Sources' Spectra, Roadway Surfaces and the Potential for Uplight Scattering

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Introduction

The interaction of the atmosphere with radiant energy is necessary for understanding ambient "light pollution" or skyglow. The fundamental concept is that the source itself is not visible, only light redirected by the atmosphere is visible as skyglow. Photons moving up into the sky must be redirected back down to an observer to be seen. The cause of this redirection is atmospheric scattering, the interaction of the constituent particles of the atmosphere with photons.

Photonic scattering is very complex and beyond the scope of this work. Unpredictable and transitory effects on photonic scattering from dust, water vapor, frozen water vapor, and pollutants are difficult to evaluate or emulate. Furthermore, these effects would interfere with the view of the night sky regardless of the quantity of luminous flux present.

It is possible to evaluate selected aspects of atmospheric scattering of light using the conceptual basis of "all other things being equal", to investigate the relative effects from selected differences. Of particular interest is the relative performance of different light sources typically used in outdoor lighting. Using radiation data for specific light sources, the sources' potential contribution to skyglow is evaluated by calculating the relative potential for atmospheric scattering of light.

For this discussion, light can be modeled as photons, each associated with a one frequency[1]. A photon's associated energy content can be determined using Plank's constant. Therefore, at a given wavelength (which is inversely related to frequency), every photon has the same energy content, but they differ from those at any other wavelength. For equal amounts of radiant energy at different wavelengths, there are more photons associated with the longer wavelengths, but each of those photons has a lower energy content[2].

Although several different interactions can occur between atmospheric particles and photons, Rayleigh scattering is the dominant form[3,4,5,6]. This phenomenon makes the sky blue during the day and provides the colors of sunrise or sunset. Rayleigh scattering does not effect all radiation equally. The spectral nature of radiant energy is the basis for Rayleigh scattering, and all radiation passing through the atmosphere is affected. In fact , "the scattering for blue light (400 nanometres) is about six times larger than for red light (640 nanometres)"[6]. Rayleigh scatter can redirect radiation in any direction, with a high probability for redirection ahead or back and lower probability for redirection perpendicular to the initial direction. Rayleigh scattering is a function of the wavelength of the photon being scattered as well as how many photons there are.

The next most significant form of atmospheric scattering is Mie scattering, which has distinctly different characteristics. With Mie scatter, the angular change is small and the effect is the same for all photons with no regard for wavelength. The "white halo" around the sun or moon or any other source results from Mie scatter. Because the angular redirection by Mie scatter is small, its effect is not included in this work.

Another potentially significant form of atmospheric scatter is inelastic, so-called because the collision changes the frequency (and wavelength) of the photon. This form of scatter has a small contribution and great variability. Therefore it is not considered in this work.

After Rayleigh scatter, no appreciable additional scatter is required, in the high atmosphere on a clear day, to account for the brightness of the blue sky[6]. Any skyglow returning to our eyes when we look up into a clear night sky is coming back to us from atmospheric scatter that is dominated by Rayleigh scatter. When the sky is clearer, with less dust, moisture and air pollution, Rayleigh scatter is more responsible for skyglow, the visual brightening of the skydome against which the celestial bodies are observed. Therefore the relative contribution to skyglow from different light sources can be compared using the Rayleigh Scatter Index defined and illustrated in this paper.

Procedure

The amount of flux at a given wavelength and the value of the wavelength are independent variables for Rayleigh scattering [3,4,5,6]. Rayleigh scattering is proportional to the inverse fourth power of the wavelength associated with the photons and directly proportional to the number of photons, the radiant power at that wavelength. We combine these two relationships into one equation with a scaling factor F to produce the following definition of the Rayleigh Scatter Index (RSI).

Eq #1: $RSI = F * \sum [\, S(\lambda) * (1/\lambda)^4 \,]$

The summation is made over the range of 360 to 770 nanometers.

A range of values for F was investigated, and the choice was made to use 5.0E11 (five times ten to the eleventh power) when the wavelengths are in nanometers and the radiation is scaled to 1 Watt total over the range of 360 to 770 nm for each source. This value of F generally corresponds to RSI values between zero and ten. The commutative characteristic of the RSI means that other scalings can be directly applied, and that the absolute values of the RSI results are arbitrary, while the relative results are valid.

Seven different sources are evaluated. These sources are: an equal energy source (EE) with constant radiant power across the spectrum; CIE D65[7]; CIE Illuminant A[7]: four High Pressure Sodium sources in different wattages (C100, C150, C250 and C400); 250 watt horizontal Metal Halide (M25H), 250 watt universal Metal Halide (M25U), 400 watt horizontal Metal Halide (M40H) and 400 watt universal Metal Halide (M40U). Philips Lighting supplied the HPS and

MH sources' spectral power distribution data used in this work. Table 1 reports the characteristics of the sources, derived as discussed below.

For these RSI calculations, the radiant power distribution of each source was scaled to 1 Watt total radiant energy over the visible spectrum from 360 to 770 nm. While scaling adjusts the overall magnitude of a particular source's radiant energy, it does not change the relative spectral distribution for that source.

Each source's initial total radiant energy was evaluated to establish the corresponding photopic lumens and scotopic lumens, using the appropriate CIE visual sensitivity curve[1,7]. The calculation of the luminous flux from a source applies a spectral sensitivity function to the source's radiant power. The equation for calculating the luminous flux of a source with radiant power distribution S(λ) evaluated for spectral sensitivity by a v(λ) function is:

Eq #2: $\text{Lumens}_{\text{source}} = K * \sum (S(\lambda) * v(\lambda))$

The summation is made over the range of 360 to 770 nanometers. The value of the factor K depends on which spectral sensitivity function is used, either photopic (K=683) or scotopic (K=1700) [1]. The sources' chromaticity coordinates were determined using CIE XYZ sensitivity functions[1,2,7].

Spectral reflectivity data was obtained from the ASTER Spectral Library[8] – a compilation from various sources including the Jet Propulsion Laboratory, Johns Hopkins University, the Beckman Laboratory, and others. All data is reported as hemi-spherical reflectivity. The spectral reflectivity profiles for different asphalt and concrete surfaces are included in this data set, but only one asphalt and one concrete surface have data extending down to 360 nm. Only these two surfaces were evaluated under the set of sources for this work. Where necessary, the surface reflectivity data was expanded to provide data in single nanometer bandwidths.

The luminous flux off a surface is calculated by multiplying together the source radiant power distribution S(λ), the surface radiant reflectivity p(λ) and the spectral sensitivity function v(λ) at each wavelength and then summing over the spectrum and multiplying that sum by constant K.

Eq #3: $\text{Lumens}_{\text{surface}} = K*\sum (S(\lambda)*p(\lambda)*v(\lambda))$

The summations are made over the range of 360 to 770 nanometers. Again, the value of the factor K depends on which spectral sensitivity function is used. The surfaces' chromaticity coordinates were calculated using CIE XYZ sensitivity functions[1,2,7].

The luminous reflectance for a surface is calculated for a specific source by determining the luminous flux from that source off the surface and dividing that value by the luminous flux onto the surface from that source. Based on photopic lumens, the reflectances of the asphalt and concrete surfaces were calculated. The CIE chromaticity coordinates of the surfaces under D65 and the reflectance of the surface materials under the seven different sources of illumination are shown in Table 2.

Considering the vast numbers of potential interactions of photons and atmospheric particles, along with the randomness associated with uplight, it seems reasonable to consider the potential for scatter to correspond in a relative way to the actual scattered radiation. Therefore the potential for scatter which is calculated by the RSI can be interpreted as a spectral power distribution of the scattered radiation. The magnitude of this SPD for scattered radiation is not valid except in comparison to other magnitudes from SPD's generated in the same way. The information is suitable for comparisons, but should not be considered as establishing actual quantities.

One check on this assumption was made by comparing the SPD's for sunlight and skylight. For sunlight we used the SPD for a blackbody radiator at 6600K[2] which is a reasonable model of the radiation from the sun that reaches the top of our atmosphere[1]. The source was scaled and RSI values calculated, then the resulting profile used as an SPD representing the scattered radiation. CIE chromaticity coordinates were calculated for both the blackbody and the scattered radiation. The x,y coordinates, color samples (for L* = 75) and locations on a CIE Chromaticity diagram are shown in Figure 1 for both the blackbody at 6600K and the corresponding scattered radiation.

The RSI profiles were also evaluated as SPD's, for comparison purposes. The total radiant energy and the photopic and scotopic lumen values were determined from SPD's of scattered radiation. Finally, the values for radiant energy within the band from 445 to 485 nm were established, since this band corresponds to the portion of the visual spectrum that is of interest to researchers[9] into interactions between melatonin and "light".

Results

Table 3 shows the Rayleigh Scatter Index (RSI) values for radiant energy scaled to one Watt of radiant power. The values for the sources are for one Watt of radiant energy direct from the lamps, while the values for asphalt and concrete refer to radiant energy from the sources and reflected, also scaled to one Watt.

The scattering for radiant energy off of the asphalt surface compared to radiant energy off of the concrete surface is significantly different. The RSI values for asphalt are between 12% and 19% higher than for concrete for the D65, Equal Energy and Metal Halide sources. However, for the CIE A and HPS sources, the RSI values for concrete are 2% to 4% more than the RSI for asphalt.

The RSI values for the HPS sources are very consistent, with values between 4.6 and 5.0 for flux from the sources or off the surfaces. The ratio of maximum-to-minimum is 1.08 for the four different HPS sources.

There is a greater variety in scattering values for the MH sources, between 6.4 and 8.0. The ratio of maximum-to-minimum is 1.24 for the four different MH sources.

Table 4 shows the differences between the averages for HPS and for MH. The average HPS values are 61% of the average MH values for radiant energy direct from the sources and 64% or 75% of the MH values for radiant energy from the roadway surfaces.

Because of its commutative characteristic, the RSI can be scaled to a "per lumen" basis simply by multiplying the per-Watt values by a suitable factor. Table 5 shows the RSI values per 100 photopic lumens, which can be derived from Table 4 by multiplying each source's RSI value by a factor equal to 100 divided by the source's photopic lumens per Watt value, shown in Table 1. The results from this scaling exactly match RSI values calculated from radiant source data scaled to 100 photopic lumens, confirming that this scaling procedure is entirely appropriate for RSI.

Table 6 shows the relative results of the evaluation of the scattered radiation from sources scaled to 100 photopic lumens of uplight. The Rayleigh Scatter Index calculates the probability profile that the radiation from a given light source will be scattered. This probability profile is a relative profile of the radiation scattered back to the observer by Rayleigh scatter under clear sky conditions. The probability profile can be used as a SPD, and Table 6 shows the results for evaluating the scattered radiation as photopic lumens or scotopic lumens or as radiant energy over the entire spectrum (RSI value) or just between 445 and 485 nm. The differences between the sources is tremendous. As shown in Table 6, for a scotopically adapted viewer, Metal Halide sources produce skydome brightness 2.8 times as great as that produces by High Pressure Sodium sources. For radiation in the band between 445 and 485 nm, the skyglow from Metal Halide sources is over three times that for High Pressure Sodium sources.

Conclusions

This work investigates the relative contribution to skyglow from different spectrally defined sources and surfaces. Although atmospheric scatter is a complex and dynamic phenomenon, the application of Rayleigh Scatter Index to compare different light sources is a beginning for addressing issues about light pollution. When Rayleigh scatter is the dominant phenomenon in atmospheric scatter, conditions for viewing the night sky are improved, and the significance of RSI increases.

For technical evaluations, scaling RSI to equal amounts of radiant energy is the most appropriate approach, since it indicates the relative scattering for equal amounts of radiant energy In this way differences are strictly based on the spectral power distribution of the radiant energy considered.

However, since exterior lighting is commonly measured, installed and evaluated based on photopic lumens, for general discussions scaling for photopic lumens may be more appropriate. RSI can be scaled as desired. Any consideration of the basis for scaling RSI should recognize that this scaling is applied to the uplight, not to the resulting scattered radiant energy.

For lighting specified on the basis of equal radiant energy or photopic lumens, High Pressure Sodium illuminants produce about half to two-thirds of the scattered light compared with Metal Halide illuminants. This ratio approaches three-quarters when roadway surface reflections are considered. The differences between HPS and MH on a "per lumen" basis are higher than on a "per Watt" basis.

When the potential for scatter calculated as the RSI is used as a SPD for scattered radiation, the evaluations of the scattered radiation show tremendous differences between the sources. The results indicate that Metal Halide sources produce three times the scotopic lumens as HPS sources, which may be significant for astronomical observers.

Further work on this topic should include incorporating appropriate mesopic sensitivity functions.

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Table 1: Source Characteristics

	EE	D65	CIE A	C100	C150	C250	C400	M25H	M25U	M40H	M40U
Radiant Watts	411	35590	45065	23	39	71	118	77	63	124	116
Photopic Lumens	72,983	7,217,299	7,369,201	9042	15210	27040	47063	24946	20979	38271	38466
Scotopic Lumens	165,021	17,787,048	10,407,014	5733	10272	17329	31623	40643	31401	67795	57109
x	0.33	0.31	0.45	0.52	0.51	0.52	0.52	0.39	0.38	0.37	0.40
y	0.33	0.33	0.41	0.42	0.42	0.41	0.42	0.40	0.40	0.39	0.40

Table 2: Surface Characteristics

	EE	D65	CIE A	C100	C150	C250	C400	M25H	M25U	M40H	M40U
Asphalt											
Reflectance	7.6%	7.6%	7.6%	7.7%	7.7%	7.7%	7.7%	7.6%	7.6%	7.6%	7.6%
x	0.34	0.32	0.46	0.53	0.52	0.53	0.52	0.40	0.39	0.38	0.40
y	0.34	0.34	0.41	0.42	0.42	0.41	0.42	0.41	0.40	0.40	0.41
Concrete											
Reflectance	26%	26%	27%	28%	28%	28%	28%	26%	26%	26%	26%
x	0.37	0.35	0.48	0.54	0.53	0.54	0.53	0.42	0.41	0.41	0.43
y	0.36	0.36	0.41	0.42	0.43	0.42	0.42	0.42	0.42	0.42	0.42

Table 3: Rayleigh Scatter Index (scaled to 1 Watt radiant power)

	EE	D65	CIE A	C100	C150	C250	C400	M25H	M25U	M40H	M40U
Sources	7.8	7.7	3.8	4.7	4.7	4.6	4.8	7.6	8.0	7.8	7.5
off Asphalt	7.4	7.3	3.8	4.7	4.7	4.6	4.8	7.3	7.6	7.4	7.2
off Concrete	6.2	6.3	3.9	4.9	4.9	4.8	5.0	6.5	6.7	6.6	6.4

Table 4: Rayleigh Scatter Index Comparisons of MH and HPS (scaled to 1 Watt radiant power)

	AvgHPS	AvgMH	MH/HPS
Sources	4.7	7.7	165%
off Asphalt	4.7	7.4	157%
off Concrete	4.9	6.5	134%

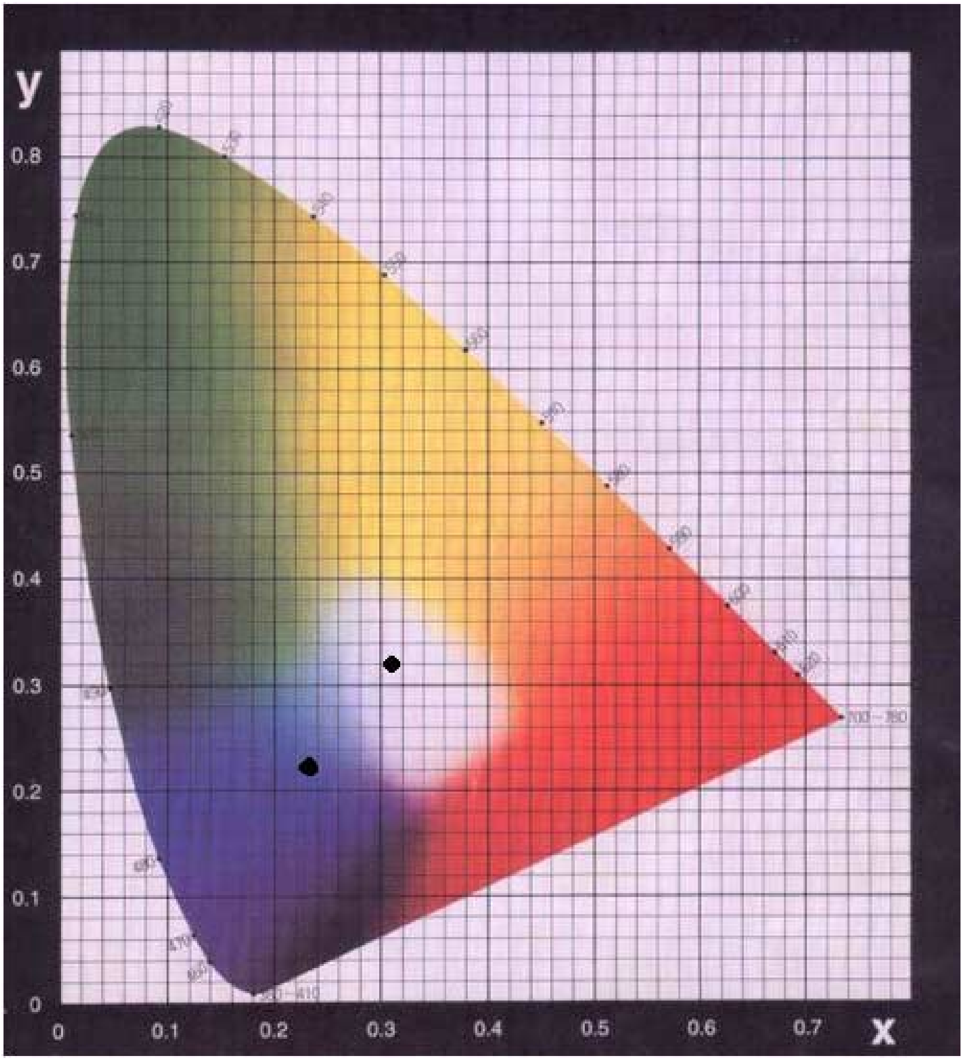
Table 5: Rayleigh Scatter Index Comparisons of MH and HPS (scaled to 100 Photopic Lumens)

	AvgHPS	AvgMH	MH/HPS
Radiant Watts	0.26	0.31	121%
Sources	1.2	2.4	200%
off Asphalt	1.2	2.3	189%
off Concrete	1.2	2.0	162%

Table 6: Scattered Radiation Analyzed for Photopic and Scotopic Sensitivity

	Source Radiation			**Relative Scaled Scattered Radiation**			
	Radiant Watts	Photopic Lumens	Scotopic Lumens	RSI Value	Photopic Lumens	Scotopic Lumens	445 to 485 nm
EqEnergy	0.57	100	226	4.5	5.4	18.8	7.4
BB6600K	0.54	100	246	4.8	5.5	20.7	8.4
D65	0.48	100	246	3.4	5.5	20.6	8.6
CIE Illum A	0.62	100	141	2.3	4.9	10.5	2.9
AvgMH	0.31	100	160	2.4	5.1	12.3	6.5
AvgHPS	0.26	100	66	1.2	4.4	4.5	2.1

Figure 1: Blackbody at 6600K source and scattered radiation



Blackbody@6600K
x = 0.31, y = 0.32

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Scattered Radiation
x = 0.23, y = 0.22

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