ANSI/IES TM-37-22

Illuminating
ENGINEERING SOCIETY

TECHNICAL MEMORANDUM: DESCRIPTION, MEASUREMENT, AND ESTIMATION OF SKY GLOW

AN AMERICAN NATIONAL STANDARD

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Publication of this Technical Memorandum
has been approved by IES.
Suggestions for revisions
should be directed to IES.

Prepared by
The IES Sky Glow Calculations Committee

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Prepared by the IES Sky Glow Calculations Committee.

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Preface

Numerous human benefits derive from the use of light at night. Unfortunately, increased brightness of the night sky, or *sky glow,* also directly accompanies the alteration of natural lighting levels by human-based light sources. The first, most easily observed effect of sky glow is decreased visibility of the night sky (see **Figure P-1**). Associated expressions of concern began almost simultaneously with the widespread deployment of electric lighting, and are now common around the globe.

Figure P-1. Effects of sky glow from Las Vegas are very evident from Lake Mead, about 76 kilometers distant. (Image courtesy of Dan Duriscoe)

More recently, apprehension has expanded to include the potential adverse influences on animals and plants from light at night occurring at "unnatural" periods during the normal diurnal cycle. The ongoing large-scale conversion of outdoor lighting sources from low- and high-pressure sodium to white light-emitting diodes (LED) has been especially criticized for LEDs' greater content of wavelengths in the portion of the visible range between 380 and 550 nm. Because the natural night sky has relatively low levels of wavelengths within this range (see **Section 2.2.2**), any such addition from human-based sources does in fact represent a significant departure from natural conditions.* While some amount of detrimental effect more or less accompanies all anthropogenic light at night, a mounting body of evidence indicates that these shorter wavelengths can be particularly disruptive, affecting natural ecosystems in addition to imposing outsized interference on the work of the astronomical community. In all cases, human-based sky glow can be considered an environmental pollutant akin to other acknowledged pollutants that engineers and designers strive to minimize while still meeting the wide-ranging needs of modern society. Global calls for action can be expected to continue and grow as documented impacts of anthropogenic light at night become better measured and understood.

It is important to recognize that all white light sources emit wavelengths within the noted range. Any white light visible from any source in any outdoor location (e.g., light emitted from building interiors) contributes to the issue, and thus multiple approaches are available (and will be necessary) to effectively address it. It is also important to recognize that lighting is intrinsically linked to a broad host of other concerns, among them safety, security, and energy use and its attendant effects.

This Technical Memorandum represents the beginning steps of a proactive response from the lighting community toward addressing the panoply of concerns in the most well-rounded and practical manner possible. While more work is needed, it is clear that improved understanding and estimation of the associated sources, quantities, characteristics, and resulting behaviors of light entering the night sky will be essential components of a comprehensive remediation strategy.

This document provides guidance on means of reducing human contributions to light in the night sky and information on estimating the relative effectiveness of the different options available.

A glossary of relevant terms is included in **Section 8.**

* Although the moon introduces these wavelengths to varying degrees and intensities over the course of a lunar cycle, moonlight's cyclical nature, vulnerability to weather conditions (e.g., cloud cover), and inseparable role in the evolutionary development of life on Earth render it distinctly different from continuous ground-based electric lighting.

1.0 Introduction and Scope

1.1 Introduction

Human-based light in the night sky mainly originates from outdoor sources intended to enable or enhance use of exterior spaces when natural light levels are insufficient for the intended purpose. To a lesser extent, light at night also comes from building interior lighting that escapes via windows or other means. Sky glow resulting from light reaching the night sky is a distinct phenomenon from other potential undesirable effects of the use of light, such as light trespass or exposure to the direct or reflected glare from an outdoor luminaire (sometimes included under the broader term "light pollution"), or light at night to which an individual may be exposed from interior sources (e.g., televisions, smart phones or tablets, clocks, nightlights). The various effects experienced by an individual would often involve a combination of such sources; this Technical Memorandum (TM) focuses exclusively on the brightness and related characteristics of the night sky and how these are influenced by the human-based light reaching it.

All light released to the external environment propagates through Earth's atmosphere to at least a limited extent. The atmosphere is a complex and dynamic combination of elements that influence the amount and characteristics of light beams traveling through it. As in other forecasts involving the atmosphere (e.g., weather), such complexity ensures that no estimation procedure or model can ever achieve perfect accuracy. The precision of the results varies from that ideal in proportion to: 1) the degree of inaccuracy introduced by any simplifying assumptions required; 2) the level of computing power necessary and available to conduct the estimation; and 3) the impacts of variable inputs. This last group includes, for example, real-time localized atmospheric conditions and particulate loading (including quantities, sizes, and shapes); presence of other lighting sources not considered in the estimate*; growth of vegetation and local geographical conditions that are difficult to precisely represent throughout a widespread scenario; blocking by buildings; and varying reflectivity of nearby surfaces.

Despite the associated challenges, such complexity does not preclude the potentially valuable insight to be gained from carrying out an "imperfect" estimation. At the community or regional level, however, knowledge of the absolute amount of sky glow present before and after planned installations is required in order to keep track of cumulative impacts. At present, this is assessed most quickly and accurately through pre- and post-installation measurement because accurate methodologies for prediction are still very much under development. This TM proposes a workable future methodology, although multiple components of it remain to be developed (see **Section 4.0**). In the interim, locations undergoing large-scale changes (e.g., a street lighting conversion) should consider conducting pre- and post-measurement of night sky brightness levels, not only for their own immediate purposes, but also to provide useful documented data to help with future methodologies. **Section 6.0** introduces measurement of night sky brightness.

Careful selection and implementation of lighting equipment does, in fact, directly influence the amount and properties (see **Sidebar – Properties and Characteristics**) of light that ultimately winds up in the night sky, as well as how far that influence extends away from the illuminated area. Such attention also helps address other important light pollution issues, such as light trespass and nuisance glare, while reducing costs of operation. Identifying when lighting is needed and when and where it is not, and then

SIDEBAR – Properties and Characteristics

This document refers to both "properties" and "characteristics" of light. These terms are often elsewhere used interchangeably, but a distinction is made here. "Properties" refers to qualities inherent in a given light beam, such as its spectral content and intensity, whereas "characteristics" is used as a broader term that includes additional influences from attributes of the lighting application, such as hours of use, initial directions of emission (which may differ from the portion of that light reaching the sky), and reflectances of surfaces being illuminated.

* Including natural sources such as airglow caused by cosmic rays, chemiluminescence, and other atmospheric effects. Other than moonlight, natural sources are typically low in magnitude relative to human-based sources.

designing the system accordingly, forms the foundation for achieving all these objectives.

Avoiding production of unneeded light from the outset is always the first best approach, eliminating operating and possibly capital costs, energy use, and associated adverse effects simultaneously. Once the possibilities of that approach are exhausted, however, the relative effectiveness and accompanying tradeoffs of remaining options present more complexity, and the best path forward often depends on the collective set of other circumstances. The discussion, equations, methodologies, and tools outlined in this TM are intended to facilitate this evaluation process for engineers, planners, and others engaged in the design and deployment of outdoor lighting systems. Others looking to balance the benefits of lighting with reduced downstream adverse effects should also find the document helpful.

1.2 Scope

This TM describes the causes, characteristics, and potential impacts of human-based sky glow, and provides the current state of the science for conducting estimations to facilitate its quantification and control. Virtually all lighting applications with exposure to the exterior environment fall within this purview, including street and area lighting, sports lighting, signage and advertisement lighting, industrial lighting, light escaping the interior of commercial and residential buildings via windows, and landscape lighting. Mobile sources, i.e., vehicular lighting, also contribute to sky glow and are included in the discussion, even though they are traditionally outside of IES scope.

This document only provides an introduction to light's potential downstream consequences, e.g., impacts to human health or wildlife, and provides the basis of a methodology for one or more new metrics. The process often involves the application of a dedicated action function specific to the effect in question and therefore requires special domain expertise that is beyond the ability of this document to provide.* However, the methodology will enable estimates of underlying inputs such as the spectrum, intensity, duration, and timing of the light that are necessary to conduct such expert assessment.

Consequently, this TM focuses on the causes and characterization of light that may be introduced to the night sky from the use of electric lighting, and available means of influencing it. A proposed method for its numeric quantification is also included, for detailing individual contributions to light in the sky, application by application. More work is needed to fill in the details of this method and create the ultimate recommended practice, but the methodology establishes a practical framework. In the meantime, **Section 5.2** provides a few brief references to models and tools that are currently available for estimating sky glow, while **Section 7** provides general recommendations for reducing sky glow that should prove useful throughout the lighting community.

2.0 Effects of Light Output, Distribution, and Spectral Content on Sky Glow

The characteristics of a lighting application of relevance to sky glow include its directional distribution, radiant output (or flux), and wavelength-specific spectral content (rather than simply correlated color temperature or chromaticity coordinates). These types of data are readily available for standard outdoor luminaire types that can be photometrically tested. They provide key inputs to any evaluation of sky glow—and thereby represent the primary means for its control. (It should be noted, however, that not all sources contributing to sky glow are easily controlled through current standard design practices, such as building interior lighting escaping via windows.) Appropriate lighting design and implementation are essential to this end. In locations with existing outdoor lighting, especially those with high illumination levels, supplemental lighting for new or updated applications (e.g., a street lighting conversion) should take such ambient lighting into account. Designing new applications without consideration of existing lighting can easily result in more illumination than needed, often significantly more. Identification of the appropriate output and distribution of lighting applications is amply covered in other IES resources, such as *ANSI/IES RP-8-18, Recommended*

* An entire body of literature is forming around the potential influences of light at night on both humans and wildlife, and the roles that various dosages of light may play in altering the natural rhythms and behaviors of ecosystems that have evolved under diurnal and seasonal light patterns, intensities, and spectral contents. (Refer, for example, to *ANSI/IES LP-11-20, Lighting Practice: Environmental Considerations for Outdoor Lighting.)*

Practice for Design and Maintenance of Roadway and Parking Facility Lighting[1]; *ANSI/IES RP-39-19, Recommended Practice: Off-Roadway Sign Luminance*[2]; *ANSI/IES RP-6-20, Recommended Practice: Lighting Sports and Recreational Areas*[3]; and *ANSI/IES LM-79-19, Approved Method: Optical and Electrical Measurements of Solid-State Lighting Products*.[4] The discussion of those topics in this document is limited to description of their associated influences on sky glow.

Human-based light in the night sky arrives via one of three pathways: directly emitted by the source above a horizontal direction; reflected into the sky from the ground or other surface encountered (e.g., a building façade); or scattered by atmospheric constituents after being emitted or after being reflected from the ground or other obstacle.

2.1 Light Output and Distribution

In isolation, the impact of light output (flux) on sky glow is scalar and therefore straightforward. All else being equal, doubling the light output in an application doubles its contribution to sky glow. Likewise, halving the application's light output directly halves its contribution. Actual conversions of lighting applications are usually more complex, in that changes exclusively involving output levels are rare; most often the distribution of that light is also changed, as is its spectral content. Changes in sky glow reflect the sum of all such influences. Nevertheless, a reduction in light output, at both the luminaire and the regional level, is usually the easiest and most effective way to reduce sky glow.

The distribution of light potentially affects all three of its potential pathways into the sky. A shorthand method for indicating distribution of individual luminaires has been developed and termed the Back Light, Uplight, and Glare, or BUG, rating, defined in *ANSI/IES TM-15-20, Technical Memorandum: Luminaire Classification System for Outdoor Luminaires*.[5] Of these three characteristics, the one most directly related to sky glow is uplight (designated by the "U" rating), indicating the amount of light the luminaire emits into the sky above the horizontal direction.

2.1.1 Uplight. Uplight is the most efficient path for producing sky glow and, for many situations, the least efficient at lighting the visual task. Emissions of direct uplight can result from both luminaire design and implementation. Older luminaires commonly employed "drop" or "sag" lenses to deliver sufficient light levels out to the far reaches of the target area of illumination. Such luminaires are still in widespread use, and their associated uplight emissions are clearly evident (see, for example, the "before" and "after" photos in **Figure 2-1**). As the perspective of this photo is from a higher elevation than that of the streetlights, any light visible from the luminaires themselves (i.e., not reflected from another surface) is direct uplight.

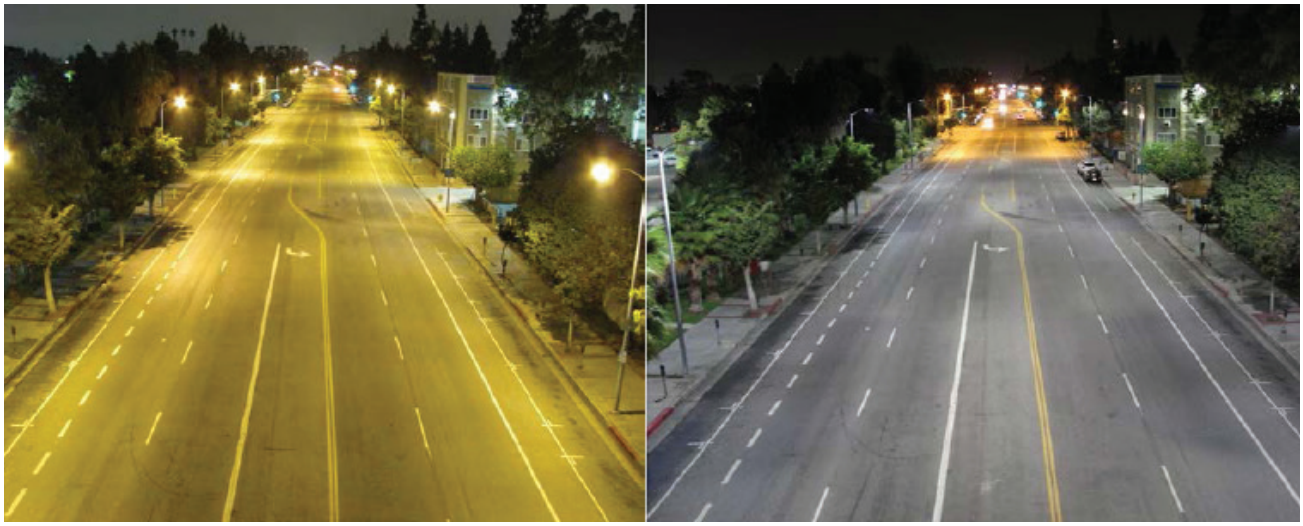


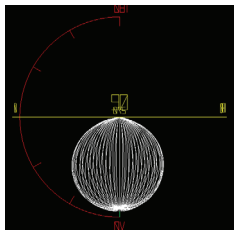
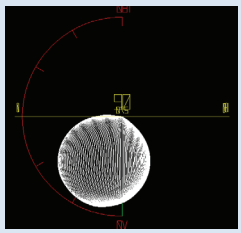
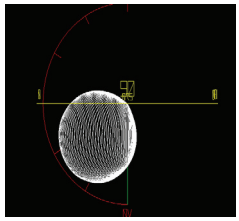
Figure 2-1. A street in Los Angeles before a conversion (left) and after (right). In the photo on the right, the difference in the uplight component is visible between new LED luminaires in foreground and the type of drop-lens cobra-head high pressure sodium luminaires in the background that they replaced.
(Image courtesy of Los Angeles Bureau of Street Lighting)

Uplight is also a common characteristic of decorative luminaires, such as those in the left-hand photograph in **Figure 2-2**, as well as a byproduct of the widespread practice of tilting luminaires, as in the right-hand photo. As with the use of drop lenses, tilting is often employed to extend the light output of a luminaire to the outer reaches of a desired area of illumination. Tilting is perhaps most frequently used with floodlighting and security lighting, but its use in roadways and parking lots is also common. It is sometimes required on a steeply angled road to adequately illuminate the road surface in both directions or to address other situations where a preferred lumen distribution is otherwise unavailable. In most cases, however, tilting is unnecessary when the selected luminaire distribution can be appropriately matched to the application.

Figure 2-2. *Left*: globe or "gumball" fixtures with high uplight component; *right*: tilted luminaires. (Images courtesy of Pacific Northwest National Laboratory, PNNL)

Table 2-1 demonstrates that tilting substantially compromises a U0 BUG rating (0% uplight), a common design feature of modern products intended to be installed in a horizontal position. The top luminaire is a "shoebox" type; the bottom is a type commonly used in roadways.

Table 2-1. Example Effects of Tilting on Two LED Outdoor Luminaires with 0% Uplight (U0)

Luminaire	Polar Plot	Tilt	Lumens Down	Uplight	Relative Sky Glow	BUG Ratings
Cosine Distribution		0°	20,000	0.0%	100%	B4-U0-G2
		20°	19,646	1.6%	approx. 120%	B3-U3-G5
		45°	17,319	13.4%	>220%	B3-U5-G5

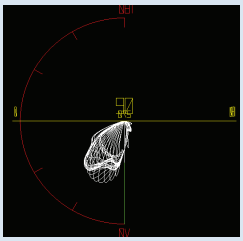
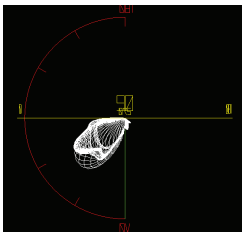
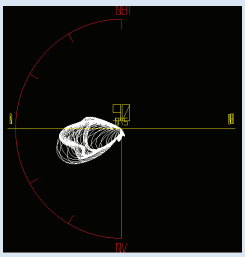
Type II Short		0°	20,000	0.0%	100%	B3-U0-G3
		20°	19,782	1.1%	approx. 112%	B2-U3-G5
		45°	15,704	21.5%	approx. 270%	B1-U5-G5

Table source: PNNL, using data supplied by LightLab, Allentown, PA. Relative sky glow calculated by DOE Sky Glow Calculation Tool.

Table notes: Each relative sky glow calculation of the given luminaire is compared to itself at 0-degree tilt. Atmospheric conditions correspond to the definition of "Clear Sky, Low Particulate" used in the Kocifaj model at the time of publication of Kinzey, 2017.[6] Ground reflectivity was assumed a uniform 15%, in alignment with the model. No scotopic weighting factor of the light is applied. It should be noted that row-by-row variations in the values do not scale linearly with tilt angle, due to downward lumens reflecting diffusely upward at the assumed reflectivity of 15%, whereas 100% of lumens emitted upward enter the sky directly in a more directional pattern. Upward and downward emitted lumens thereby have markedly different and nonlinear effects on sky glow. All values should be considered only approximations.

Over the last few decades, a major shift toward luminaires with no uplight has markedly reduced contributions to sky glow from uplight via the corresponding lighting applications. Substantial gains have also been achieved in decorative "acorn" and globe-type pole-mounted luminaires by deploying more-directional LED luminaires, shielding, partial tinting, and/or inserts to replace the original lamp-based omnidirectional emitters.

Elimination of the use of tilting would further improve these gains, however. Data reported in the table clearly reveal the increasing effect of tilt on resulting uplight and the associated consequence in terms of sky glow. In the examples shown, tilting a luminaire 20 degrees changes a BUG uplight rating from U0 to U3, and to U5 for a 45-degree tilt, in each case with correspondingly more uplight. Specifying and purchasing U0 luminaires is therefore not enough; appropriate installation is also required. The two examples in the table also illustrate that the precise impacts of tilting vary according to the individual luminaire design and associated distribution.

The angle at which uplight is emitted has a significant effect on its potential contribution to sky glow. (Refer to **Section 5.1.2 Source Emission Angle** for additional information on this effect.)

2.1.2 Reflected Light. Some portion of the light emitted by a luminaire reaching an opaque surface is absorbed and the remainder reflected. Describing the reflectivity of a given material is complicated by its

dependence on both the incoming and outgoing angles of the light to the surface of the material, its surface characteristics (e.g., roughness, oxidation, the presence of inhomogeneities), the specific ranges of wavelengths examined, and absorption and scattering within the body of the material. Furthermore, depending on the lighting application and circumstances, distributed light from a single luminaire might encounter multiple surfaces. A generally useful simplification divides the angular components of reflection from each relevant surface into specular and diffuse subcomponents.

The specular component is largely independent of wavelength unless the material is metallic or metal-like, or the angle of incidence is nearly 90 degrees from the normal, i.e., very close to the surface. The specular component becomes especially important to sky glow in lighting applications such as those using wall washers or in the floodlighting of billboards, where the light source is below the surface being illuminated. Because specular reflectance at angles near the surface can be very high, one means of reducing light in the sky involves limiting this type of lighting or using surfaces that are sufficiently matte or that employ some other form of surface relief to reduce or block the specular skyward component.

The diffuse component reflected from a surface is a result of the combination of diffuse incident light on the object, surface contours and roughness, and absorption and scattering within the body of the material. Diffuse reflection leads to light in the night sky from most illuminated surfaces, including roadways and other transportation infrastructure, signage, paints, vegetation, and construction materials like those used in building façades. In contrast with specular reflection, however, varying absorption within the body of the material means that this reflection may be highly wavelength dependent. **Figure 2-3** shows example reflectance values across the visible spectrum for various common surfaces.

The reflection spectra shown in **Figure 2-3** are illustrative of some of the shapes and magnitudes for typical surfaces found in the environment. However, significant variations in magnitude are common in actual situations. For instance, in comparison with the

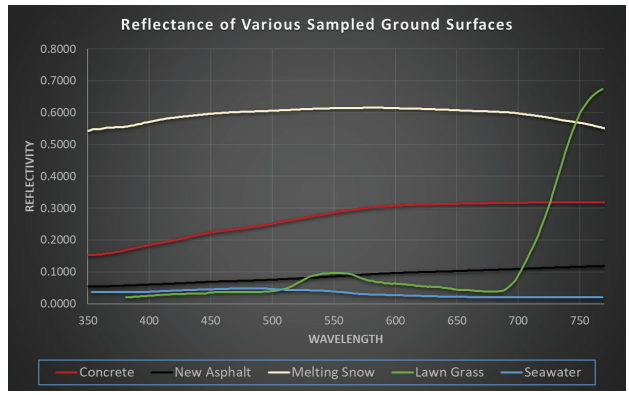


Figure 2-3. Measured diffuse reflection spectra for a sample of ground surfaces across the visible spectrum. (*Note*: Actual values depend greatly on the materials' intrinsic characters as well as other factors; see text for discussion.) (Data source: USGS; data for lawn grass below 380 nm omitted due to measurement issues.)

reflectance of the melting snow sample displayed in the figure, reflectance values for fresh snow can extend to as high as 90 to 95 percent, and worn samples or concrete and asphalt can have reflectances that are half the values shown. Variations appear and evolve quite rapidly within many high-reflectance materials as they age or become worn or dirty. Moreover, different forms of the same-labeled material (e.g., "grass" or "vegetation") may have widely varying characteristics even from the outset. A web search for graphed plots of "grass" and "asphalt" spectral reflectance, for example, yields multiple variations among the two, with the reflectance of grass sometimes exceeding that of asphalt over various portions of the visible spectrum, while other plots show almost the reverse.

Light sources are optimized for human vision, with most of their output falling within a relatively narrow wavelength range between 450 and 700 nm. A salient feature of **Figure 2-3**, which does not change regardless of the specific samples selected for plotting, is the wide disparity among average reflectivity values of the different surfaces within this range. **Figure 2-4,** displaying values calculated using the specific samples included in **Figure 2-3**, effectively illustrates that variations in reflectance make a larger contribution to the reflected radiant flux than do properties of the light source.

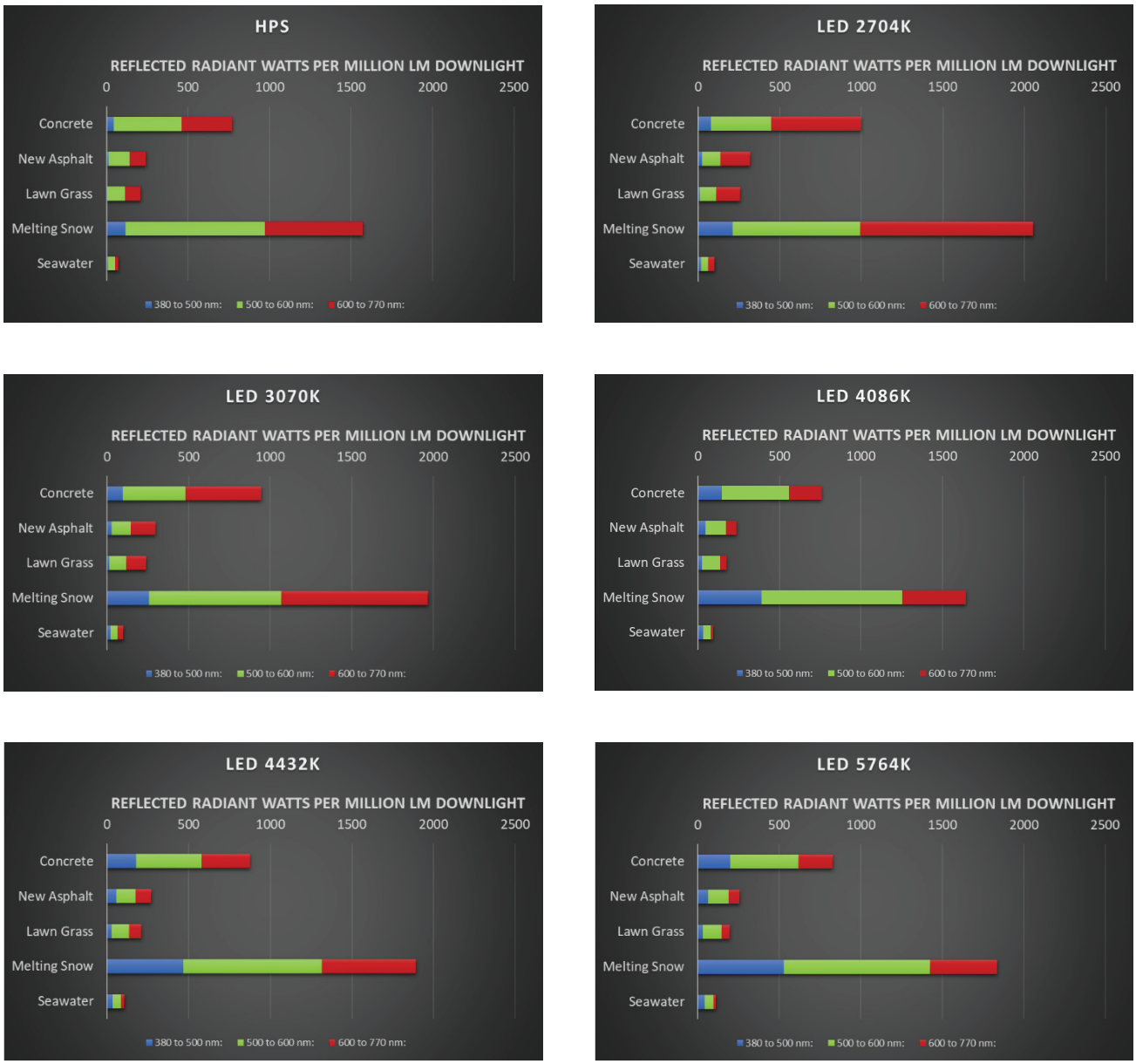


Figure 2-4. A range of normalized graphs for different SPD samples showing reflected radiant watts per million lumens of incident light for different ground coverings, based on the samples used in Figure 2-3, divided into three constituent wavelength bands. While varying the spectral content of the source influences the resulting properties of reflected light, much greater variation is driven by the type of ground cover encountered. (Sources: PNNL, calculated using CIE SPDs and USGS reflectivity data)

For practical purposes, a single value of reflectance (e.g., 10%, 15%) is often assumed, along with a perfectly diffuse or Lambertian distribution of the reflected light in order to simplify calculations. As previously noted, actual reflectance values and distributions present in any given instance may diverge widely from these conditions, however, with resulting influences on sky glow extending in either direction.

A more accurate method of estimating reflected light from surfaces involves the use of a bidirectional reflectance distribution function (BRDF). In this manner, increases in reflectivity of smooth surfaces (such as asphalt that has been worn by vehicle traffic) at shallow angles of incidence may be taken into account.

2.1.3 Scattered Light. Sky glow specifically results from scattered light reaching an observer. The degree to which a light ray is scattered or absorbed depends upon its spectral content and the amounts, locations, sizes, shapes, and chemical constituents of the particulate and gaseous components encountered as that ray travels through the atmosphere. More precisely, scattered light results from the combination of Rayleigh scattering, caused by air molecules (particularly the diatomic molecules of oxygen and nitrogen), and Mie scattering* from aerosols such as dust, smoke, and haze. Scattering is wavelength-dependent; the extent to which each of these phenomena occurs in a given instance depends on both the specific wavelength content of a light ray and the density and aerosol loading of the surrounding atmosphere (in turn influenced by additional factors such as altitude).

Rayleigh scattering in the atmosphere occurs with a probability approximately proportional to λ^{-4}, where λ is an individual wavelength. The physics of this relationship favors shorter wavelengths; the shorter the wavelength, the greater likelihood of Rayleigh scattering in air. The earth's sky appears blue to the human eye because of Rayleigh scattering; the setting (or rising) sun, on the other hand, appears to be reddish because Rayleigh scattering by many thicknesses of earth's atmosphere have scattered away much of the blue light.

Particulate scattering (Mie scattering), in contrast, is less dependent on wavelength and exhibits a strong forward anisotropy in angular distribution (see **Figure 2-5**). Multiple Mie scattering causes an otherwise clear sky to appear pale blue or white in heavily polluted urban areas and is responsible for the white or gray color of clouds (see **Figure 2-6**). Furthermore, scattering behavior varies between the two types, as depicted below. (See also **Section 2.2.1 Spectral Behavior in the Atmosphere**.)

* Mainly applicable to particle sizes comparable to or larger than the wavelength.

Figure 2-6. The change of sky color at sunset is caused by Rayleigh scattering by air molecules, rapidly attenuating the blue wavelengths from visible light. The gray and white colors of the clouds are caused by Mie scattering from water droplets, which are larger than the wavelengths of visible light. (Photo courtesy of Pacific Northwest National Laboratory)

2.2 Spectral Content

Relative to output and distribution, spectral content and its effects had not received as much explicit treatment or attention by the IES until the recent appearance of LEDs in exterior lighting applications. The spectral content of white-light LEDs vary greatly, but all have

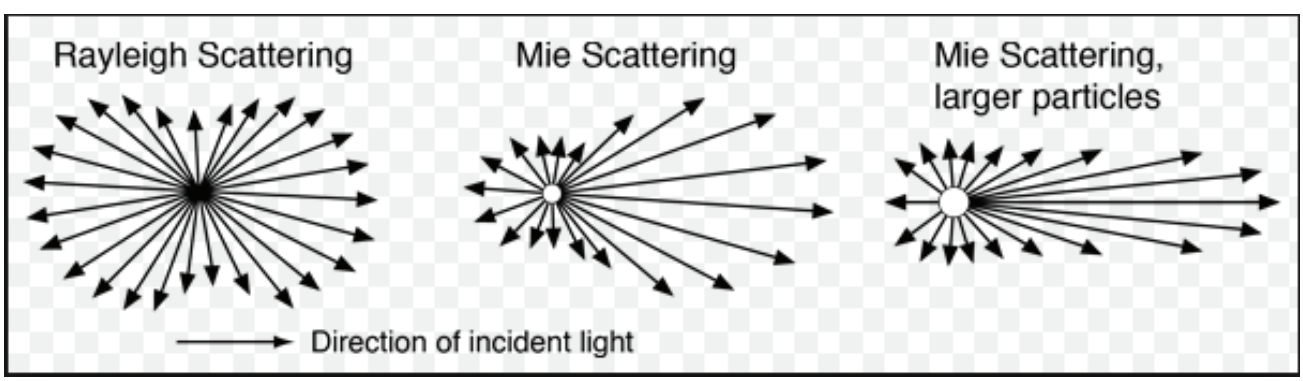


Figure 2-5. An illustration of Rayleigh vs. Mie scattering.

a greater short wavelength (or blue) content than the high pressure sodium (HPS) outdoor lighting products typically being replaced. Because blue light is more strongly scattered in the atmosphere, it is more likely to be eventually redirected back toward earth, creating the physical manifestation of sky glow. In addition, advances in biology are showing that many living organisms are sensitive to light at night, and particularly blue light. Spectral content and its potential effects thereby warrant additional, detailed attention here.

With the exception of low pressure sodium (LPS), all common light sources used for exterior lighting emit a range of wavelengths across varied segments of the visible spectrum. These are typically documented as the light source's spectral power distribution (SPD; depicted in graphical form in **Figure 2-7**), obtained from a spectroradiometric test of a given product. Broad-spectrum sources such as white-light LEDs, incandescent, fluorescent, metal halide, and even some later HPS products achieve a whitish appearance from the blending of colors corresponding to the collective wavelengths in those sources. It is impossible for the unaided eye to visually identify the specific wavelengths contained in different sources of the same correlated color temperature (CCT), yet each emitted wavelength retains its own individual properties and behaves the same as if it were emitted independently.

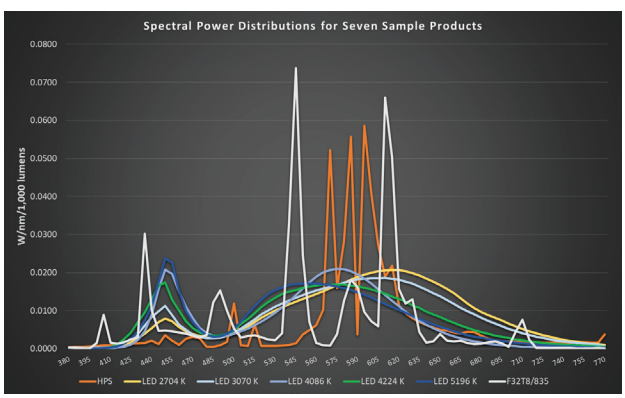


Figure 2-7. Spectral power distribution plots for seven sample products, normalized to 1,000 lumens of output. (HPS: high pressure sodium, 2200 K; LED: light emitting diode, various CCTs shown; F32T8/835: fluorescent, 3500 K, CRI > 80.) (Source: Spectral data obtained from ANSI/IES TM-30-20[7] dataset.)

2.2.1 Spectral Behavior in the Atmosphere. Because the amount of scattering varies according to wavelength, the spectral content of the scattered light is not identical to that of the source. Light of shorter wavelengths such as blue and violet scatters to a greater degree from the basic constituents of the atmosphere (primarily nitrogen and oxygen) than does light of longer wavelengths such as yellow and red.* Molecular (Rayleigh) scattering is fairly uniform in its angular distribution relative to the original direction of the light beam (see **Figure 2-5**, in **Section 2.1.3 Scattered Light**), with the result that a significant portion of the scattered light is directed back toward earth and becomes visible as sky glow.

Aubé[8] found that for the view toward zenith, the combined effect of Rayleigh and Mie scattering results in a wavelength dependency described by $\lambda^{-\alpha}$, where α varies from 3.6 to 2.7 as the distance from the center of an urban lighting source increases, as summarized in **Table 2-2.**

Table 2-2. Scattering Exponent Versus Distance From City Center

Distance (km)	0	5	10	20	30	50	80
Exponent α	3.60	3.59	3.58	3.59	3.35	2.85	2.70

While the tabulated values are derived from an assumption of standard atmospheric conditions (see original source for details), the Aubé model is sensitive to the weighted contributions of Rayleigh and Mie scattering. The reported range of values of the scattering exponent α (3.6 to 2.7) can consequently be expected to vary as nighttime sky conditions differ from the assumed standard conditions.† Future versions of this table or others like it may further refine the values

* Longer wavelengths also scatter and cause sky glow, but their effect tends to be more pronounced over longer distances. The latter effect is often observable as an orange-ish dome above populated areas when viewed from a distant location.

† The original use of the exponent was intended only to rank the relative contributions of different light sources to light pollution at given distances from the city center, and this original utility continues unaltered. The values in the table are for a relatively clear sky, as this gives the best viewing conditions for star viewing. Dirtier air will affect the values but are unlikely to affect the trend.

provided. It can be seen that shorter-wavelength blue light will be present in sky glow in a larger proportion closer to the source, while longer-wavelength red light may dominate sky glow from distant sources.

The greater short-wavelength content of broad-spectrum light sources has led to heightened concerns about potential corresponding increases in resulting sky glow, with LED getting the most attention due to its increasing prominence in the market. **Figure 2-8** displays the same comparison of product samples as in **Figure 2-7** but with the previous fluorescent and higher-CCT LED SPDs removed to better illustrate the source of present concern: the greater content of short wavelengths in the LED products relative to the HPS products they are most often replacing in street and roadway applications. *If all else remains equal* (see **Sidebar**), substituting one source with greater short-wavelength content for another source with less short-wavelength content will result in increased scattering and associated sky glow, especially in the immediate vicinity (defined as being within 5 to 10 km of the source by Bará et al.[9]).

SIDEBAR – If All Else Remains Equal

This is an important caveat, as most conversions do not maintain equality because of, for example, improved control over light distribution that typically enables newer luminaires to address the same application with substantially fewer lumens than previously needed. These reductions are typically manifested in reduced *average* illuminance levels (while still meeting specifications) and reduced off-target light spill. Lumen packages for modern LED replacements for HID equipment in street lighting applications, for example, are often half or less those of the incumbents. Supporting data can be found in virtually any LED luminaire manufacturer's product catalog.

After dusk, light visible in the sky originates from both natural and human-based sources. Because human-based light is usually intended to significantly increase nighttime illuminance over natural levels, the relative amounts of light provided by human-based sources tend to be much greater, and the influence of their

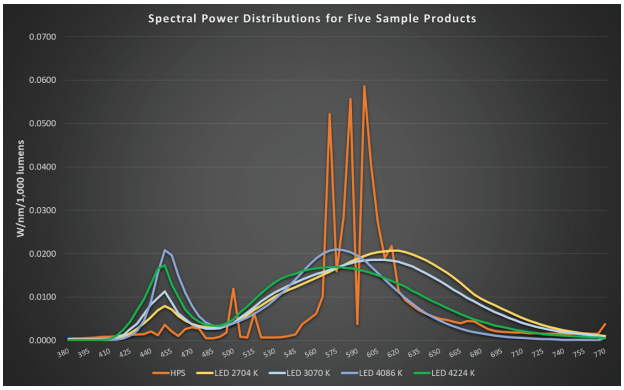


Figure 2-8. Spectral power distribution plots for five sample products. Similar to Figure 2-7, but with fluorescent and 5196-K LEDs removed for clarity. Most LED street lighting conversions in the U.S. are replacing HPS and emit a larger fraction in the blue region of the visible spectrum. While a general trend is evident among LEDs, where a higher CCT corresponds to a higher blue peak, this trend is not universal. For example, it may be noted that the blue peak of the 4224-K LED is lower than that of the 4086-K LED in this particular collection.

spectral content thereby generally dominates regional sky glow effects. Nevertheless, the amount of sky glow produced at any given location is a combined function of the intensity of all composite light beams (natural and human-based), the wavelengths they contain, and the precise makeup and character of the atmosphere in that moment, all of which contribute to the scattering behavior that underlies sky glow.

The effects of atmospheric scattering are evident in a set of sky glow SPDs captured outside the town of Hinckley, IL, approximately 76 km west of Chicago in August 2019 (see **Figures 2-9** and **2-10**).* At the time, Chicago was in the midst of a conversion of about 270,000 streetlights from HPS to 3000-K LED. These measurements represent a composite of both HPS and LED outdoor lighting, as well as contributions from all other sources exposed to the exterior environment. **Figure 2-9** shows the results of a near-horizontal reading, taken at only 4 degrees above the horizon, looking in the direction of Chicago,

* In **Figures 2-9** and **2-10** the relative magnitudes of the B and V bandpass filters used by astronomers to characterize the amount of light available in the blue and mid-range portions of the spectrum are shown as smooth curves. These bands and the magnitude values in the box in the upper corner are discussed in **Section 8.0 Glossary;** see *B band* and *V band*.

whereas **Figure 2-10** shows the results of a zenith (vertical) reading from the same location. It should be noted that the radiant power of the wavelengths in the zenith reading range only between about 1/50 and 1/100 of those of the near-horizontal reading, as indicated on the *y*-axes, and that they collectively amount to a reduction in the visibility of stars of 3.9 V magnitude in the comparative sky brightness according to the values at upper right in each chart (see **Section 8.0 Glossary**).

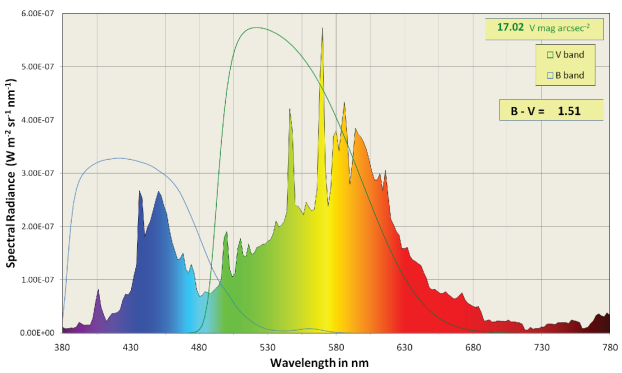


Figure 2-9. Near-horizontal spectrometer measurement of sky glow from Chicago in Hinckley, Illinois, 76 km distant, viewing at 4 degrees above the horizon. (Source: Night Sky Metrics, LLC)

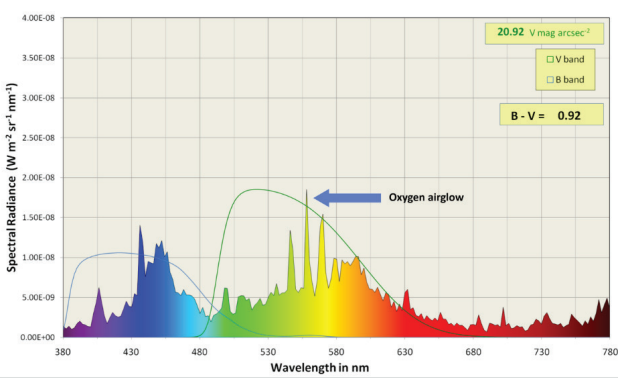


Figure 2-10. Zenith spectrometer measurement of sky glow from Chicago present over Hinckley, Illinois, 76 km distant. The low magnitude of this reading relative to the near-horizontal reading shown in Figure 2-9 increases the relative influence of natural contributions, such as indicated by the oxygen airglow line at 558 nm. (Source: Night Sky Metrics, LLC)

It is also important to point out that natural-sky brightness varies significantly on timescales of minutes or hours, including the ratios of natural-sky emission lines, and that the main cause of these variations is solar activity.

Clouds, even thin clouds, also have a major impact on sky brightness—by suppressing the natural sky glow and increasing scattering of light from anthropogenic sources. A rule of thumb is that in places with little or low light pollution, clouds make the sky darker. In places with more light pollution, downward reflection from clouds makes the sky brighter.

Figure 2-11 shows a "natural sky" reading from an entirely different location (Bishop, California), to provide a point of comparison with **Figure 2-10.** Under conditions of natural sky glow only, the oxygen and sodium airglow dominate the background sky brightness (see **Figure 2-11**). It also varies throughout the hemisphere, sometimes exhibiting banding or bright zones, and is brighter near the horizon than at the zenith. When comparing **Figure 2-11** with **Figure 2-10**, it can be seen that the airglow intensity was markedly greater at the Bishop site than at the Hinckley site.

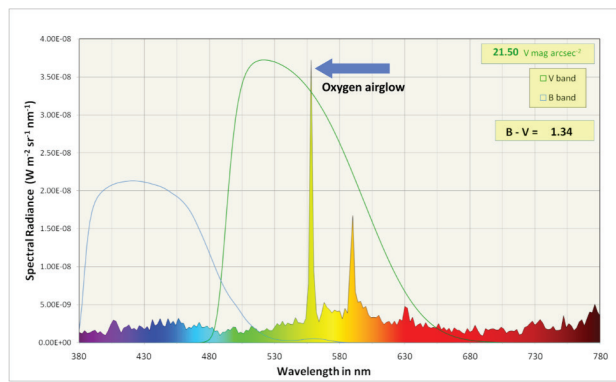


Figure 2-11. Zenith spectrometer measurement in Bishop, California. (Source: Night Sky Metrics, LLC)

Differences in the relative wavelength content of the light are also visible in the Hinckley measurements; for example, longer wavelengths (greater than about 530 nm) comprise a larger percentage of the near-horizontal reading than of the zenith reading. Shorter wavelengths tend to suffer random directional scattering more often within a light path along the horizon, and so are attenuated to a greater degree from the point of view of the observer than are the longer wavelengths.

In the zenith reading (see **Figure 2-10**), in addition to other light in the sky directly reaching the instrument, the observer sees a larger percentage of blue light, which is downward Rayleigh scattering of light from the source that has reached higher levels in the atmosphere. In contrast, longer wavelengths dominate the near-horizontal reading (see **Figure 2-9**) because: a) they propagate farther in the original direction from the forward bias of Mie scattering; b) shorter wavelengths in that same beam have already been partially filtered out by Rayleigh scattering on their way to this location 76 km distant; and c) the magnitude of light originating in the city overwhelms contributions from natural sources of sky glow, such as the oxygen airglow line visible in the zenith reading.

Consequently, natural sources of sky glow make a markedly greater contribution to the zenith than to the horizontal reading, as the measured brightness of 20.9 V magnitudes is much closer to an "unpolluted" sky brightness level of 22 V magnitudes (though not as close as the dark conditions apparent in **Figure 2-11**). The 17 V magnitude measured looking toward Chicago means a sky *100 times* brighter than natural, while the 20.9 V magnitude means a sky "only" about three times brighter than natural. The oxygen airglow line indicated at 558 nm, for example, presents the highest peak value in this chart, whereas it is indistinguishable among the other sources in the near-horizontal measurement (note also the order of magnitude difference between exponents in **Figure 2-9** and **Figure 2-10**). Natural sources are also the likely dominant origin of zenith wavelengths evident beyond about 700 nm.

2.2.2 Spectral Influences on Astronomical Observation. Like any light source, sky glow gains a collective SPD determined by its constituent wavelengths. The sky glow reaching an individual observer is a weighted aggregation of all scattered portions of light beams arriving at that observer's location from everywhere within the observer's collective field of view.

Increased brightness of the night sky due to sky glow obscures visibility of celestial objects by decreasing their contrast against the background luminance of the sky. Whereas the bulk of concerns of amateur astronomers might result from the aggregate effect of scattered wavelengths on overall sky visibility, particularly under the scotopic lighting conditions generally associated with stargazing activities, professional astronomy can also be substantially affected by individual wavelengths within that scattered whole. Naturally occurring sky glow happens to be very low in blue-green wavelength content (approximately 380 to 550 nm), and thus provides a "quiet zone" that ground-based astronomers use to obtain information with less natural interference than found in other ranges of the visible spectrum (see **Figure 2-12**). The entire range below the oxygen airglow peak at 558 nm is especially valued by that community, where an absence of interference from corresponding light in earth's atmosphere is critical for work involving deep imaging and spectroscopy.

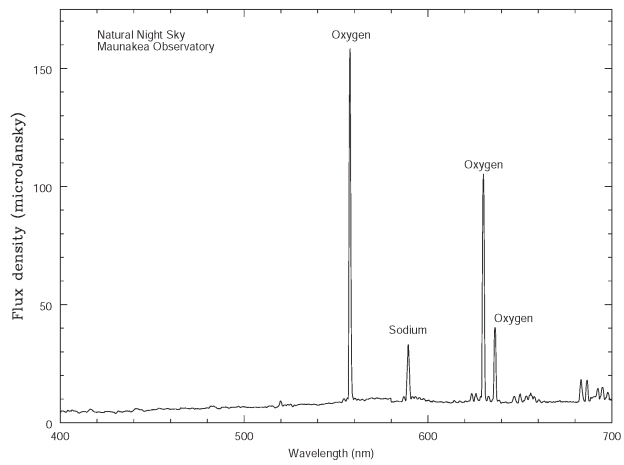


Figure 2-12. Natural sources of sky brightness above Mauna Kea Observatory, Hawaii (circa 1995). (Graph courtesy of Richard Wainscoat using data from Chuck Steidel)

Measuring the spectrum of a celestial object involves splitting the light arriving at a telescope into its constituent wavelengths. This might be done to identify the presence of specific chemicals or to characterize motion of distant objects, or for a variety of other reasons. Unfortunately, the additional wavelengths contributed by sky glow lower the signal-to-noise ratio or completely overwhelm the signal from cosmic sources (see **Figure 2-13**). Accurate determination of the light spectra originating at extremely faint celestial sources requires an unadulterated signal and is critical to the work of the astronomical community. (Human-based

ultraviolet sources, though not common at present, can be particularly damaging to astronomy due to high Rayleigh scattering.) Even a modest increase in brightness of the atmosphere can preclude measurement of the faintest objects from locations on Earth's surface. For this reason, the International Astronomical Union has recommended that the artificial sky brightness not exceed the natural sky brightness by more than 10% at any wavelength at major observatories.

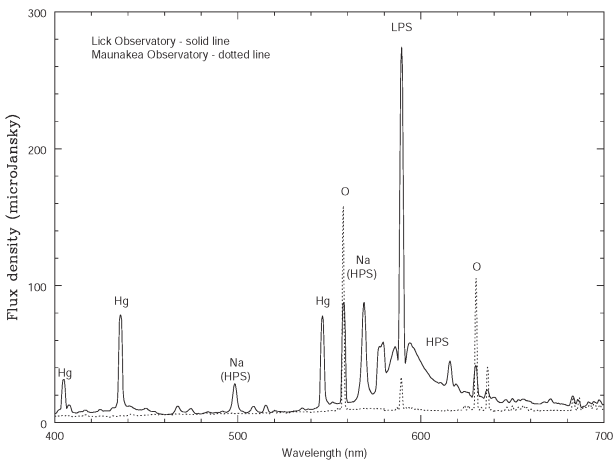


Figure 2-13. Night sky measured above Lick Observatory (California) reveals peaks from LPS, HPS and mercury vapor streetlights prior to San Jose's LED street lighting conversion (about 22 km distant). The natural sky above Mauna Kea (shown in Figure 2-12) is superimposed here as a dotted line, to illustrate the relative scale of anthropogenic vs. natural sources. (Graph courtesy of Richard Wainscoat using data from Chuck Steidel)

3.0 Characteristics of Lighting Applications

The properties of light reaching the night sky begin with those of the light emitted by a source or group of sources. As noted, sky glow results from all light entering the sky from both human-based and natural sources, with human-based sources tending to dominate when present. Street and area lighting, landscape lighting, sports lighting, billboard advertisements, building façade lighting, security lighting, and building interior lighting spilling out of windows are all applications that contribute to the total. Vehicular lighting also contributes, in some cases significantly. Often, the respective contributions are difficult to accurately measure and are therefore only roughly estimated or even ignored altogether in sky glow calculations. However, in urban settings any of these applications may be significant contributors to the whole (see **Figure 3-1).**

Figure 3-1. A city skyline contains many light sources. (Photo by Reynaldo #brigworkz Brigantty from Pexels)

As a result, the night sky is usually infiltrated by light from many source technologies, even some that are not commonly associated with exterior applications, such as fluorescent. This fact underscores the need for observations of existing sky glow conditions before attempting to predict the impacts of sky glow from a proposed new installation. An aggregate estimate of the existing human-based contribution might be generated by measuring the current sky brightness on a series of moonless nights (see **Section 6.0**), and then comparing the readings to the expected value of a natural sky to generate an estimate of the present cumulative human contribution. Any city contemplating a widespread change would be wise to go through such a process with highly qualified people.

3.1 Spectral Properties of Light Sources Commonly Used in Exterior Applications

The light sources listed in **Table 3-1** provide example properties for a variety of exterior lighting products. In this table, the properties reported are intended to be representative rather than comprehensive. Ranges are provided for white LED products because their properties are much less consistent than those of the older source technologies, with substantially greater

variability in spectral content. The reported ranges were derived from original laboratory tests of large samples of LEDs at each specified correlated color temperature (CCT) and included only products listed as "commercially available" in the ANSI/IES TM-30-18 dataset. The table indicates the number of LED samples underlying each nominal CCT; for instance, the tabulated range shown for Row A, White LED, 2700 K, is based on a tested sample of 50 products (as listed in the right-hand column), whereas 183 products underlie the ranges provided for 3000 K in Row B.

In order to eliminate outlier values, the LED ranges reported in the table at each nominal CCT have had the top and bottom 5% of samples in the original data set removed, based on their respective values in the % Blue category. This effectively consolidates the reported values into the main bulk of SPD samples in the data set. For example, while the table lists 183 sample SPDs at a nominal 3000 K, the original data set contains 203 SPDs at this CCT. About 10 of the original SPDs have been removed from each of the top and bottom "% Blue" contents in generating the ranges reported at 3000 K.

Table 3-1. Comparison of Spectral Properties of Common Light Sources, Normalized to 1,000-Lumen Output

Row	Light Source	CCT (K)	R_f*	% Blue**	No. of SPDs
A	White LED, 2700 K	2550 - 2850	≥ 70	0.06 - 0.13	50
B	White LED, 3000 K	2850 - 3250	≥ 70	0.07 - 0.16	183
C	White LED, 3500 K	3250 - 3750	≥ 70	0.10 - 0.19	65
D	White LED, 4000 K	3750 - 4250	≥ 70	0.11 - 0.23	86
E	White LED, 4500 K	4250 - 4750	≥ 70	0.16 - 0.25	35
F	White LED, 5000 K	4750 - 5250	≥ 70	0.19 - 0.29	34
G	White LED, 6500 K	6250 - 6750	≥ 70	0.22 - 0.36	15
H	Narrowband Amber LED	1606	2	0.00	N.A.
I	Low Pressure Sodium	1718	0	0.00	N.A.
J	PC Amber LED	1872	46	0.09	N.A.
K	Amber LED	1494	3	0.00	N.A.
L	2200-K LED 1	2162	77	0.06	N.A.
M	2200-K LED 2	2254	76	0.06	N.A.
N	2200-K LED 3	2209	71	0.07	N.A.
O	High Pressure Sodium 1	1959	34	0.12	N.A.
P	High Pressure Sodium 2	2041	42	0.09	N.A.
Q	High Pressure Sodium 3	2007	42	0.06	N.A.
R	Metal Halide 1	3145	83	0.19	N.A.
S	Metal Halide 2	4002	78	0.28	N.A.
T	Metal Halide 3	4041	90	0.27	N.A.
U	Mercury Vapor 1	6910	22	0.36	N.A.
V	Mercury Vapor 2	4035	49	0.35	N.A.
W	Incandescent	2836	99	0.07	N.A.
X	Moonlight‡	4681	98	0.23	N.A.

Table notes:

* R_f is an updated color fidelity metric defined and discussed in ANSI/IES TM-30-20[8] (see **Glossary**). The white LEDs selected for evaluation were limited to those with $R_f \geq 0.70$.

** The % Blue values pertain to a range of 380 to 500 nm and are based on radiant wattage emitted by the light source in those wavelengths. The values shown do not include the influence of atmospheric effects and therefore do not indicate the resulting percentage of blue light in any associated sky glow, i.e., they quantify only the original properties of the light source itself.

‡ Moonlight CCT provided by Telelumen, LLC.

Table source: The bulk of underlying SPDs were obtained from ANSI/IES TM-30-20 dataset; tabulation prepared by Pacific Northwest National Laboratory.

Because the table is normalized for lumen output, all the values listed can be directly compared among products on a lumen-for-lumen basis.*

Figure 3-2 provides graphs of four example LED SPDs at nominal 2700 K to illustrate the sort of variabilities indicated in **Table 3-1**. It should be noted that such variability is not described in the simplified descriptor CCT.

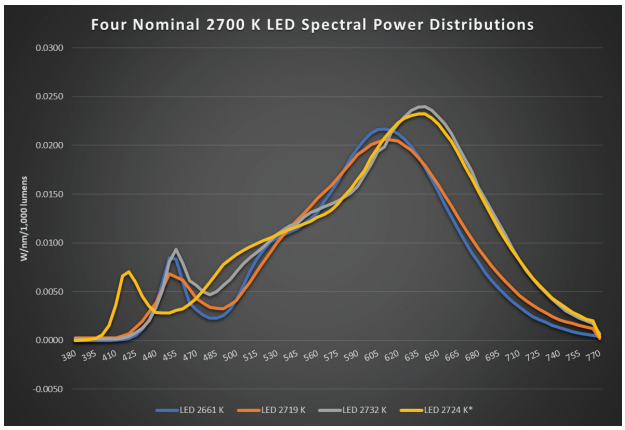


Figure 3-2. Spectral power distributions (SPD) of four LED light sources, all nominally 2700 K.
* ***Figure note*: The 2724-K sample is a violet-pump rather than blue-pump design; violet wavelengths are more subject to Rayleigh scattering than even blue wavelengths are, so this design is of potentially greater concern from an astronomical perspective.** (Graphic courtesy of Pacific Northwest National Laboratory).

Table 3-1 ultimately reveals that most common sources possess enough "blue" to pose similar potential concerns if their light emissions are not sufficiently controlled. The table also helps explain why sky glow is neither a new phenomenon nor attributable to any individual light source or application; indeed, with only a few slight exceptions, the % Blue values of all the listed sources fall within fairly narrowly defined ranges of other products at the same nominal CCTs, including LEDs.

* It is important to note that a similar caveat applies to this statement as was provided earlier: most conversions from HID incumbents to modern LED products are not "equivalent," but instead involve substantial reductions in the lumen package output of individual luminaires, often 50% or more in the example of street lighting. It should also be noted that LEDs are more easily dimmed than HPS luminaires, adding further opportunity for reducing exposures.

The data plot in **Figure 3-3** provides a further useful comparisons between the properties of white LEDs and those of the other (or "supplementary," a term that includes conventional, non-white LED, and moonlight) sources listed in **Table 3-1. Figure 3-3** reveals not only the range in "% Blue" within each white LED CCT but also how these compare against the other listed sources. It is important to note that, while a clear overall trend exists between CCT and % Blue content, significant overlap occurs among the values of adjacent CCTs (e.g., 3000 K to 4000 K). Other measures of potential interest, such as melanopic DER (refer to the **Glossary**), are also highly correlated to % blue.[10]

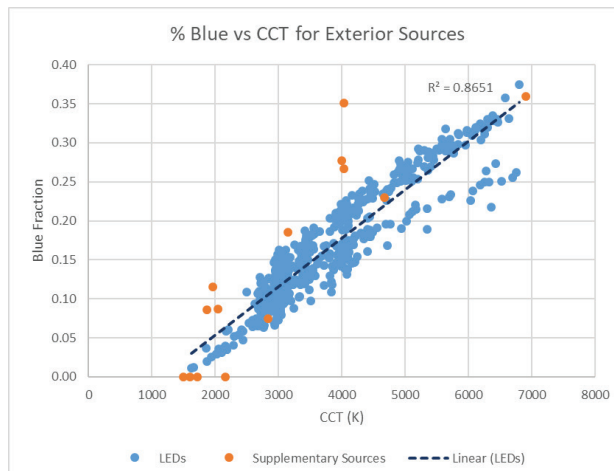


Figure 3-3. Percent blue vs. correlated color temperature (CCT) for numerous exterior lighting sources listed in Table 3-1. Here, "blue" refers to wavelengths between 380 and 500 nm. (Data source: Most data points drawn from ANSI/IES TM-30-20[8] dataset; plotting prepared by PNNL)

The plot in **Figure 3-3** also makes another point evident: while general correlations are apparent, so is the imprecise nature of CCT as a predictor of the exact spectral content and related properties of a light source. CCT provides a convenient shorthand way to describe the appearance of a light source, and the term enjoys an advantage of widespread familiarity, but close inspection of both **Table 3-1** and the plot in **Figure 3-3** show it is not a reliable metric for properties that depend heavily on the precise group of wavelengths present. In **Figure 3-3**, for example, the % Blue at 3000 K varies by more than a factor of 2.

3.2 Lighting Characteristics of Related Applications

Historically, a range of electric light sources appeared in the decades following the invention of a cost-effective incandescent lamp to meet the output levels and other characteristics needed by different lighting applications. Many have remained in use through multiple evolutions and are still in widespread use today. The situation is rapidly changing, however, led by the advent of LED lighting technology and its ready adaptability to almost any lighting application.

Despite this convergence, much diversity remains in the specific properties desired within each application. It is the intent for future versions of this and related documents to generally characterize each relevant lighting application and its associated influences on sky glow. Such characterizations will enable any location to detail the individual sky glow contributions arising from the relevant applications based on their respective quantities in that location, along with the means to estimate the collective result. The greatest opportunities for reductions in each location are thereby also clarified. The characterizations and proposed methodology for deploying them are described in **Section 4.0 Calculating Sky Glow from Lighting Characteristics.**

4.0 Calculating Sky Glow from Lighting Characteristics

As noted, sky glow originates from all light accumulated in the night sky. Numerous human-based lighting applications contribute to the total, each adding its own individual set of properties. The properties of light most relevant to sky glow include the predominant angles of travel (i.e., directional characteristics), quantity emitted, and spectral content. Each lighting application determines these properties and imparts further influence from their typical hours of use and the surfaces being illuminated.

At its most basic, the creation of sky glow occurs in two phases. The first involves the production and characteristics of light migrating into the sky from a given area, and the second pertains to how that light interacts with the atmosphere as it propagates away from its source to other locations.

4.1 Phase I – Production and Migration of Light Into the Night Sky

Quantifying results of the first phase requires a methodology that enables light from the various applications to be evaluated separately, so that the relative impact of individual installations can be evaluated and so that impacts from applications can be summed, despite wide-ranging differences in their properties. This allows for an overall view of the problem as well as each application's contributions to it. The key to deriving useful quantities here lies in a modular approach. Calculations begin on a micro level within each application and then aggregate to the macro level. For example, regarding light escaping building windows, calculations are conducted on a single representative window unit and then aggregated according to the number of windows (or units of window surface area) found on a representative building. Calculations may involve more than one representative window and/or representative building type, depending on the level of accuracy desired in the results.

Likewise, for vehicular lighting sources, the approach begins with detailing the light emission characteristics of an individual vehicle and then multiplying by the number of vehicles in the specific situation. As in the windows example, as many representative vehicle types can be detailed as deemed necessary. A modular approach enables customization of the analysis to the extent needed.

A convenient method for describing in an approximate way the directional characteristics of light output from each lighting application is derived from the IES Luminaire Classification System (LCS),[5] which includes the previously described BUG ratings. Because the directional characteristics relevant to sky glow are only a subset of those of the LCS, and no formal classification scheme is involved, the LCS emission zones can be consolidated into just four solid angles. The difference between forward and backward emissions, for example, does not usually describe a meaningful component of sky glow and thus enables this distinction to be disregarded.

Figure 4-1 shows the LCS zonal distribution categories, and **Figure 4-2** illustrates their consolidation into the angular information of principal interest for the purposes of sky glow.

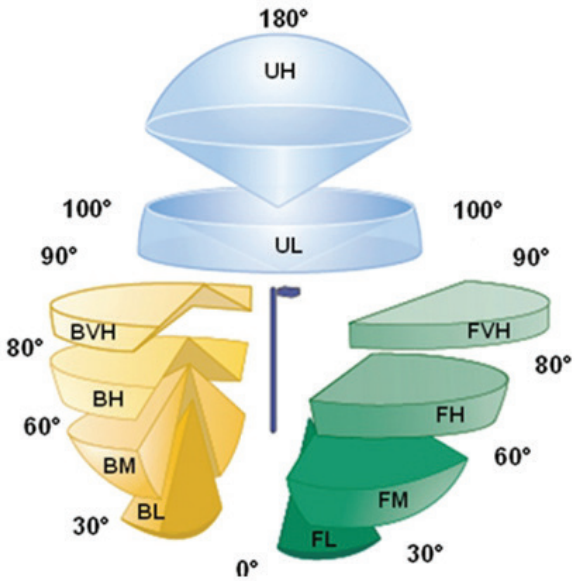


Figure 4-1. The distribution zones of the IES Luminaire Classification System. (© Illuminating Engineering Society)

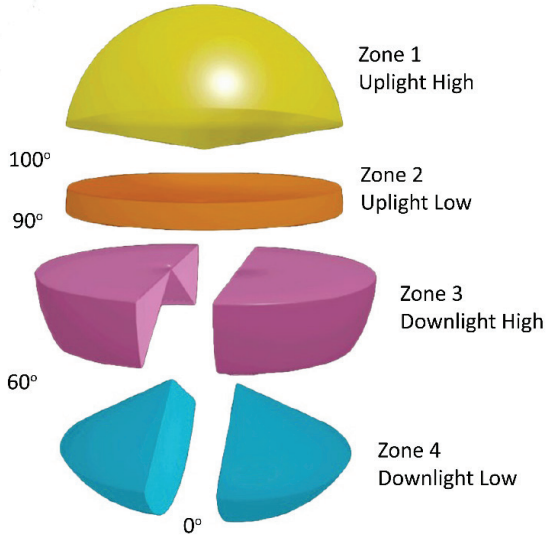


Figure 4-2. Four consolidated solid-angle emission zones for sky glow.

Generating an aggregate estimate of light migrating into the sky from each respective lighting application (or subcomponent of it) into the four solid-angle zones requires these steps:

1. Identify the relevant source technologies and associated flux and spectral contents used.
2. For each identified technology, detail the percentages of light output that are directed into each of the four solid angles indicated in **Figure 4-2.**
3. Multiply the quantities in Step 1 by the percentages in Step 2 to obtain the per-unit light output and initial directional distribution of the application at the micro (or unit) level.
4. Subtract percentage of light blocked, and account for that reflected.
5. Multiply the results of Step 4 by the relevant number of units to produce an estimate for the overall application, which may involve more than one step. For an estimate of the contribution of a building's interior lighting, for instance, the emission unit may be a single window (or unit of window area) that is summed over the entire building. The analysis may also require descriptions of multiple representatives or subcomponents within that application (e.g., high-rise offices as a subcomponent of all building types). Estimates for area-wide contributions from each such subcomponent then require multiplication by their respective quantities across the study area.
6. Where multiple subcomponents of the given application exist (e.g., high-rise offices, shopping centers, fueling stations, multifamily housing), Steps 1 through 5 are repeated for each as needed.

Ultimately, any methodology produces an estimate of light migrating to the sky from the overall application (e.g., the entire building sector) that includes total flux, angular distribution, and spectral content. The results for each application can in turn be summed into aggregate quantities, including the collective angular detail, across the area of interest. Contributions from individual lighting applications can then be examined and evaluated in the context of the whole. Use of this method provides an approximate and relatively simple way to do this analysis. The analysis can be made as simple or complex as desired, with the understanding that increased complexity also increases the workload. For example, users of the methodology may or may not prefer to distinguish between forward and back light

emissions in the downward direction, depending on the number of light sources being analyzed and the associated increase in complexity of calculating that distinction.

Key inputs to the procedure include accurate representation of the subject application (i.e., the source's lumen output, distribution, and spectral content; and physical characteristics of the target area such as type of ground cover). Also useful is knowledge of the area's existing aggregate level of sky glow (via careful measurement) to help in calibrating the results. The technique can be used at any scale; the user might be looking to estimate the isolated influence of a particular industrial plant located away from other light sources, for example, or to estimate the expected impact of converting a city's entire street lighting system. However, as the contribution of the subject application diminishes in magnitude relative to the contributions of the surrounding sources, measurement and estimation errors likely become a larger portion of the end result.

The aggregate quantity and properties of light entering the sky mark the end of the first phase in the creation of sky glow. Because emitted light is the primary driver, having such detail at this "gateway" enables useful interim assessment of a region's impact (or possible change in impact) to any sky glow that might result. This ability in turn enables identification of the best opportunities for addressing areas of special interest, such as minimizing light in the night sky that falls within specific ranges of spectral content.

The characteristics of light entering the sky also happen to coincide with the bulk of influence that society is able to exert via lighting system design and implementation. Other options, such as addressing the presence of certain atmospheric aerosols, e.g., smog or industrial particulates, while beneficial in their own right will generally not significantly alter the relative merits of designs that limit emissions of light to the sky. Moreover, all analyses, tools, and topics up to this stage in the evaluation are inherently familiar to the lighting community.

4.2 Phase II – Interactions of Light With Atmospheric Conditions

The second phase in the creation of sky glow is driven by the myriad atmospheric conditions encountered by the light entering the sky from the first phase. Subsequent calculations require additional understanding of atmospheric constituents such as aerosol particle size, shape, and density, and how these are affected by altitude and changing weather conditions such as temperature, rain, clouds, wind, and humidity. In general, uplight at low angles (Zone 2 in **Figure 4-2**) tends to directly produce more sky glow. Scattering is the physical mechanism causing sky glow (see **Section 2.1.3**), and light that travels through a longer path has a higher chance of being scattered. Low-angle uplight travels through the longest atmospheric path before exiting to space. Therefore, light in Zone 2 tends to produce more sky glow.[6] High-angle uplight (Zone 1) also causes sky glow directly, although its impact is better confined to the general proximity of the source and it scatters less on its shorter atmospheric path to space. Downlight in Zones 3 and 4 generally does not produce much sky glow. However, light that is emitted downward will reflect off the ground and other surfaces, and upward-reflected light will eventually contribute to sky glow (see **Section 2.1.2**). Accurate treatment of such dynamic interactions requires calculations of greater complexity than in the first phase and continues to be a focus of the scientific community as they strive for both better understanding and improved mathematical representation (see **Section 5.0**).

In the meantime, the simplest approach to estimating sky glow impacts employs assumptions that are based on standard atmospheric conditions. Aube´,[8] for example, incorporated such assumptions into the supercomputer-based Illumina model to derive ångstrom (Å) exponents for describing scattering behavior over a range of distances from the source (see **Table 2-2**). Such methods can serve as useful substitutes when the much higher computational strength demanded for calculating dynamic conditions is unavailable or proves too costly or complex (see **Section 5.0 Introduction to Modeling Approaches and Issues**). Future planned spreadsheet tools as companions to this TM and its descendant documents will likely incorporate such an approach.

5.0 Introduction to Modeling Approaches and Issues

Modeling of sky glow and its myriad components have been the subject of numerous peer-reviewed articles in the recent past.[8,11,12] Approaches often vary in the level of complexity pursued in the different influences considered, for example, focusing on only single-scatter vs. multiple-scattering events, or representing urban areas as symmetrical and uniformly emitting surfaces vs. having more true-to-life shapes and emission profiles. This section describes some of the specific challenges confronted in modeling sky glow and a few current approaches to addressing them.

5.1 Variability and Uncertainty in Estimating Scattering

Some degree of variability in light scattering occurs as a function of both location and time. Variations in modeled results stem from differences in the selection of the physical conditions, such as the estimated distribution of particulate levels at different altitudes, and from the methodologies chosen for estimating light scatter at fixed particulate levels (typically derived from standard conditions).

With the exception of water vapor, the molecular makeup of the bulk atmosphere is essentially fixed. Water vapor in the atmosphere over the United States typically ranges from near zero to about 80 mm of liquid if all the liquid in a column of air were precipitated as rain.[13,14] Because very high levels of precipitable water usually correspond to clouds and rain, the variation in molecular scattering from atmospheric water vapor generally remains about one percent or less.

Although the overall mass of the atmosphere is effectively constant, its density varies spatially as well as temporally. The biggest source of natural variability in its density is altitude. The reduction in density that naturally occurs with increasing altitude strongly influences the amount of light scattering at moderate or large distances from a source. Changes in the altitude of a source or of an observer's viewing position determine the total atmosphere above that location and thus the amount of light that scatters to it.

5.1.1 Wavelength Dependence. Particle size is an important determinant of the specific scattering behavior exhibited by a given light beam impinging on that particle. Light scattered via the molecular components of the atmosphere (primarily nitrogen and oxygen) follows the Rayleigh scattering distribution with a strong wavelength dependence. Over the approximately 2:1 wavelength range of the visible spectrum, the shortest wavelengths scatter almost 17 times more strongly by molecules alone than do the longest ones. In contrast, light scattered from larger particulates such as dust, smoke, and aerosols follows the Mie scattering distribution and exhibits a much weaker dependence on wavelength.

Particulate sizes tend to be smaller at low humidity levels, but even at zero humidity with very fine particulates, the range in scattering efficiency over the visible spectrum appears to be at most 3:1, again with shorter wavelengths scattering more strongly than longer ones. For moderate humidity levels in urban environments the wavelength dependence drops to 2:1, and for maritime environments at near saturation humidity levels the Mie scattering may be essentially independent of wavelength.[15]

The wavelength distribution of scattered light is also affected by absorption and its selective removal of wavelengths that would otherwise be scattered. The absorption of light passing through a medium (e.g., air) is expressed in terms of the absorption coefficient of the medium. Absorption coefficients are expressed in units per centimeter-atmosphere (cm-atm), which represents the amount of gas present at standard temperature and pressure (273.15 K and 101.235 kPa) in a path 1 cm long.

The absorption spectra of the trace atmospheric gases ozone (O_3) and nitrogen dioxide (NO_2) are shown in **Figures 5-1** and **5-2**, respectively. The absorption coefficients are shown per cm-atm. **Figure 5-1** provides the estimated absorption coefficient for ozone from 380 nm to 780 nm. Absorption is an exponential function of the absorption coefficient multiplied by the amount of gas measured in cm-atm along a given path.

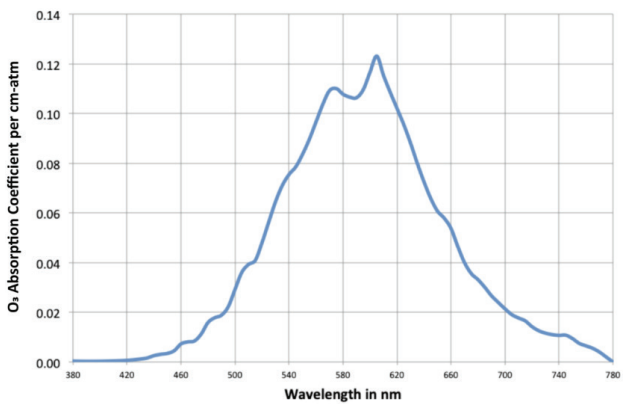


Figure 5-1. Estimated absorption coefficients from earth to space for ozone (O_3) as a function of wavelength. (Graphic courtesy of Robert Clear; data sources: McClatchey[16] and National Renewable Energy Laboratory[17])

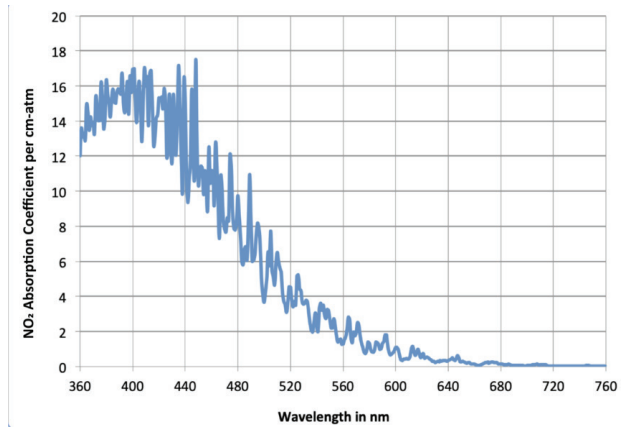


Figure 5-2. Absorption coefficients for nitrogen dioxide (NO_2) as a function of wavelength. (Graphic courtesy of Robert Clear; data from Rudek et al.[18])

The reduction in scattering caused by ozone is negligible. Ozone is produced both naturally and by anthropogenic sources as a small component of photochemical smog in the troposphere. However, even a concentration at the EPA-approved one-hour limit of 120 ppm (0.012 cm-atm/km) extended up to 2 km in elevation only decreases light scattering by 2%.

Nitrogen dioxide is primarily a pollutant produced via fuel combustion from stationary and mobile (vehicular) sources, although minor amounts are also produced during lightning strikes. Only in smog-prone areas do concentrations become sufficiently high to be noticeable.

Figure 5-2 shows the corresponding absorption coefficients of nitrogen dioxide over the range of 380 to 780 nm. Whereas absorption by ozone peaks in the middle of the visible spectrum, nitrogen dioxide best absorbs in the deep blue to ultraviolet range and has a peak absorption 100 times that of ozone.

Because nitrogen dioxide concentrations are high near ground level and drop rapidly with height, however, much of the light absorption by nitrogen dioxide happens before scattering can even occur.

Thus, like ozone, the ultimate effect of the atmospheric presence of nitrogen dioxide on scattering is negligible.

5.1.2 Source Emission Angle. The greatest predictor of sky glow is the angle of emission from the source, which determines the amount of atmosphere and associated constituents a light beam will encounter before being absorbed, scattered, or emitted into space. **Figure 5-4** plots the estimated ratio of source lumens for a clear sky that are backscattered to the earth to emitted source lumens as a function of the emission angle for the five sources depicted earlier (refer to **Figure 2-7** in **Section 2.2 Spectral Content**), ranging from HPS and mercury vapor lamps to a metal halide and two LED sources (note that the two LEDs are slightly but not significantly different from those shown in **Figure 2-7**). Despite substantial variation among their spectral power distributions, their scattering effects are very similar because of the dominance of the length of travel path that results from the emission angle.

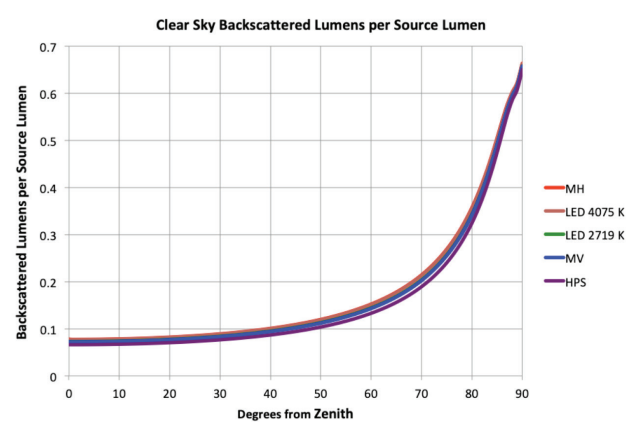


Figure 5-4. Estimated photopic backscatter for the five light sources shown in Figure 2-7 (in Section 2.2 Spectral Content). (Graphic courtesy of Robert Clear)

Graphs similar to the one shown in **Figure 5-4** could be provided for the fraction of backscattered-to-source melanopic radiation or backscattered-to-source scotopic illuminance as a function of the angle from zenith. However, the fairly large range in effective melanopic watts or scotopic lumens per photopic lumen (M/P and S/P, respectively) of these sources serves more to simply separate the curves rather than change their basic shapes when the ratio (y-axis) is defined in terms of the source photopic lumens. For broadband light sources, the amount of backscattered melanopic or scotopic radiation continues to be primarily determined by the angle of emission of the source, followed next by either the M/P or S/P of the source, respectively, rather than the source's precise spectral power distribution or the atmospheric efficiency of scattering different wavelengths.

5.2 Models and Approximations

The development of models for sky glow began in the 1970s and 1980s. The primary goal of early models was to estimate the impact of a source, such as a city, on the sky brightness of a remote location, such as an observatory, in terms of astronomical visibility.

Garstang's seminal 1986 paper[19] relied on several key simplifications, the first being an approximation of the source as a uniform circle with an estimated light output equal to a linear or power-law function of the population (i.e., lumens per capita). An empirical function was used for the angular distribution of the source light, and molecular and particle densities of the atmosphere were both modeled as single exponential distributions. Scattering was calculated at a single wavelength (550 nm), and the angular scattering function for particulates was approximated by a three-section fit to a reference model, which in turn was based on a model particle size distribution and a Mie theory estimate of the resulting integrated angular distribution. The calculations assumed a flat Earth and were based on a single scatter event plus an approximation for a second scattering event. Garstang improved the initial methodology with an earth-curvature correction factor in 1989.[20] Garstang's methodology continues to underlie many modeling efforts today.

While improvements to his approach have been ongoing since its introduction, some refinements have more impact than others. For example, while improvements in computing power have made it easier to assume a spherical rather than flat earth, the improvements in accuracy are most likely small. In particular, a calculation for a horizontal ray with minimal scattering (clear sky and 700-nm light), regardless of its location on earth, shows the total fraction of light scattered to ground from a single scattering event differing by only about 3% between the two models. Increasing the amount of scattering through assumed greater turbidity further reduces this difference between the flat-earth and spherical-earth models to only about 1%. On the other hand, increased computational power has greatly facilitated the necessary calculations of scattered light in terms of melanopic, scotopic, photopic, or any other desired wavelength sensitivity function. This is a benefit for amateur sky-gazers, wildlife researchers, and all other special interests.

An advanced research model cited in recent literature is Illumina, developed by Martin Aubé at the University of Sherbrooke.[8,21] Like the original Garstang model, Illumina computes sky glow at a distant location from a dispersed source such as city but has incorporated several major refinements. The first accounts for topographic features that prevent direct light from the source from being directly visible at that distant location. The model also allows adjustment of calculated absorption and scattering optical depths in order to match measured values. A third important refinement is the explicit ability to calculate two scattering events rather than only one, although this feature increases the required calculations exponentially. In order to keep the problem tractable, other factors needed to produce the results in the 2015 Aubé paper[8] were kept simple: a uniform ground reflectance with a Lambertian angular distribution, a circular city of fixed size, and a set of just five wavelengths for estimation of wavelength dependencies. This remains a very computationally intensive model, however, and the results in the paper still required several weeks of supercomputer time.

Another recent modeling approach, under continuing development, is from Miro Kocifaj at the Slovak Academy of Sciences.[11,12,22,23] This approach employs an inversion technique for converting remote sky-brightness measurements over a source (e.g., an urban

area) into original emission characteristics (spectrum, angle, geometric spread) from that source. Whereas spot measurements at distance are not only subject to the characteristics of the emission but also to any light-scattering phenomena between the measurement point and the source, this inversion method allows for systematic characterization of the light-emitting source itself. Once characteristics at the source are determined, numerical prediction of properties of sky glow across a range of distances is possible.

Garstang's model and the work described above provide an estimate of the impact of sky glow at a distant location from an existing dispersed source. The Pacific Northwest National Laboratory (PNNL) has developed a spreadsheet tool based on Kocifaj's work that compares the impact of changes in sky glow from different luminaire characteristics at two potential locations: the city perimeter and 40 km away from the city center. This relatively simple Sky Glow Comparison Tool (see **Annex A**) provides an ability to compare the sky glow influence of one luminaire against the relative influence of one or more alternative luminaires. The comparison tool does not provide strictly quantitative values but instead relative values (i.e., percent increase or decrease in resulting sky glow impact) and is primarily intended as a simplified method to help in the design of systems that will produce less sky glow.

In response to growing interest in estimating sky glow over wider areas, another program has been developed for an outdoor luminaire manufacturer that computes the total amount of radiation that scatters back to earth, regardless of location, as a function of the angular distribution and spectrum of the source light. This program uses the same assumptions of a homogeneous sky and Rayleigh and Mie scattering distributions as the original Garstang model, but performs a numerical integration of all scattering angles to determine the backscattered flux to the ground from the first scattering event. Molecular and particulate absorption are ignored in this program, given that absorption is a relatively small effect except under conditions of heavy smog or particulate pollution. As such, the accuracy of the backscattered light will be far more accurate for clear skies and long-wavelength light than for conditions that produce large amounts of second- and higher-order scattering. The program may eventually include a procedure to handle such higher-order scattering but presently does not.

The IES Sky Glow Calculations Committee is developing a very simple spreadsheet tool based on this latter work, which will estimate the backscatter fraction as a function of angle. That tool is expected to be available with a future update of this TM.

6.0 Means of Measuring Sky Glow

The measurement of the radiance reaching an observer on the ground from the night sky via natural and artificial sources is an important component in evaluating the environmental impact of outdoor lighting. Such measurements also contribute to the verification of or as input to models, tracking long-term trends, and identifying thresholds for protection of the natural nocturnal environment. For a given outdoor lighting project, measurements before and after the installation provide an accurate means to assess the effectiveness of sky glow mitigation measures employed in the design. This section first introduces the human visual perception of sky glow and its effect on the ability to observe natural features in the sky, then discusses methods for measurement and interpretation of sky radiance with references to available instruments.

6.1 Human Visual Indicators of Sky Glow Impact

The human eye-brain combination is an excellent instrument for measuring sky brightness at night. Sky glow directly affects the visibility of stars; thus, observations of them provide a good first estimate of the quantity of sky glow. At least semi-quantitative evaluation of sky brightness may be achieved by an observer with the unaided eye, a little training, and sufficient time to complete the observations. With the addition of observations of standard stars of known brightness, precision and accuracy are improved. The deviation of the appearance of the night sky from its natural appearance (that is, a sky free of artificial sky glow) may be quantified in terms of certain classes of

objects, or *indicators*, in the natural night sky. Two of the visual indicators that may be observed or modeled from photometric measurements and that also relate to the cultural, historic, and spiritual value of natural night skies are the naked-eye limiting magnitude and the number of stars visible.

6.1.1 Naked-Eye Limiting Magnitude. Naked-eye limiting magnitude (NELM) is a commonly reported indicator of sky quality. It is usually based upon actual visual observations made by individuals but also may be accurately modeled from background sky brightness measurements. It is reported in the astronomical photometric system of V magnitudes (see **Glossary**). It is often generally accepted that the faintest stars that may be seen by the dark-adapted human eye using averted vision are of 6th magnitude.[24] However, documentation of related observations of much fainter stars exist in the literature. The professional astronomer H. Curtis observed stars fainter than magnitude eight under tightly controlled conditions at Lick Observatory in California in 1901.[25] Stephen James O'Meara writes that his own observations at the 9,000-ft (2,743-m) elevation level on Mauna Kea, Hawaii "consistently detected stars as faint as magnitude 8.4 with the unaided eye."[26]

A technique known as averted vision is required to detect such faint objects. It is a method where the rods in the retina are primarily used rather than the cones, which are used with direct vision.[27] The rods are much more sensitive to photons than the cones (if properly dark-adapted), typically by 30 or 40 times. O'Meara reports that stars 3 magnitudes fainter may be seen with averted vision than with direct vision.[26] It is important to note that the rods are also more blue-sensitive than the cones, following the scotopic response curve, and dark adaptation is more severely affected by blue light than red light. Therefore, sky glow with a blue cast will be more effective in masking fainter stars.[28]

Specific methods for obtaining NELM visually in the field are given by various authors,[27,29-35] and large world-wide databases have been constructed and used effectively for scientific research and verifying models.[36]

The relation between NELM and sky brightness has been investigated and modeled. Specifically, a model that predicts the NELM based upon background sky brightness is a useful tool that may be employed if brightness measurements made by an instrument are available for the area near a particular star of interest.[37-40] A verification of one of these models with simultaneous observations of NELM and sky brightness has been reported.[41] These observing recommendations and models all use the dark-adapted averted-vision method of detecting faint stars.

The U.S. National Park Service (NPS) has conducted a program of sky brightness measurements with a CCD camera concurrent with visual observations by experienced observers using averted vision and after a period of dark adaptation, from 2001 to present (the data remain unpublished). These studies resulted in a one-parameter model, following the methods of Garstang,[38] which may be employed to predict the NELM at a given location in the sky if the sky brightness is known in V magnitudes per square arc second (V mag/arcsec^2). **Table 6-1** shows a wide range of brightness values with the associated predicted NELM for each.

Table 6-1. Predicted Naked-Eye Limiting Magnitude Given Background Sky Brightness

μ_{sky} (V mag/arcsec^2)	milli-cd/m^2	NELM (m_o) (V mag)
22.5	0.11	7.55
22.0	0.17	7.21
21.5	0.27	6.92
21.0	0.43	6.67
20.5	0.68	6.45
20.0	1.08	6.23
19.5	1.71	6.01
19.0	2.71	5.79
18.5	4.30	5.54
18.0	6.81	5.28
17.5	10.80	4.99
17.0	17.12	4.68
16.5	27.13	4.34
16.0	43.00	3.99
15.5	68.14	3.62
15.0	108.00	3.24
14.5	171.17	2.87
14.0	271.28	2.51

Table notes: Predicted naked eye limiting magnitude (NELM), m_0, in V magnitudes given background sky brightness, μ_{sky}, in V mag/arcsec^2, derived from a polynomial fit to measured background sky brightness and visual observations made by the U.S. National Park Service. The NELM values used by NPS assume a skilled observer with at least 30 minutes of dark adaptation using averted vision, and have been corrected for extinction (extinction coefficients and the locations in the sky were always known and recorded during observations). Values in V mag/arcsec^2 are converted to luminance according to: [value in cd/m^2] = $10.8 \times 104 \times 10^{(-0.4 \text{ x [value in mag/arcsec^2])}}$.

6.1.2 Number of Stars Visible. While the visual limiting magnitude of stars near the zenith is a common indicator of the amount of artificial sky glow, the total *number of stars visible* over the hemisphere of the sky is a more meaningful measure of night sky quality. In dark locations, a total enumeration is extremely difficult to complete by an individual observer, although sampling methods have been employed using a tube or pipe as a mask that reveals a known area of sky and counting the number of stars in a sample of areas.[42] A theoretical number may be derived based upon methods such as those presented in **6.1.1 Naked Eye Limiting Magnitude** applied over the whole sky, as suggested by Cinzano and Falchi.[43,44]

The U.S. National Park Service sky brightness monitoring program (see **Section 6.1.1**, last paragraph) calculates and utilizes the ratio "percent reduction in number of stars visible" as an important indicator of the amount of sky glow. The single-parameter (sky brightness at each star's specific location in the sky) method described in **Section 6.1.1** is run for a natural sky with no artificial sky glow,[45] and the result is compared with the amount obtained using the observed sky brightness over the hemisphere for a particular data set.[46] The method predicts progressively smaller numbers of stars visible as artificial sky glow increases, with a reduction of 92% in urban areas such as Washington, D.C. It is acknowledged that the method will over-estimate what an individual observer might actually count by 10% or more, primarily because many individual stars in the catalog are too close together in the sky to be resolved by the human eye and are generally seen as one.

The Bortle Scale is a semi-quantitative visual rating system of night-sky quality using integers ranging from 1 to 9 and is partially derived from the indicators discussed in the two preceding paragraphs. Class 1 is pristine, or free of artificial sky glow, and offers ideal observing conditions. Class 9, by contrast, represents an inner-city environment surrounded by bright outdoor lighting where the entire sky is awash in sky glow and celestial objects are nearly obliterated. First proposed by John Bortle in 2001,[47] the system has retained popularity among amateur observers.[48] Moore and Duriscoe[49] examined correlations between Bortle class and photometric measures and concluded that visual observations are much better at resolving the classes where sky glow is slight than at brighter sites.

Data and graphic representations from six different observing sites are shown in **Figure 6-1**, demonstrating the effectiveness of the "number of stars visible" indicator. The six examples approximately span Bortle Classes 1 through 7, and all are from protected areas managed by the National Park Service. It can be seen from the images in **Figure 6-1** that the zenith sky brightness does not significantly reduce star visibility until example ***d*** or ***e***, where the total number of stars visible has been reduced to 62% and 27%, respectively. This implies that zenith-limiting magnitude is not a very sensitive indicator in rural sites where domes of light from distant cities ring the horizon. The 6th example, ***f***, near Morristown, New Jersey, is about 35 miles from New York City and is considered a rural area.

Table 6-2 lists actual observations from the National Park Service for the six sites depicted in **Figure 6-1**, plus an urban site managed by the NPS, Rock Creek Park in Washington, D.C. The table includes observed NELM (see **Section 6.1.1**), Bortle class, and zenith brightness. NELM changes little until class 5 or 6 is reached. In addition, the commonly used value of magnitude 6 for NELM of "average observers" at dark sites is nearly achieved under Bortle class 7 skies. These data demonstrate the weakness of using zenith NELM or zenith brightness measurements as an indicator of sky glow severity over the entire possible range of values. Also, while Bortle class more accurately captures the range at darker sites, under more severe sky glow the amount of sky glow is more difficult to estimate using visual methods alone.

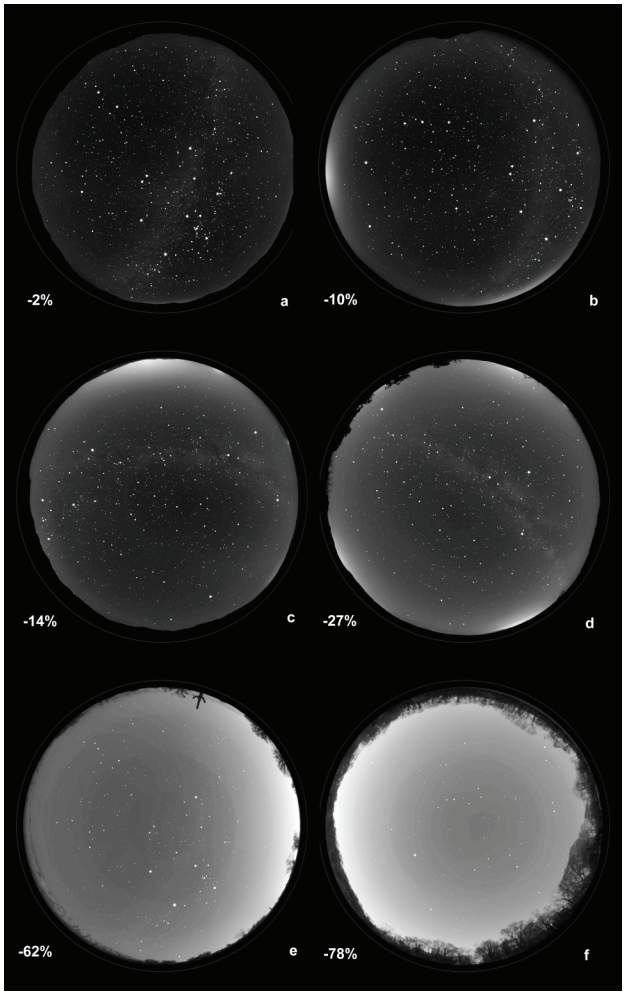


Figure 6-1. Graphic representation of reduction in number of stars visible at six different sites ranging from pristine (a) to suburban-rural (f); the theoretical reduction in the number of stars visible is shown to the lower-left of each image. The sky brightness depicted is from calibrated all-sky imaging; the stars are simulated based upon the time, date, and location of each observation. (Image courtesy of Dan Duriscoe)

Table 6-2. Observational Data from Seven Observing Sites

Location	NELM	Bortle Class	Zenith Brightness (V mag/arcsec^2)	Percent Reduction in Number of Stars Visible
Death Valley National Park – Eureka Valley	7.2	1-2	21.71	2
Death Valley National Park – Dantes View	7.2	3	21.82	10
Mojave National Preserve – Ivanpah	7.1	4	21.37	14
Bandelier National Monument – Fire Lookout	6.8	5	21.17	27
Saguaro National Park – Mica View Picnic Area	6.7	6	20.13	62
Morristown National Historical Site – Jockey Hollow	5.9	7	19.36	78
Rock Creek Park, Washington D.C.	5.2	8	17.70	92

6.1.3 Comparing Indicators. The indicators discussed in **Sections 6.1.1** and **6.1.2** are conveniently compared in a nomogram by Henk Spoelstra,[50] reproduced here as **Figure 6-2**. It is important to note that a Bortle class "4.5" is created to resolve ambiguities in the original work. The "approximate visible magnitude" scale is also placed somewhat conservatively compared to the NPS observations listed in **Table 6-2**. Whereas NPS values assume a "skilled observer," Spoelstra's values are more intended to represent those of "lay observers." A particularly useful aspect of Spoelstra's nomogram is that the first three columns directly compare magnitudes, luminance, and brightness factor to a "natural sky."*

* There is some debate over what properly represents a "natural sky." Spoelstra used a value of 0.25 mcd/m^2 or 21.6 V mag/arcsec^2, for example, whereas Falchi in 2016[76] used 0.17 mcd/m^2 or 22.0 V mag/arcsec^2. Various papers also note a relationship between CCT and the conversion of cd/m^2 to V mag. (Bará S. DOI: 10.26607/ijsl.v19i2.77; Bará S. DOI: 10.4302/plp.v11i3.926.)

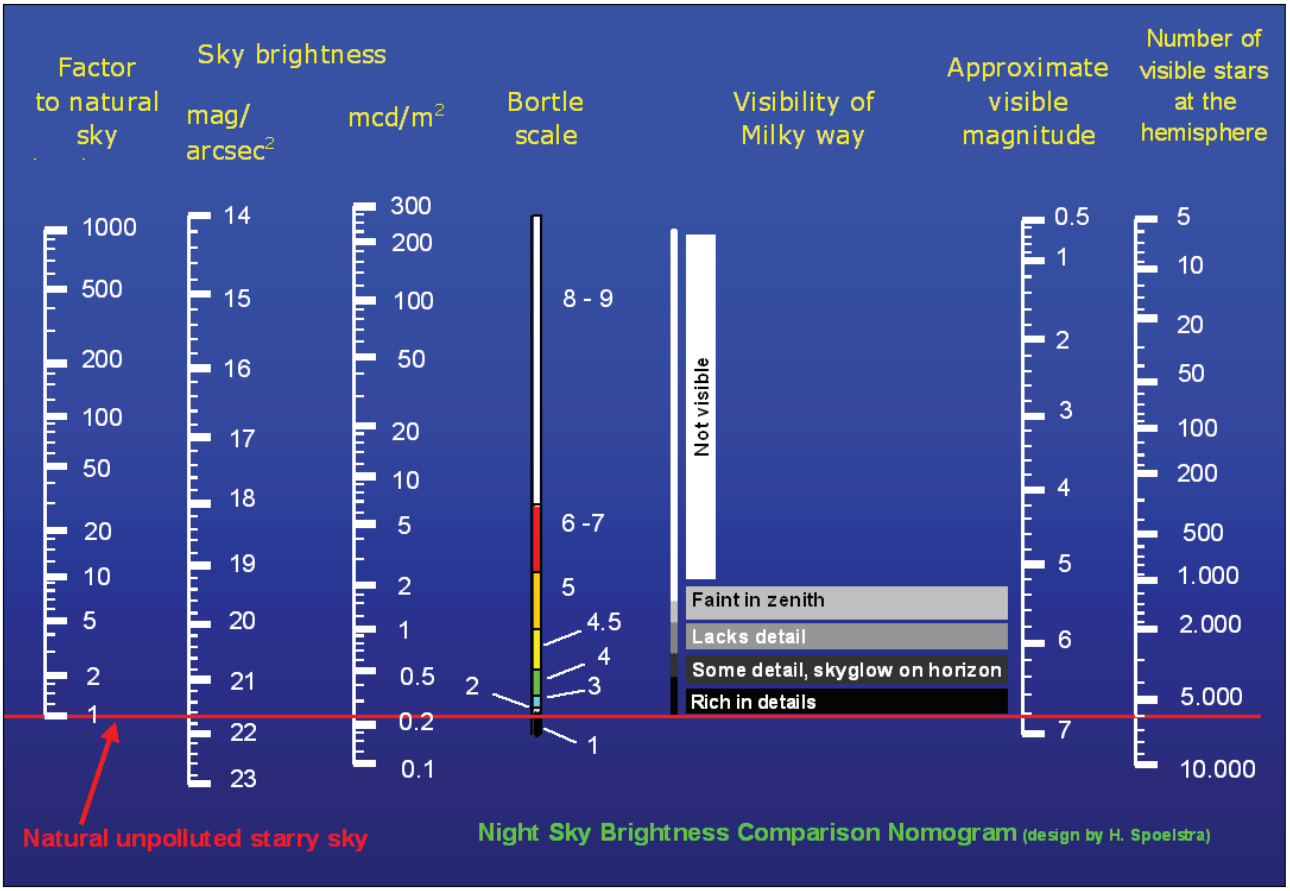


Figure 6-2. A nomogram designed by H. Spoelstra that compares at a glance visual indicators of sky quality with sky brightness measurements. A detailed explanation is available on the Dark Skies Awareness website.[51]
(Image courtesy of Henk Spoelstra*)

* Mr. Spoelstra notes that this nomogram was produced around 2007 from the various scales found on the internet and should be used only for general correlation purposes. For example, the approximate visible magnitude assumes values for an unexperienced rather than experienced observer who might see higher magnitudes with a dark-adapted eye.

6.2 Night Sky Radiance Measurement

Accurate measurement of sky radiance over the entire hemisphere of the sky may be obtained using broadband and narrowband radiometric instruments. A recent review paper describes many of the most recent instruments in detail.[51] A summary of the types of measurements that may be taken and references to specific instruments are provided in the subsections that follow.

6.2.1 Single-Channel Measurements. The bulk collection of photons arriving from the night sky (or a portion of the sky) and conversion into units of radiance by detector and associated electronics is the simplest method. It is important to identify the spectral response curve of the instrument employed when reporting data in absolute radiometric units. Instruments may be fitted with filters to obtain a measurement in a desired photometric system, such as photopic luminance (candelas per square meter, cd/m^2) or sky brightness (V mag/arcsec^2), and optics that confine the angle of view and amplify the signal. An instrument with a narrow angle of view (less than 5 degrees FWHM**) and high dynamic range will produce the most-useful data. This is because the narrower the field of view, the higher the resolution and therefore the better the

** Full width at half maximum (FWHM): The width of a curve or function measured between the points that are half the maximum amplitude.

information will be when interpretations are made. For example, higher angular resolution allows the Milky Way and bright stars to be avoided when making sky brightness measurements. Documenting sky brightness involves a decision pertaining to use of either a single measurement or "all sky" with multiple measurements. In general, a large gradient of sky brightness exists over the hemisphere because of sky glow that originates from sources on the ground. Quantification of this gradient requires an instrument with a narrow field of view.

Photomultiplier tubes combined with a circular orifice that, in conjunction with a concentrating lens, determines the field of view, have been historically used for surface brightness measures by professional observatories using large telescopes,[52,53,54] and with portable instruments at remote locations.[55,56] This type of instrument is accurate and sensitive, and versions are still available for use today.[57]

Broadband measures using portable devices employing a silicon photodiode may be accurately and efficiently collected. One such type, due to its wide, 120-degree field of view, is primarily designed to be aimed at the zenith (i.e., to minimize bias from dark ground or light-trespass glare sources) and is essentially an irradiance meter, with electronics and an algorithm that produce a measurement in radiance that closely matches the V mag/arcsec^2 values. Its photometric capabilities have been investigated by Cinzano.[58] Such devices may be available with permanent mounting housings and filters designed for continuous monitoring. A hand-held version would be appropriate for opportunistic measures, giving the observer an instant result. However, the value of data collection is greatly enhanced by recording the location, date, and time of the observation. For this reason, the continuous monitors are preferred. Excellent long-term records of the sky brightness at sites may be obtained with an appropriate instrument.[59,60]

The best opportunistic use of this type of device is in areas with relatively high light pollution. This is because, while these devices are capable of accurately measuring sky brightness as faint as 22.0 V mag/arcsec^2, any measures darker than 21.0 under clear sky conditions will include a significant fraction of natural sources, which are variable. This can result in misinterpretation of the readings if small differences are attributed to artificial sky glow rather than the natural airglow, zodiacal light, or the Milky Way.[61] In addition, it is critical that the device be shielded from nearby light sources if used in mobile situations to describe sky brightness geographically; the moon in the sky may also produce stray light on the detector.[62] While a narrow-field device may be used to characterize the brightness of the entire sky rather than the zenith alone,[63,64] the field of view is may still be too broad to be used within less than 20 degrees of the horizon without the surface brightness of the land being included in the measurement.[65]

Some single-channel instruments have been developed that can accept custom bandpass filters. Some photometers have been calibrated in absolute radiometric units.[66] Commercial enterprises that measure sky brightness exist, and smartphone apps are available that utilize the built-in camera as a photometer.

6.2.2 Imaging Array Measurements. Imaging instruments (essentially, digital cameras) use a detector array, allowing for coverage of large areas of the sky and making thousands or millions of measures in one step. The imaging detector-filter-optics system will need to be calibrated in radiometric units or a standard photometric system. The primary limitations to such cameras are a potentially lower sensitivity (requiring a longer integration time at dark sites) and a smaller dynamic range, as each pixel in the array has a miniscule photon collection area and full well depth compared to most single-channel detectors.

6.2.2.1 All-Sky Fisheye Systems. A fairly large detector array may be employed to capture an image of the entire sky using a fisheye lens. In this manner, a single exposure contains measurements over the entire hemisphere. While more difficult to calibrate than cameras with narrower angles of view, several systems have been developed, and comparisons between them and other systems reveal an accuracy of within 10% to 20% compared to standard photometric systems.[67-72] Either a scientific grade, thermoelectrically cooled CCD*

* CCD: charge-coupled device

camera or a consumer grade CMOS DSLR* camera may be used. A monochrome CCD sensor may be accurately calibrated to photometric systems if custom filters are employed to allow the desired spectral bandpass and match the spectral response curve of the system of interest. For cameras with RGB filters integrated into the sensor, the green channel is normally extracted for calibration in photopic luminance units (cd/m^2) or V mag/arcsec^2, while the red and blue channels may be used to compute correlated color temperature (CCT) values for each pixel. **Figures 6-3** through **6-5** illustrate sample output from three of these systems.

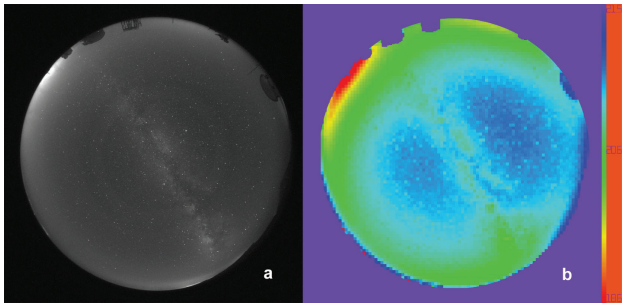


Figure 6-3. Sample images from the ASTMON (All Sky Transmission Monitor) system: monochromatic representation of the V band (a), and false color photometric calibration (b).
(Image courtesy of Dan Duriscoe)

Low-cost, small-sensor-size cameras have been explored as a means of making all-sky imaging for sky brightness measurement readily available to citizen science projects. Adler Planetarium in Chicago has developed a low-cost fisheye camera that automatically collects images throughout the night and stores them for future retrieval via Wi-Fi or cable. Known as the GONet camera system (for *ground observation network),* the project produced 50 cameras at a cost of less than $100 (U.S.) each using students and volunteers to design and assemble the instruments. These cameras have a relatively narrow dynamic range and are useful only at brighter sites. **Figure 6-6** displays a photometrically calibrated image at a suburban site compared to simultaneous data from a mosaic CCD camera.

* CMOS: complementary metal oxide semiconductor; DLSR: digital single-lens reflex

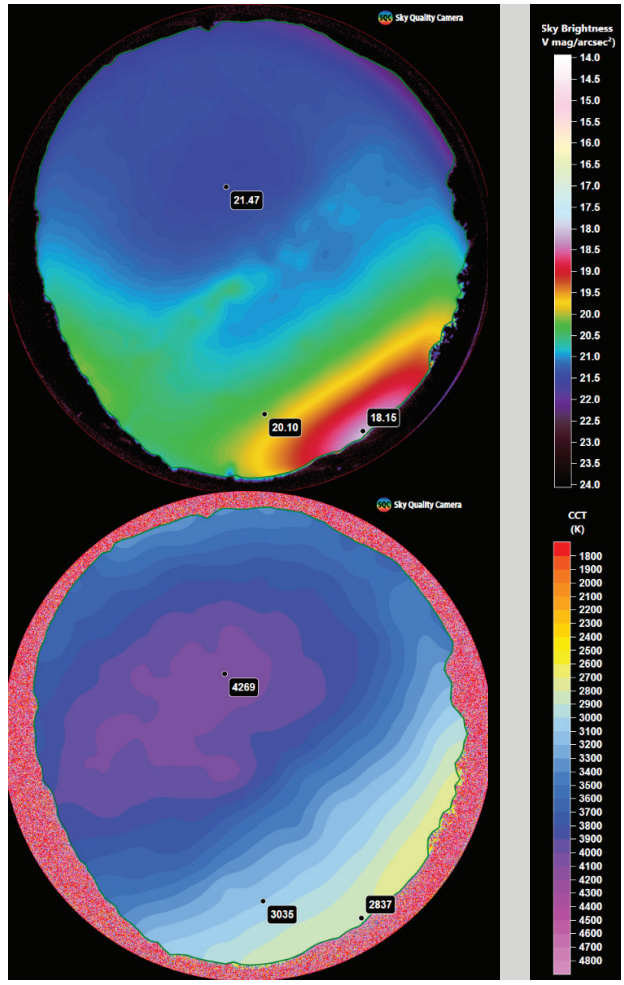


Figure 6-4. Output from Sky Quality Camera software, showing calibrated V-band sky brightness (top) and CCT (bottom) from a relatively dark site.
(Image courtesy of Night Sky Metrics, LLC)

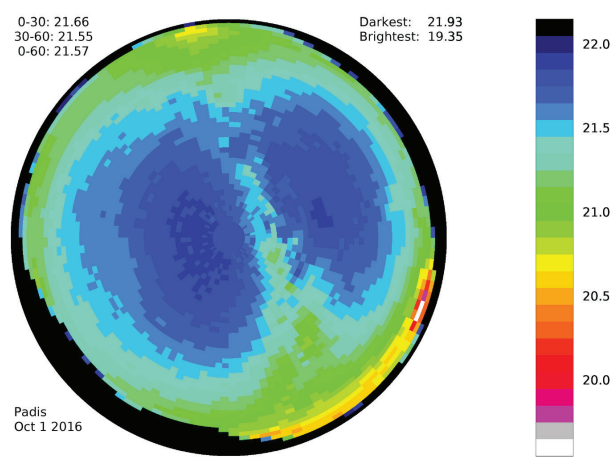


Figure 6-5. Output from *DiCaLum* software showing photometrically calibrated sky brightness map derived from a fisheye DSLR image. (Image reproduced from original by Kolláth and Dömény[70])

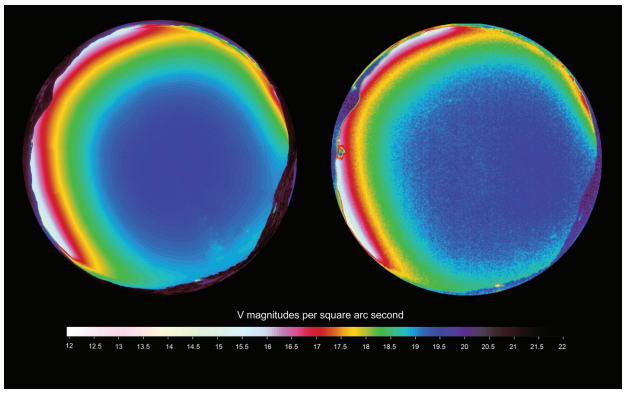


Figure 6-6. Comparison of mosaic CCD camera data (left) with fisheye data from the GONet camera (right). The GONet data is a stack of five individual images and has been median-filtered to reduce noise. It should be noted that the color map is shifted in comparison to others in this document, to enhance contrast. (Image reproduced from original from Night Sky Metrics, LLC)

6.2.2.2 All-Sky Mosaic Systems. A wide-field CCD camera mounted on a robotic telescope mount has been used to produce photometrically calibrated mosaics of the entire hemisphere of the night sky.[73,74] The major advantages to such a system are the much higher resolution of a mosaic compared to a single image and the greater ease of obtaining an accurate flat frame from the optics, resulting in a more accurate calibration (the system used by NPS reduces systematic errors to less than 4%). The biggest drawbacks are the need for a camera mount that accurately points to pre-determined horizon coordinate points, the need for alignment of the mount in the field, and the resulting longer duration required to complete all the images covering the hemisphere. **Figure 6-7** shows an all-sky mosaic calibrated in the V photometric band in false color; it also shows how including an extra five degrees below the level horizon may reveal important sources of artificial sky glow.

Other advantages of a mosaic system include: the ability to easily utilize custom broadband or narrowband filters in the optical system without distortion of the image; accurate stellar photometry for calibration; and the ability to measure luminance or illuminance of specific unshielded light sources using a neutral density filter in the optical path. The NPS system also collects sky brightness data in the Johnson-Cousins B band; when

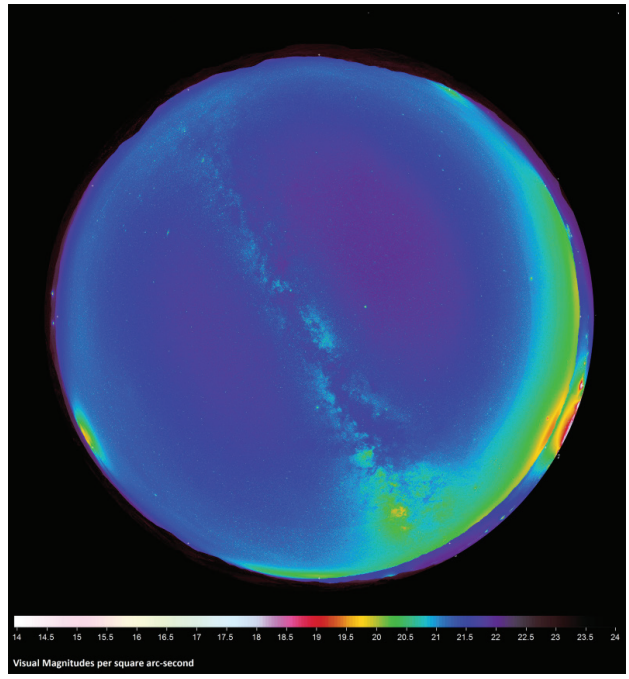


Figure 6-7. Mosaic of 45 images in false color calibrated in the V band (visual magnitudes per square arc-second, V mag/arcsec^2) from the NPS CCD all sky imaging photometer. The light dome from the town below the horizon can be seen from this high mountain top location. (Image courtesy of Dan Duriscoe)

combined with the V band mosaic, a map of the B – V ("B minus V") color index is produced, similar to a CCT map (see **Glossary**).[75]

6.2.2.3 Natural Sky Brightness Contribution. In order to accurately assess the amount of artificial sky glow in measurements, the natural sky brightness at each point in the sky should be estimated and subtracted. For imaging systems, a model of the natural sky brightness may be constructed at the same resolution as that of the observed sky brightness data.[45] For single-channel systems (see **Section 6.2.1**), a similar model for a given location in the sky may be employed, such as the one utilized in calibrating the New World Atlas of Artificial Sky Brightness.[76] By computing the artificial component, an important indicator, the all-sky light pollution ratio (ratio of average sky luminance from artificial sources to that from natural sources) may be derived.[77,78] This indicator intuitively predicts the severity of environmental impact on sky glow relative to a natural reference condition.

6.2.3 Spectroscopic Instruments. While broadband radiometric measurement instruments are relatively inexpensive, easy to deploy, and rapidly complete measurements, the spectral response of each individual instrument essentially defines its own photometric system. As the spectrum of sky glow, both artificial and natural, is complex and highly variable from place to place and night to night, comparison of measures from different broadband instruments may lead to significant systematic errors.[79] In this regard, spectroscopic instruments definitely produce more accurate and more easily interpreted data. If calibrated in absolute units of spectral radiance, broadband measures may be synthesized from the spectral radiance data if the band falls within the wavelength range of the instrument.

Spectroscopy has long been a primary tool of astronomy, and it is not surprising that the first such measurements of radiance from the night sky were made by astronomers. In the 1970s, observations at Lick Observatory in California revealed the presence of light pollution in the night sky spectrum, primarily caused by the mercury vapor lamps of the time, and resulted in a recommendation for the use of the nearly monochromatic low pressure sodium lamp to mitigate the problem.[80] Since then, sporadic night sky spectroscopy has been conducted at observatories around the world.[54,54,81-83]

While portable spectrometers have been available for decades for measuring lamps, television screens, and computer monitors, the low radiance levels of sky brightness, particularly in areas remote from sources, has prevented their use under night sky conditions. Recently, instruments have been developed with reasonable spectral resolution requiring relatively short integration times that may be aimed at points in the sky for measurement.[84,85] Example output from one of the instruments is shown in **Section 2** (see **Figures 2-9** through **2-11**).

7.0 General Recommendations for Reducing Sky Glow

Some amount of human-based light in the night sky is unavoidable if civilization is to continue using illumination in its many forms. It is important to note that while outdoor lighting and controls technologies are rapidly evolving in terms of capabilities that can greatly reduce their contributions to unwanted light at night, the use of supplemental lighting should not serve as the given default, but instead be evaluated against such tradeoffs as energy and environmental consequences, loss of the natural landscape and nighttime views, and aesthetic and other preferences. Some geographic areas are more sensitive to light at night than others and need to be protected via environmental regulation. Standards or thresholds may differ accordingly. Because sky glow can be visible over many tens or even hundreds of kilometers from the source (see **Preface, Figure P-1**), considerations with respect to lighting zone should extend beyond that of the installation's immediate location to the larger region of potential influence. This should involve measurements and monitoring of sky glow within any sensitive regions to confirm that thresholds are not exceeded.

In keeping with this, the IES and the International Dark-Sky Association (IDA) have established the Five Principles for Responsible Outdoor Lighting.[86] To the extent that they are properly implemented, the measures discussed in the subsections that follow can lead to improvements in this regard, but in all cases, balanced and thoughtful consideration is essential to determine whether anticipated benefits outweigh the perceived costs.

7.1 Eliminate Unnecessary Lighting

As a rule, avoiding the *production* of light that is neither needed nor wanted should always be the first option considered, as this approach alone reduces energy, money, and all other adverse elements simultaneously. A perceived need for lighting should be reviewed in the context of whether the need is absolute or if, for example, it might be avoided through alternatives such as the use of high-reflectance materials and paints. Furthermore, situations often change over time, and the original need for lighting in an individual location may no longer apply. One case study in the state of Vermont, for example, resulted in several municipalities removing between 27% and 47% of their previously existing street lighting prior to undertaking conversions to LED.[87] In such cases, capital costs are reduced in addition to

avoiding the higher operating costs of legacy sources, while associated adverse effects of the lighting are also eliminated.

This approach also includes eliminating light that is otherwise being directed into unwanted areas. The use of shielding is a common element in discussions of controlling such unwanted light, but a far superior approach is finding an alternative luminaire with a distribution that better matches the given application, if available, so that shields are unnecessary. While recognizing that a requirement for shielding is sometimes unavoidable, it is also important to acknowledge that blocking light that energy and money have been spent to produce represents a waste of resources. Modern LED products, through use of advanced optics and internal aiming, offer much more precise tailoring of light distribution to the given application than do any others to date. More attention to this approach is needed in order to leave the outdated inefficiencies of shielding behind.

Finally, a familiar approach that can be used in many outdoor situations is flipping the default paradigm from always lighting even when the actual need is rare, to employing motion detection to provide lighting only when actually needed. This approach does not imply an all-or-nothing format. Lighting in an urban bus shelter typically only occupied for a few minutes per night, for example, can be dimmed to a very low level when it is not occupied and raised to full as soon as a user enters it. Motion-detection dimming after hours in parking lots and alleyways may add a further measure of security, as lights coming up to full brightness after detecting movement call attention to it. The associated lighting savings in such situations can be substantial.

7.2 Eliminate Uplight

When lighting is needed, light emitted above the horizon (uplight) has the greatest opportunity for scatter and hence exerts the greatest influence on sky glow (see **Figure 5-1**, in **Section 5.1.1 Sources of Natural Variability**). With a few possible exceptions, light emitted within about 10° of the horizon, if not blocked by nearby buildings, shielding, or geographic features, has the greatest likelihood of scatter because it has the longest travel path through the atmosphere. Eliminating uplight thereby generally offers the single largest impact toward reducing sky glow.

A systematic shift toward luminaires with 0% uplight (or a U0 BUG rating) over the last few decades has achieved a substantial reduction in contributions to sky glow from new or replacement exterior luminaires of all types. Significant gains have also been achieved in decorative acorn and globe-type pole-mounted luminaires, in this case through deployment of more-directional LED luminaires and inserts to replace the original lamp-based, omnidirectional emitters. However, despite the progress noted, many luminaires and lighting design practices remain that result in continued emission of uplight. Examples include:

- Older street and area lighting inventory still using drop- or sag-lens luminaires
- The practice of tilting fixtures to throw light a greater distance forward
- Inadequately aimed landscape and architectural lighting, partially (or entirely) missing the intended target
- Security wall pack and floodlighting mounted where light is emitted above the horizontal plane or outside of the intended target area
- Bottom-lit billboard lighting and internally lighted LED signage
- High-rise apartment and office structures remaining lighted all night regardless of occupancy
- Older sports lighting installations, particularly in school and park environments, where funding may not be available to upgrade to better-focused and shielded luminaires*
- Vehicular lighting, which can comprise a continuous source along busy streets and highways

Light that is emitted downward but in a nearly horizontal direction (85 to 90 degrees from nadir) may in some circumstances also travel long distances before directly

* However, sports lighting entails other considerations as well, such as a need for vertical light in aerial sports where the ball in play may travel above the level of the lights, e.g., baseball or football. The IES Sports Lighting Committee is presently determining the levels of skyward lumens required for any given field; when available, these recommendations will be referenced in a future version or annex to this document.

intersecting a surface, and thus may also contribute significantly to light scatter. For instance, light from a streetlight 10 meters in height emitted at 1 degree below the horizontal travels over 570 meters before intersecting the ground. If the ground surface slopes downward at an angle of a few tenths of a degree or more, this distance can extend to kilometers, or even become virtually equivalent to direct uplight. Other than in applications such as vehicle headlights or pathway bollards mounted close to the ground, light emitted in this zone does not typically provide much useful ground illumination and has high accompanying glare and light trespass potential. Much of it is a good target for elimination via improved optics.

Many uplight issues arise due to a simple lack of attention during design and/or implementation. The not uncommon practice of tilting luminaires, for example, may suggest an inappropriate selection of product for the intended application. Where this applies, selection of an appropriate product with, for example, an asymmetrical distribution and flat lens, properly installed in a horizontal position, may result in adequate light distribution and no uplight.

Over time, eventual replacement of older products along with improvement in lighting design practices can help to eliminate much of the sky glow associated with direct uplight.*

7.3 Reduce Lumen Output

Even if all the direct and near-horizontal light were eliminated via optical control, there would still be light in the night sky and associated sky glow from surface reflections. Reflections have much lower influence than direct emission of light into the sky, however; whereas eliminating one lumen of uplight directly translates into one less lumen in the sky, an average ground reflectivity of, e.g., 10% would mean that ten lumens of downward output would need to be eliminated to achieve an equivalent reduction. (Note that winter conditions can raise reflectance values significantly, however—to as high as 95% for fresh snow.) The light output of the source has a scalar effect on reflected light and thereby generally offers the largest practical influence on this component. Reducing luminaire output by half, for example, likewise reduces the fraction of light reflected by half. Careful attention to providing just the precise amount of light needed for the application, eliminating over-lighting and off-target light spill, also reduces reflected light. Reductions in output can be pursued both in the initial design as well as during operation via dimming.

7.3.1 Reducing the Initial Lumen Package. In the past, control over distribution of light output was challenged by the large size and omnidirectional emission pattern typical of legacy light sources. Accurate delivery of light output to the target area required well-designed reflectors and secondary optics, though with mixed results that sometimes also needed further shielding. Not only do these approaches reduce luminaire efficiency, meaning that much of the light produced by the source never emerges from the luminaire, but the light output may *still* not follow the precise distribution desired. The characteristic "hot spot" often seen directly underneath an older outdoor luminaire is a visible manifestation of this issue.

A distinct attribute of LED products is the superior control possible over their distribution, in comparison with products utilizing traditional light sources like metal halide or high pressure sodium. Modern LED luminaire installations routinely achieve distribution uniformities that are virtually unattainable with omnidirectional sources. The benefits of this attribute are often captured during design of an LED system, enabling the use of luminaires with much lower lumen packages compared to the incumbent products they are replacing. The remaining lumen packages can meet the required light levels with many fewer lumens—for example, by eliminating the "hot spot" noted in the preceding paragraph. Each such reduction achieves the scalar effect on reflected light described in **Section 7.3 Reduce Lumen Output**. Proper sizing of the initial lumen package is the first, best approach to reducing lumen output; among other benefits, it minimizes light introduced to the sky in the early evening hours when people are most likely to be viewing the night sky and reduces effects on wildlife. In some cases, lumen output

* Recognizing that some applications require some amount of uplight, such as the sports fields mentioned in the previous footnote.

will be governed by local ordinance, e.g., maximum lumens per acre for the region, light zone, or adjacent sensitive receptor areas. Measurements of existing sky glow conditions may also guide the decision.

7.3.2 Reducing Output via Dimming. A second capability, essentially introduced to outdoor applications by LEDs, is the ability to dim their output without damaging either luminaire efficacy or expected lifetime. Dimming of LEDs offers multiple benefits in addition to immediately reducing the amount of light entering the night sky. Lowering their operating current reduces their temperature and thus increases their expected lifetime. LEDs also become more efficacious as they are dimmed (meaning, energy use drops more rapidly than light output).

Because all light sources fade as they age, outdoor lighting systems are typically over-designed (often by more than 30%) in order to ensure that the required light levels are maintained, at a minimum, over the entire economic life of the luminaire. With earlier lighting systems, this meant that substantially more light was produced over the first years of operation than was actually required by the application. In contrast, systems that can instead be dimmed to just the design output level from the first day of operation, and then increased in output to compensate for fading as needed, avoid years of excess energy use and the associated sky glow that has historically been generated.

Dimming of LED installations still faces some hurdles among the outdoor lighting community related to concerns (real or imagined) about acceptable lighting levels and liability, along with general cost effectiveness and demonstrated reliability of dimming control systems. It should be noted that despite the multiple benefits offered, dimming is limited to reducing impacts rather than eliminating them; furthermore, only during those periods is this advantage realized. For example, the main impact of light at night for some species occurs during the early hours of the evening, when dimming may not yet be underway.[88]

Nevertheless, several U.S. sites have taken the initiative to install dimming equipment and are successfully operating nighttime dimming schedules (typically engaging after midnight). One helpful justification derives from the fact that IES recommended light levels are often based on the potential for pedestrian conflict, which decreases in the later hours of the evening or early morning. In many situations, these decreases can be used to redefine the lighting requirement in specific locations. Through this kind of innovative approach, these cities and other sites are achieving significant further reductions in their quantities of light output in addition to the other benefits noted. Dimming of outdoor lighting during appropriate periods is expected to become much more standard practice in the future.

7.4 Control Spectral Content

Because short wavelength (blue) light backscatters to the earth more strongly than longer wavelengths, a common recommendation for addressing sky glow is to minimize or even eliminate the short wavelength content of outdoor lighting sources. Whereas earlier broad-spectrum sources intended for exterior lighting offered only limited selection of spectral content, this situation has changed with the advent of LED technology. Options range from phosphor-converted LEDs with embedded phosphors that convert the bulk of their original blue emission to longer wavelengths, to use of monochromatic (e.g., amber) LEDs with no blue content whatsoever (hence being similar to traditional HPS, which have very little blue light content). Monochromatic sources, such as products containing only red or amber LEDs marketed as turtle- or bat-friendly, are sometimes used for niche-application lighting where potential local adverse impacts of individual spectra outweigh the corresponding energy consequences from excluding them. Another, less common option involves the use of filters to remove any blue content from the light prior to its leaving the luminaire.

Any consideration of such approaches should include evaluation of accompanying characteristics such as energy use and color rendering ability in the context of the intended application.

7.5 Set Appropriate Expectations

The characteristics of a lighting system that affect sky glow can be influenced either during the initial design stage or, to a lesser extent, retroactively during renovation. The measures recommended in this TM apply equally

to large and small groupings of sources (even down to a single source), with the overall impact expected to be proportional to the relative contributions of those sources in the collective whole. Importantly, impacts may be less visible in the overall context when other significant sources of light in the night sky remain unaltered.

8.0 Glossary

An abridged list of terms relevant to the document is included here. Other lighting terms may be found in *ANSI/IES LS-1-20, Lighting Science: Nomenclature and Definitions for Illuminating Engineering*.[89]

adaptive lighting. Lighting with the ability to automatically adjust light level and spectral content based on environmental conditions in order to optimize space, human, and building performance.[89] Such conditions may include, for example, varying ambient light or traffic (e.g., pedestrian, bicycle, automobile) levels.

albedo. The percentage of total light reflected from a surface. Typically used in astronomy to describe the reflectivity of the surface of a planet or moon.

atmospheric scattering, or attenuation. Light waves traveling through the atmosphere are transmitted, absorbed, or scattered by constituents within the atmosphere (gaseous molecules, aerosols, and particulate matter). Because different wavelengths interact differently with particles of varying size, the spectral content of a given beam of light often changes as it propagates through the atmosphere, with some portions eventually attenuated given a long enough travel path and/or high enough level of atmospheric constituents. Sky glow is caused by the portion of light scattered in the specific direction of the observer's location, with its associated spectral content generally a combined function of the original content and distance from the source.

B band: In the Johnson-Cousins UBVRI photometric system (used in astronomy for classifying stars according to their colors), the B band is described by a filter centered at 455 nm and has a full width at half maximum of 94 nm. (See also *Johnson-Cousins UBVRI photometric system* and *V band*.)

brightness. Attribute of a visual sensation according to which an area appears to emit more or less light.[89]

correlated color temperature (CCT). The absolute temperature of an ideal (blackbody) radiator whose associated chromaticity most resembles that of the light source.[89]

Note: This definition refers to a perceived appearance of the light source; significant variation in spectral content can produce a similar overall appearance in terms of CCT (see **Figure 3-2, Section 3.1 Spectral Properties of Light sources Commonly Used in Exterior Applications**). Therefore, CCT provides only a general indication of the actual spectral content. *Nominal* CCT refers to a naming convention for binning groups of CCTs within specified ranges under a single value; e.g., LEDs of 3895 K, 4002 K, and 4072 K would all be *nominally* referred to as 4000 K.

downstream effect: A consequence to biological organisms that results from exposure to light at night. This kind of result often depends on individual sensitivities to particular wavelengths, illuminance levels, and durations of exposure that require detailed expertise to assess. A brief treatment cannot provide such broad-based expertise; thus, the scope of this document only extends to the point of characterizing the light exposure to which an individual might be subject. Subsequent biological responses are assessed by experts in these subjects.

Johnson-Cousins UBVRI photometric system: A common extension of the Johnson-Morgan or UVB system for classifying stars according to their colors. Measurements are made in the various bands using bandpass filters and then subtractions performed (e.g., B – V) to classify stars in the system. Known reference stars may be used to calibrate an instrument with these bandpass filters, as they are always available and never change, at least on the scale of hundreds of years.

light pollution. The human alteration of light levels in the outdoor environment from those occurring naturally. The term is sometimes used synonymously with *sky glow* but is more accurately applied in a broader sense to also encompass undesired effects like light trespass and glare.

lighting zones. The base or ambient light levels desired by a community, establishing a target set of criteria for designing a lighting system. The Model Lighting Ordinance (MLO) was a joint effort of the International Dark-Sky Association and the IES. It provides recommended lighting-ordinance language that communities may adopt for the purpose of dramatically reducing light pollution and glare and reducing excessive light levels. Its recommendations can be met using readily available, reasonably priced lighting equipment. The MLO defines five lighting zones, ranging from LZ0 (no ambient lighting) to LZ4 (high ambient lighting).

luminaire. A complete lighting unit consisting of a light source(s) and ballast(s) or driver(s) (when applicable), together with the parts designed to distribute the light, to position and protect the sources, and to connect the sources to the power supply. Sometimes called a "light fixture."[89]

magnitude. In astronomy, a measure of the brightness of a celestial body. Lower values of magnitude indicate greater brightness. A step of one magnitude is defined as a ratio of 2.512 times in brightness. For example, a star of magnitude 6.0 is 2.512 times as bright as one of magnitude 7.0.

melanopic daylight efficacy ratio (melanopic DER). Applies the melanopic action spectrum across a spectral power distribution to provide an indicator of the light source's ability to suppress the production of melatonin, which is a hormone related to circadian regulation and other clock functions in the body. The DER approach normalizes the M/P ratio using a CIE D65 light source.

M/P ratio. Provides a metric for comparing melanopic potential (ability to stimulate the intrinsically photosensitive retinal ganglion cells, ipRGCs) of a light source to its ability for producing light for photopic vision.

naked-eye limiting magnitude (NELM). Describes the present brightness of the surrounding sky and refers to the current threshold below which celestial objects of lower magnitude are no longer visible to an observer's unaided eye.

scale height. Assuming particulate concentration follows an exponential decay function with height, the height at which particulate concentration is reduced by 1/e. Other heights are said to be "equivalent scale heights" when their total amount of material contained equals that of the standard scale height.

sky glow. The brightening of the night sky that results from the scattering and reflection of light from the constituents of the atmosphere (gaseous molecules and aerosols), in the direction of the observer. It has two separate components: natural sky glow and artificial sky glow.[89]

- **natural sky glow:** That part of sky glow which is attributable to natural sources. It is attributable to starlight, zodiacal light (scattering of sunlight from dust in the solar system), airglow (radiation from luminescent processes in the earth's upper atmosphere), and (on a cyclical basis) moonlight.[89]
- **artificial sky glow:** That part of sky glow which is attributable to scattering of light from human-based sources of radiation (e.g., outdoor electric lighting), including radiation that is emitted directly upward and radiation that is reflected from surfaces.[89]

spectral content. The spectral power distribution of the light. For the purposes of lighting design, it generally refers to the visible spectrum, or wavelengths between 380 and 770 nm.

target area. The area intended for illumination. Off-target illumination may sometimes be referred to as "light trespass" or "light spill."

V band. In the Johnson-Morgan UBV photometric system (used in astronomy for classifying stars according to their colors): the astronomical photometric band that is closest to the photopic curve. It is described by a filter centered at 551 nm with a full width at half maximum of 88 nm.

visual magnitudes, or V mag. Measured on an inverse logarithmic scale of the apparent brightness of an object to the human eye, where a difference of 5 magnitudes represents a 100-times difference in brightness or luminance. Because the V band tracks closely to the *V(λ)* photopic curve, it is often referred to as the "visual magnitude." It is normalized to a value of 0 for the luminosity of the star Vega.

V mag/arcsec^2. V magnitudes per square arc second, a measure of sky brightness per unit of sky area.

Annex A – Sky Glow Comparison Tool

This annex is not part of ANSI/IES TM-37-21, Technical Memorandum: Description, Estimation, and Measurement of Sky Glow. *It is provided for informational purposes only.*

The Pacific Northwest National Laboratory has developed a spreadsheet type of comparison tool for evaluating lighting products with respect to their potential contributions to sky glow, based on multiple characteristics. (See also **Section 5.2 Models and Approximations.**) A description of and access to the comparison tool is provided online.[90]

https://www.energy.gov/eere/ssl/potential-impacts-led-street-lighting-sky-glow

Stakeholders interested in obtaining the sky glow comparison tool should send an email request to DOE.SSL.UPDATES@ee.doe.gov and provide their contact information.

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Process for Change to an ANSI/IES Standard under Continuous Maintenance

This standard is maintained under continuous maintenance procedures, for which IES has an established and documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the standard. Committee consideration will be given to proposed changes by June 30 of any given year for proposed changes received by the IES Director of Standards no later than December 31 of the previous year.

Submittal Format

Proposed changes must be submitted to the IES Director of Standards in the announced published format. However, changes may be accepted in an earlier published format, if the differences are immaterial to the proposed change submittal. If the Director of Standards concludes that a current form must be utilized, the proposer may be given up to 20 additional days to resubmit the proposed changes in the current format.

Specific changes in the text or values are required and must be substantiated. Any change proposals that do not meet these requirements will be returned to the proposer. Supplemental background documents to support changes submitted may be included.

Submission to the Committee Chair

The Director of Standards shall forward proposed changes received on appropriate forms to the committee chair for assigning to committee members (responders) to develop responses to submitters of proposed changes.

Review and Clarification

Responders shall review proposals and should contact the proposer if necessary for clarification.

Response Recommendation

Designated responders shall draft a recommended committee response, including any recommended changes to the standard. The 'responders' recommended responses shall be submitted to the committee chair in electronic form usable by Society Staff, including any recommended change to the standard in response to proposals received.

Options for Committee response are limited to:

a) Proposed change accepted for public review without modification
b) Proposed change accepted for public review with modification
c) Proposed change accepted for further study
d) Proposed change rejected

The responders shall provide reasons for any recommendation other than option (a) above.

The designated responders shall not recommend option (c) unless the further study can be completed by October 1 of that year, and providing the Committee can then vote for option (a), (b), or (d) no later than November 15 of that year.

Editing

The Committee chair or his or her designee shall edit the draft responses and circulate the edited drafts to the committee for review.

Form for Proposing Change to an ANSI/IES Standard under Continuous Maintenance

NOTE: Use a separate form for each comment. Submit to the Director of Standards, IES, 120 Wall Street, 17th Floor, New York, NY 10005-4001. Email: standards@ies.org. Fax: 212-248-5017.

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_____
_____
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_____
_____
_____

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