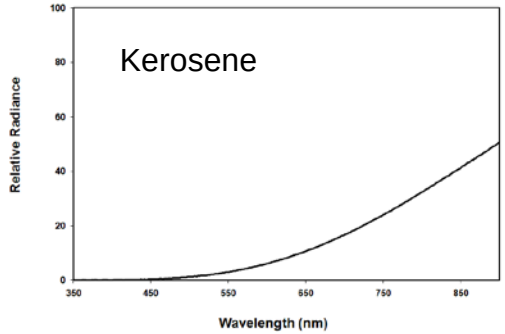


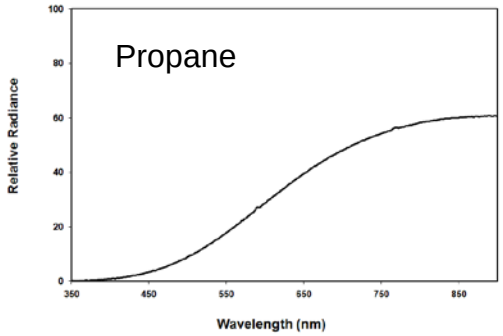










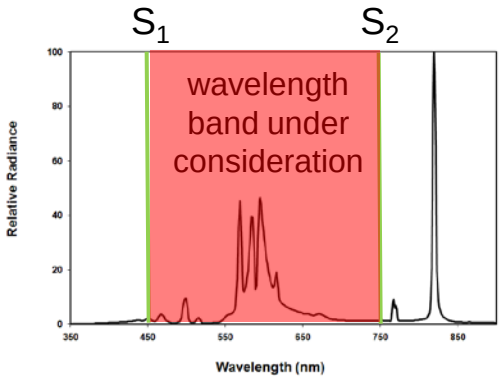


Spectral Radiant Energy Technique

For Light Type *i*

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

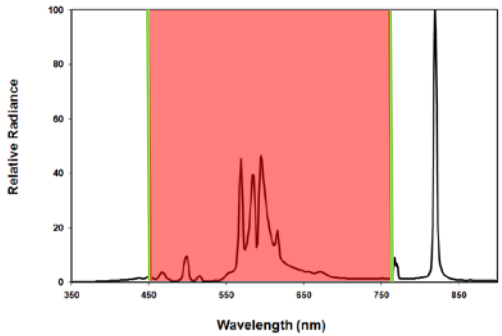
$$L_{total} = \sum_{\lambda=S_1}^{S_2} L_\lambda \, \Delta\lambda$$



HPS

2) **Bin contribution**

$$L_{\text{Jth } bin} = \sum_{\lambda=J}^{J+1} L_\lambda \, \Delta\lambda$$



HPS

Spectral Radiant Energy Technique

3) Fractional radiance

$$L_i = \frac{L_{bin}}{L_{total}} \times P_i$$

4) Final spectral radiance

- **summation over light type**

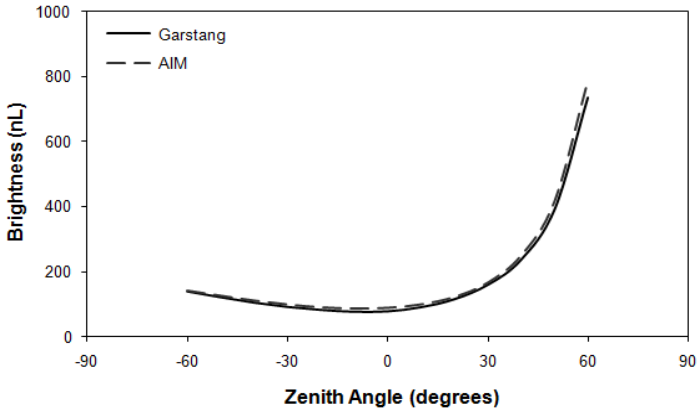
$$B_\lambda = B \times \sum_{i=1}^{N} L_{i\lambda}$$

AIM Input

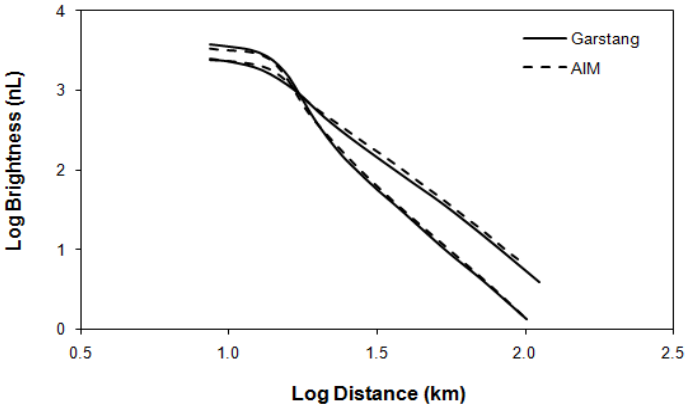
- city name, city radius, city altitude, lumens/head
- distance from observer to source, observer altitude, zenith angle, azimuth angle
- clarity factor, surface albedo, fraction of light in upward direction
- month, day, year, UTC
- beginning, ending wavelength
- light type percents
- cloud switch,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

Validation

Clear Skies



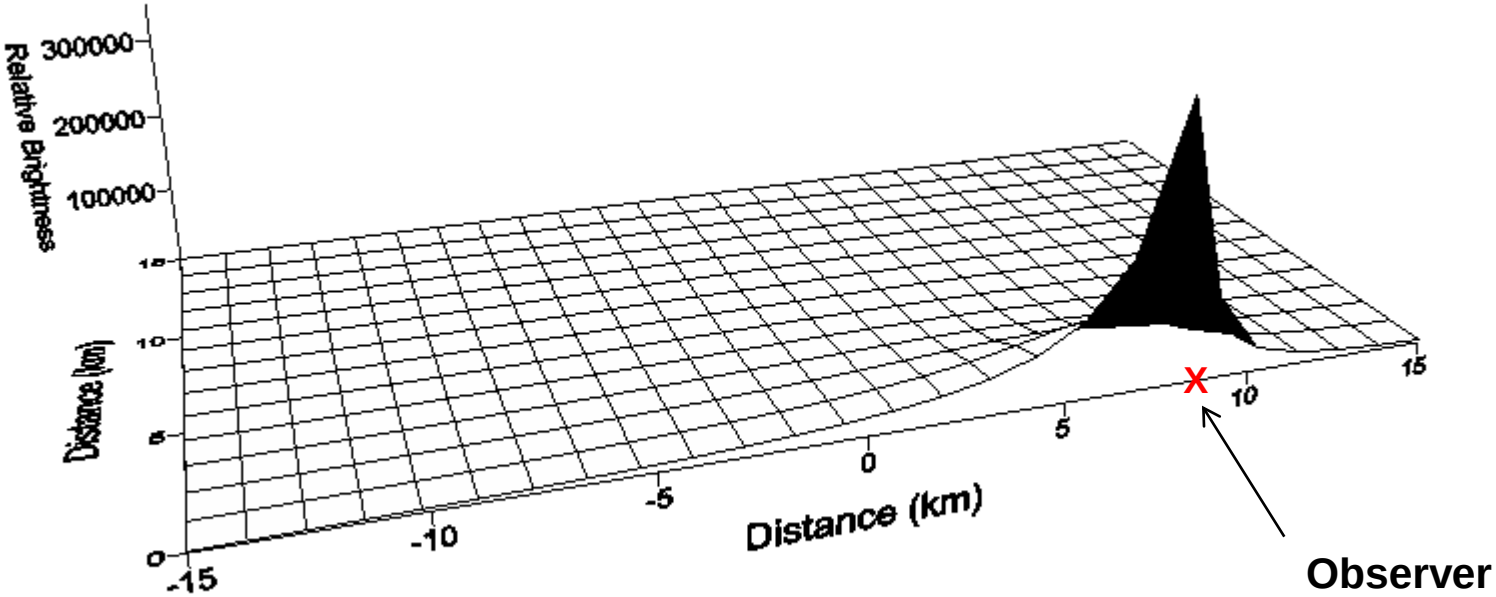
Sky brightness due to Denver as a function of zenith angle at a distance of 40 k



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

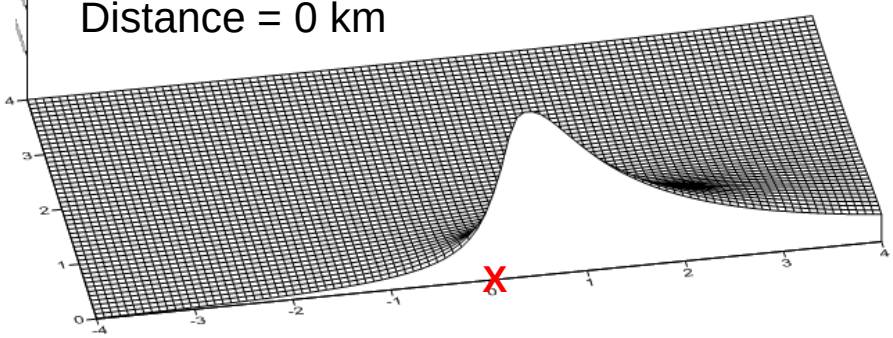
Brightness Distribution

Denver
8.6 km from city center
Zenith = 0°

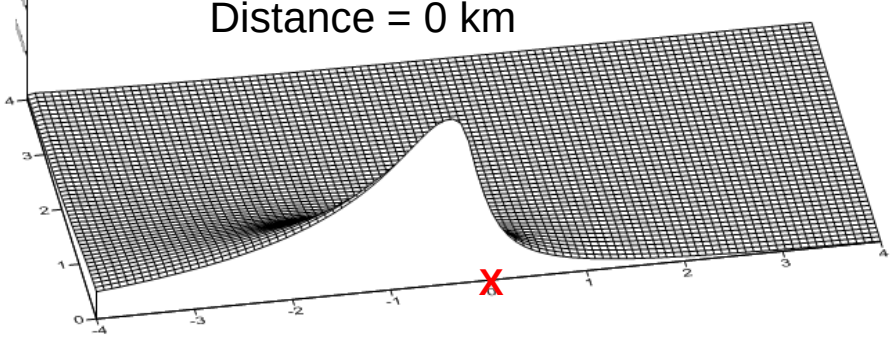


Brightness Distribution

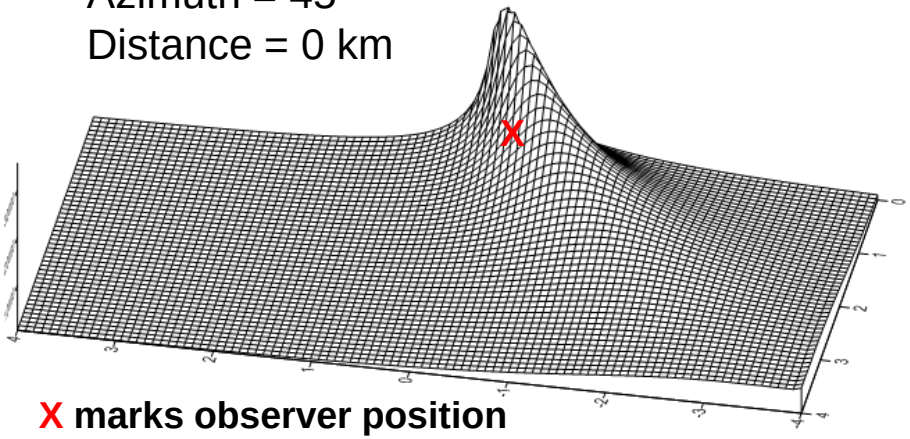
Boulder
Zenith = 65°
Azimuth = 180°
Distance = 0 km



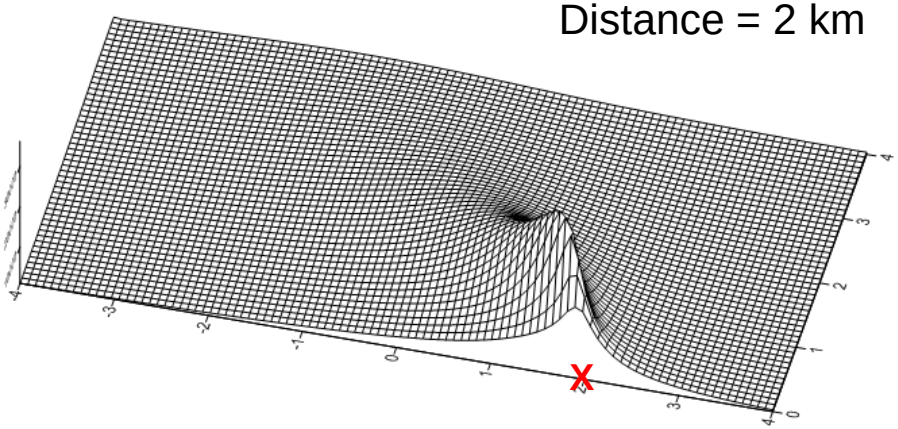
Boulder
Zenith = 65°
Azimuth = 0°
Distance = 0 km



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

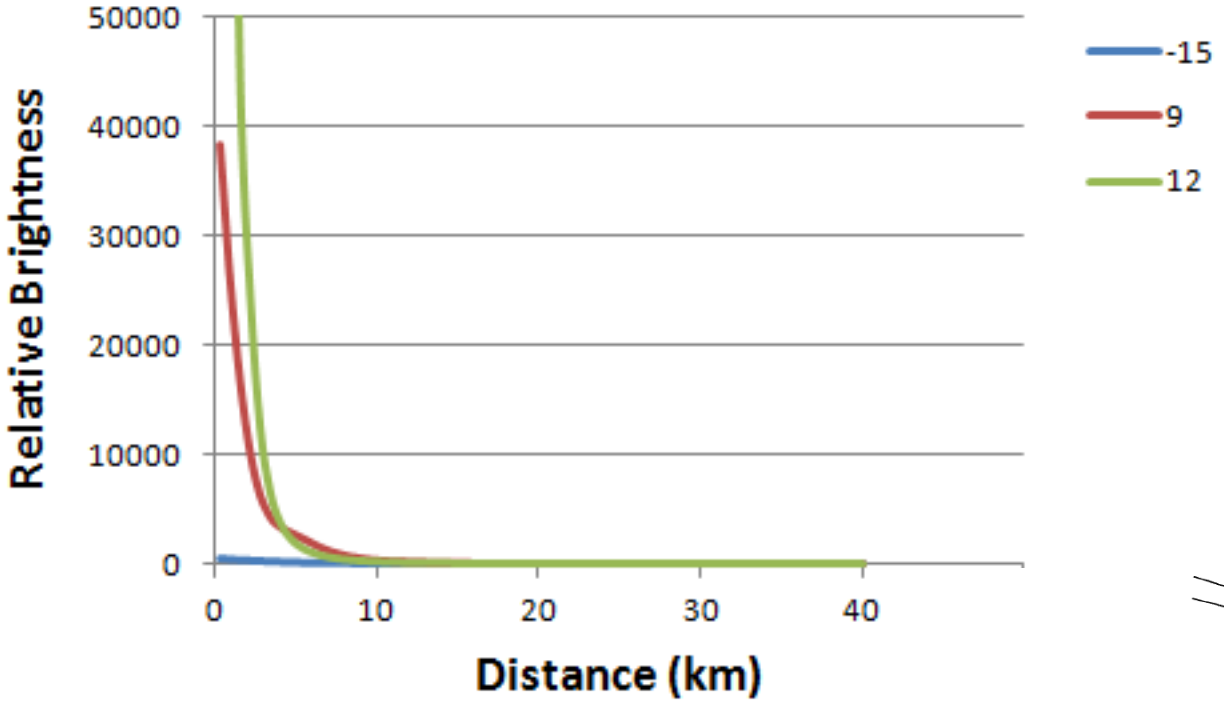


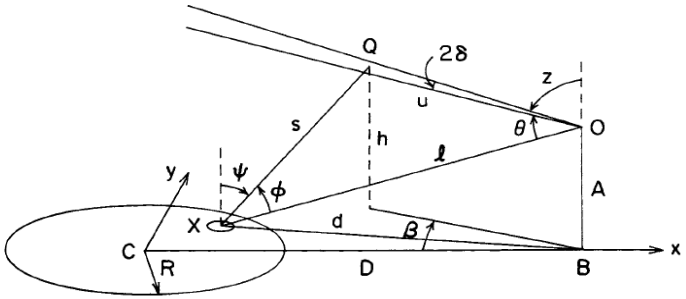
Boulder
Zenith = 65°
Azimuth = 45°
Distance = 2 km



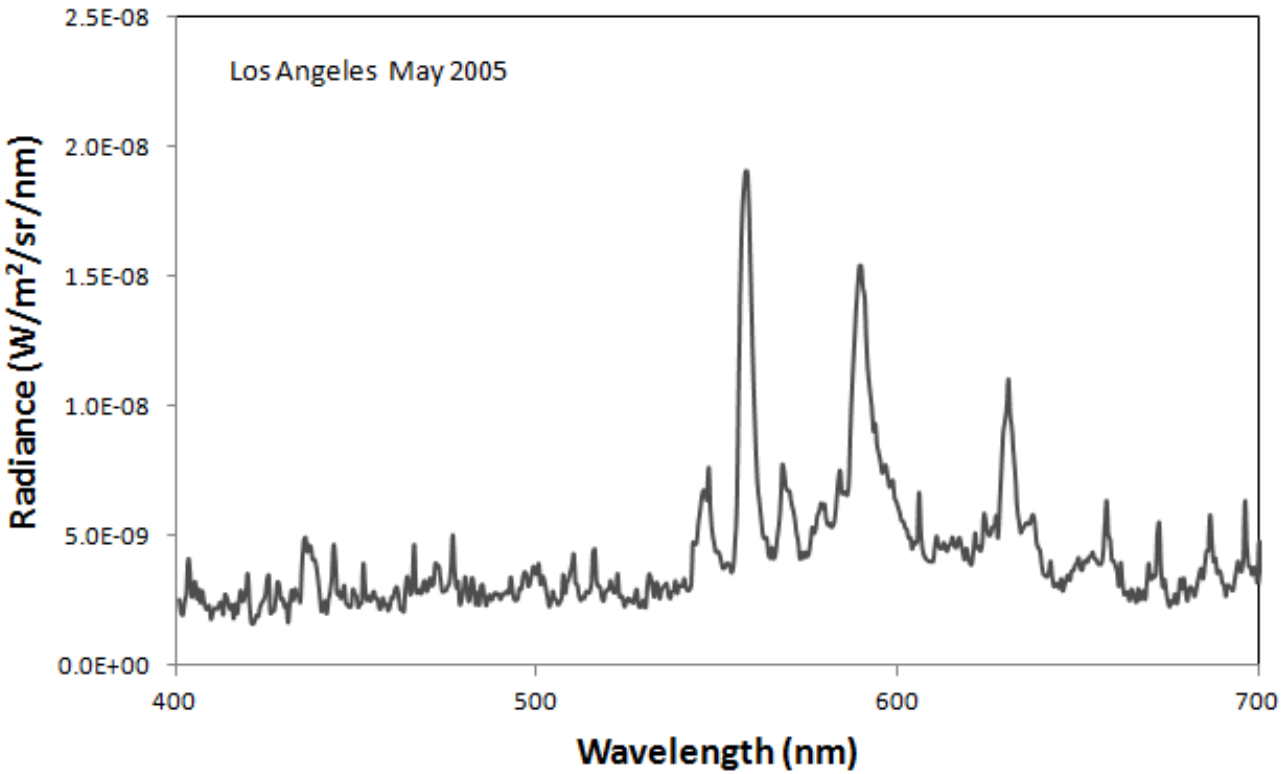
X marks observer position

Contributed Brightness along the LOS as a function of position





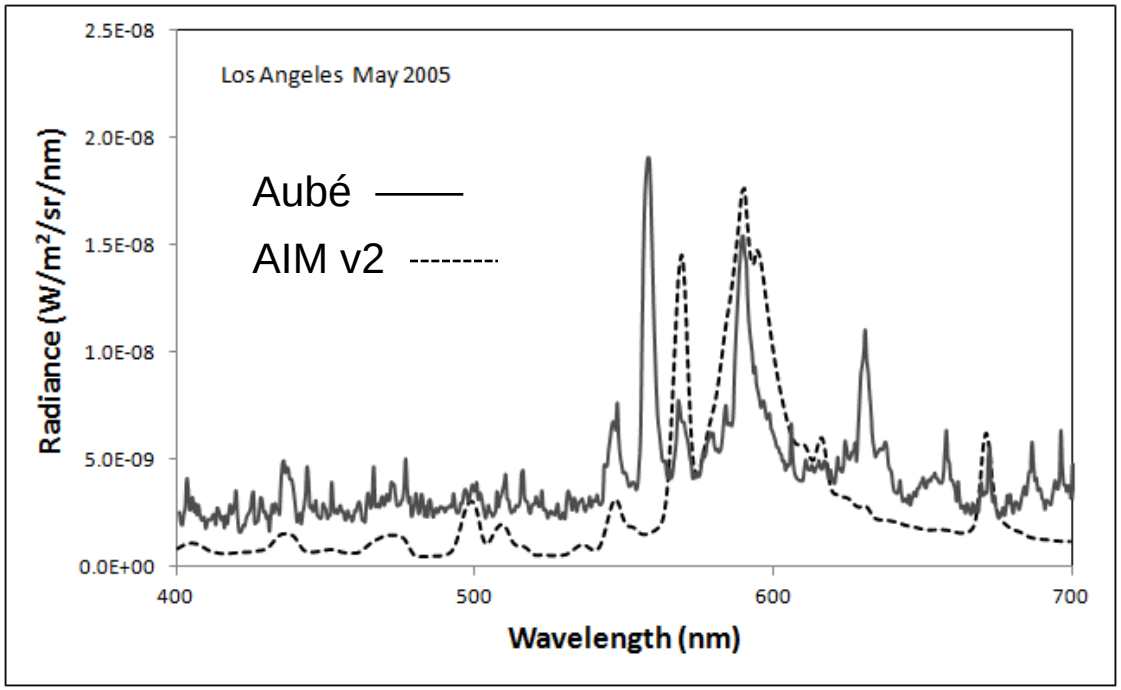
Spectral Radiance



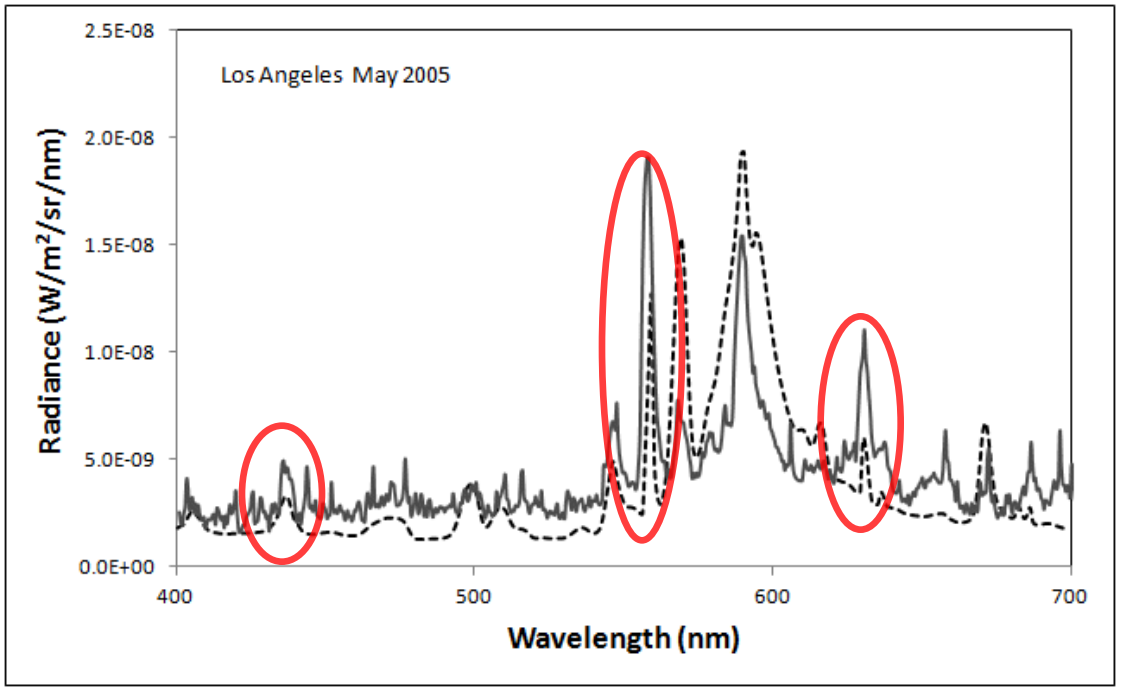
Spectrum of Los Angles

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

What's Next?

- 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


?
Zenith
upward city radiation
Y
City
z
ε
β
observer
X