REVIEW

Measuring and monitoring light pollution: Current approaches and challenges

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Understanding the causes and potential mitigations of light pollution requires measuring and monitoring artificial light at night (ALAN). We review how ALAN is measured, both from the ground and through remote sensing by satellites in Earth orbit. A variety of techniques are described, including single-channel photometers, all-sky cameras, and drones. Spectroscopic differences between light sources can be used to determine which are most responsible for light pollution, but they complicate the interpretation of photometric data. The variability of Earth's atmosphere leads to difficulty in comparisons between datasets. Theoretical models provide complementary information to calibrate experiments and interpret their results. Here, we identify several shortcomings and challenges in current approaches to measuring light pollution and suggest ways forward.

Preserving the environment and ensuring sustainability are worldwide challenges. They include the phenomenon of light pollution caused by artificial light at night (ALAN). Light pollution primarily consists of misdirected light emission, illuminating outdoor areas not intended or required to be lit. It also includes overillumination—the use of lights with much higher brightness than necessary—and the use of harmful light colors, such as lighting that emits radiation at short optical wavelengths (blue light). Light pollution produces "light domes" visible in the night sky near cities, brightening the sky over wide areas and reaching into otherwise dark areas, such as protected natural spaces (*1*). The adverse consequences of light pollution include detrimental effects to flora and fauna and to human health (*2*–*4*). Increased night sky brightness (NSB) also impairs astronomical observations of celestial objects (*5*, *6*).

Reducing the negative impacts of light pollution requires environmentally responsible urban development. This is often taken to include the widespread conversion of lighting systems from inefficient incandescent or high-intensity gas discharge lamps to light-emitting diodes (LEDs) (*7*, *8*). However, current trends in the spatial and temporal distribution of ALAN show that switching to LEDs has been counterproductive for light pollution, with observations showing continuous growth in illuminated areas and upward-directed radiance worldwide, both being ~2% per year (*9*). In inhabited locations, the rate of increase can be even higher, with contemporaneous citizen-science data pointing to an increase in observed NSB of nearly 11% per year (*10*). Mapping NSB across the globe provides a baseline for investigating the worldwide emergence of lighted areas (*11*).

It is necessary to identify sources and quantify the impact of ALAN, particularly to guide regulations and other mitigation strategies (*12*, *13*). A multitude of measurement techniques are available, providing either single snapshots of lighting conditions and influences or long-term monitoring and remote sensing of ALAN. Many measurement devices are available, all of which have advantages and shortcomings (*14*–*17*). We review the methods behind quantifying light pollution and ALAN, focusing on the diverse functions. We consider current challenges in determining light pollution influences at arbitrary places and predicting how it will change over time. We also provide recommendations on how the measurements can be used more comprehensively in the future.

> **"...outdoor lighting design should minimize the amount of blue light emitted..."**

Quantifying light pollution

Light pollution research uses a large variety of measurement techniques and devices. The right method, instrument, and analytical approach must be chosen for each application in analyzing ALAN and its effects.

Some light pollution parameters can be measured directly from the night sky itself. The enhancement of NSB caused by ALAN is generally called skyglow (Fig. 1A), most commonly occurring in and around densely inhabited areas. A clear night sky background without any ground-based light pollution has a luminance of ~200 μcd m^{-2} (*15*), equivalent to a value of 22.0 mag arc sec^{-2} in astronomical magnitudes (an inverted logarithmic scale) (*18*). Observations that include luminous celestial objects within the instrumental field of view show appreciably higher figures; for example, the brightest parts of the Milky Way are ~2.5 times as bright as the surrounding night sky (*19*). Although the highest NSB values are measured within the light domes above cities, absolute measurements are highly dependent on the distance from (and proliferation of) individual light sources as well as the observed field of view on the night sky. The zenith—the point on the sky directly overhead—is often used as a local reference direction to characterize the approximate sky quality.

Figure 2 shows a comparison of different NSB measurement techniques. Photometric measurements are usually one-dimensional, having no angular resolution (*20*), and may be either portable for single readings or permanently installed as part of monitoring networks (*21*, *22*). Figure 2 includes an illustration of an NSB measurement process using devices with a specified field of view directed toward the zenith to collect continuous NSB data throughout a night. This technique is widespread—used by researchers and activists—because of its generally low data-acquisition cost and high accuracy. However, to collect information about the entire night sky rather than small fields of view, additional techniques are required to analyze skyglow. Two methods predominate. First, the horizontal illuminance of the overall radiation field can be measured using a simple light-to-frequency counter. Second, all-sky imaging techniques measure the entire hemisphere of the sky simultaneously (*23*, *24*) (also illustrated in Fig. 2). All-sky imaging has the advantage of not only measuring any NSB increases over time but also identifying the spatial distribution and relative contributions of individual light domes around the horizon. Combined with calibration software (*25*, *26*), the resulting night sky luminance matrices provide sufficient information to identify light pollution sources and the night sky quality at the time of observation.

ALAN directed toward the sky (directly or indirectly) can also be measured by spaceborne instruments (Fig. 1B). Whereas the ground-based techniques discussed above provide data on local conditions, satellite observations probe much larger spatial scales (*27*, *28*). Satellite remote sensing measures upward-directed radiance from light sources on Earth's surface (Fig. 2) with the goal of analyzing whole cities, countries, or other large areas. These data are particularly useful for studying extensive conversions of existing lighting systems, including potential changes in their total luminous flux, radiation angles, and other properties (*29*). They can also identify the type of lights installed on the ground (*30*).

Returning to smaller observational scales on the ground, ecological light pollution is widespread. The techniques used to study it depend on both the light source and the organism or ecosystem being investigated. When these conditions are clearly defined, light pollution

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measurements can be used to assess impacts on selected species of flora and fauna, caused by either single or multiple light emissions into the nighttime environment (*31*, *32*) (Fig. 1C). These measurements must consider the specific detector parameters required, for example, to provide analogs of animal eyes and the sensitivity to radiation of different origins (*33*, *34*). Light traps are often used to observe ground-based wildlife, and unmanned aerial vehicles (drones) are used to recreate the influence of ALAN on flying animals (*35*) (Fig. 2).

In urban management, outdoor lighting is a tool used to improve safety, provide orientation, and improve wayfinding. However, its use is not usually subject to meaningful public oversight. During the planning process, luminance and illuminance analyses (Fig. 1D) can be used to determine how to achieve those goals (*36*). Parameters, including the spatial distribution and illuminance, are adjusted as needed for site-specific requirements. However, influences such as light scattering effects and nonideal construction of light fixtures potentially lead to unexpected results and can cause light pollution. Therefore, determining luminance and illuminance is necessary in urban engineering. Within cities, individual light fixtures can be optimized on the basis of such analyses (*37*), and in dark areas, ecological light pollution can be explored using the same approach (*38*).

The impact of ALAN on the environment depends not only on its luminous flux but also its spectral power distribution. Exposure to short-wavelength (blue) light at night has negative consequences for many organisms (*3*, *39*). Even at very low illuminances, blue light disrupts the human sleep-wake cycle and suppresses secretion of the hormone melatonin, whose dysregulation is associated with metabolic diseases and certain cancers (*40*). To minimize potential harm, outdoor lighting design should minimize the amount of blue light emitted wherever possible. There are two approaches for quantifying this aspect of light pollution. First, individual lamps are characterized by their spectra (Fig. 1E), and the emission at shorter wavelengths is analyzed. Second, skyglow retains information about the light sources on the ground that generated it, which allows spectrographic measurements of ALAN (Fig. 2).

To forecast changes in light pollution, or its effect under varying ground-based conditions (e.g., lighting conversions and meteorological changes), theoretical modeling is applied. Several computational methods have been developed (*25*, *41*, *42*) to simulate ALAN and its spatial and temporal distribution at arbitrary locations and chosen input parameters. The accuracy of these models is limited by the (typically) large number of lights in cities, which differ in lumen outputs, spectral compositions, directional emissions, and spatial distributions, resulting in a nontrivial cumulative light emission pattern. Modeling of the angular distribution of urban photons has sometimes used a simple analytical formula, combining direct upward emissions with an assumed fraction of ground-reflected light (*43*). This approach has been improved by adding an extinction factor that accounts for light-blocking obstacles near the horizon (*44*). Although this approach works for some cities, the angular distribution of emitted light is generally more complex, requiring a combination of several model functions (*11*). The spectral composition of light escaping an urban area changes with direction as a result of the variety of light sources. These limitations in modeling source emissions affect NSB across the modeling domain.

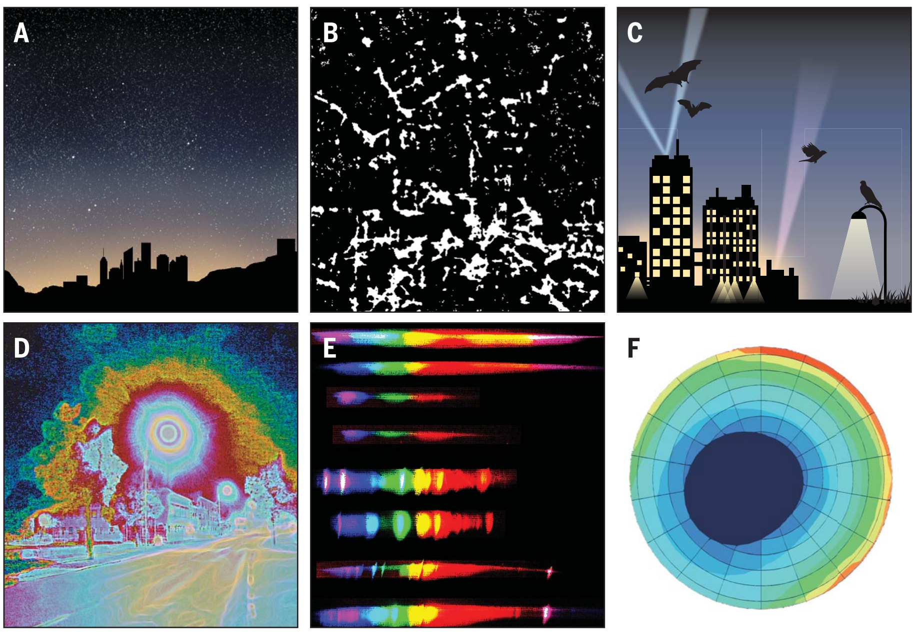

Fig. 1. Topical areas that require quantification of light pollution. Six areas that quantify the impacts of ALAN are illustrated: (**A**) Higher levels of NSB, also called skyglow. (**B**) Satellite remote sensing of upward-directed radiance from Earth's surface. (**C**) Ecological light pollution. (**D**) Surface illuminance resulting from individual light sources—the colors indicate the brightness levels on an illuminated building. (**E**) Emission spectra of individual lighting fixtures. (**F**) Computational modeling. For each application, different techniques and analysis methods are necessary.

Current challenges in measuring light pollution

Although there are many different methods of quantifying the impact of ALAN, they each have shortcomings. Despite the variety of instruments available to observe skyglow, radiance, or other characteristics, there are several common problematic aspects. Because light pollution is affected by the scattering of light in the lower atmosphere, it is influenced by the spatial and temporal instability of the atmosphere. Each night is potentially different from its predecessor or successor, depending on atmospheric and meteorological conditions, so measurements obtained on different dates might not be directly comparable. This primarily affects long-term analyses from monitoring stations because both NSB and atmospheric conditions must be recorded simultaneously and considered together. This applies to all measurement techniques; for example, fog affects satellite remote sensing as well as ground-based illuminance measurements of a single lighting fixture. Ecological light pollution studies are particularly affected because the atmospheric conditions change the spatial distribution of ALAN (*45*). Solutions to this problem can use data from atmospheric monitoring stations, if present near the measurement sites, but those are usually not available, so researchers must rely heavily (or solely) on theoretical models (*46*).

Other factors also cause light pollution measurements to vary. The types and flux density of lighting sources change over time—even during a single night, as lights are switched on and off—and vary spatially as a result of the influence of local topographical features. Parameters, including the albedo of the illuminated surface and shadowing by physical obstructions, affect the resulting light pollution and its analysis (*47*). These variations can be incorporated into a mathematical description known as the emission function (EF) (*48*). It is not possible to obtain sufficient data to determine the EF completely, but it is commonly used as an input for data analysis and processing. Several approaches have been developed to approximate the EF of urban areas (*49*, *50*).

Technical limitations of available devices also affect light pollution measurements. The

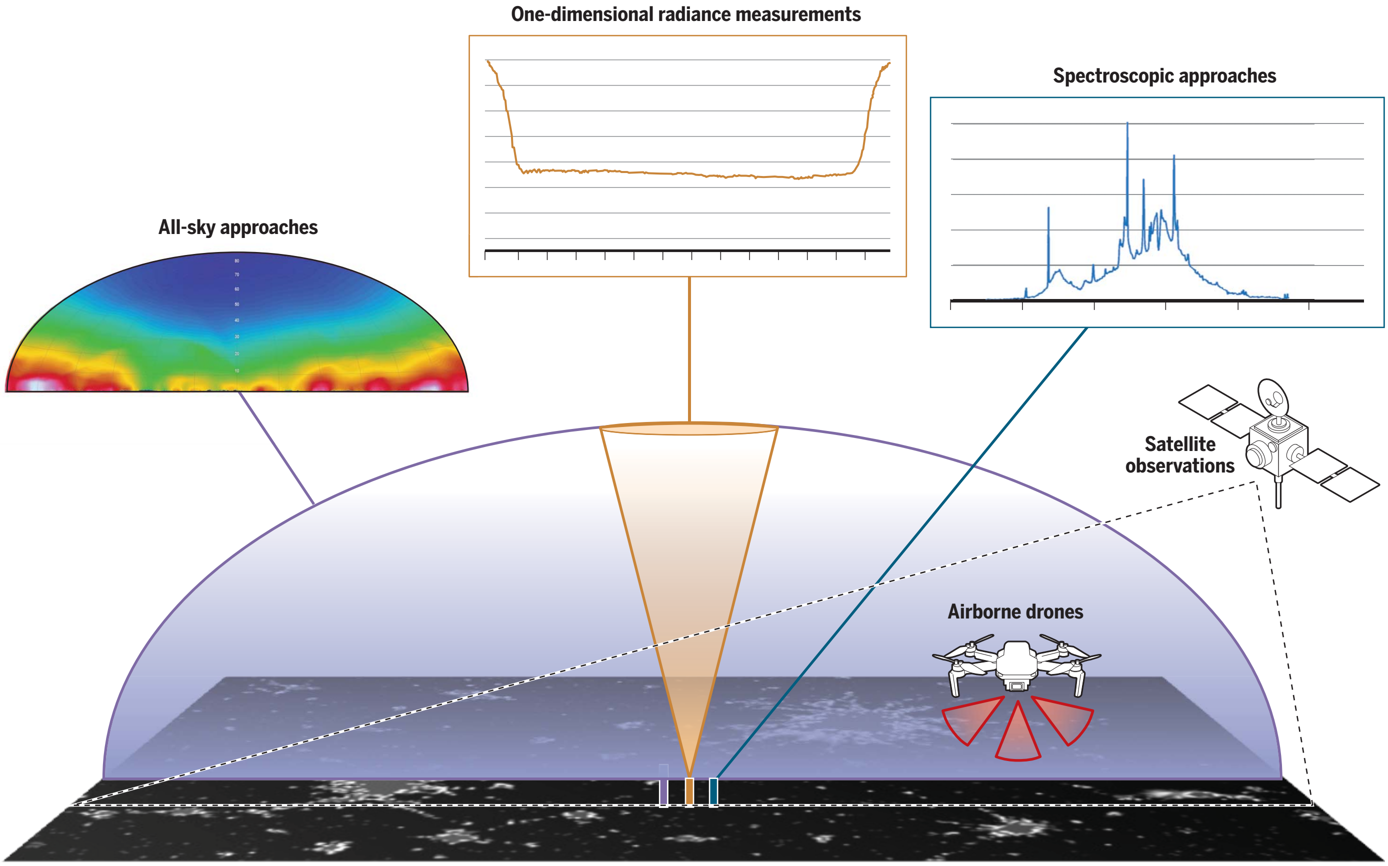

Fig. 2. Illustration of available measurement techniques for light pollution analyses. The variety of methods for measuring light pollution, their domains of applicability, and related observables are shown. All-sky approaches (purple semicircle) collect information originating in the upper hemisphere; spectroscopic approaches (blue line) provide information on the wavelengths of light; one-dimensional radiance measurements (orange cone) typically sample a small region around the zenith; satellite observations (black dashed lines) observe radiance from sources on the ground escaping to space; and airborne drones (red triangles) measure (spectral) radiance and irradiance in multiple directions.

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differing spectral sensitivities of different devices combine with the potentially varying spectral power distributions of light sources (discussed above) in complex ways that affect the measurement. If the types of ground-based light sources are unknown and not included as a variable in the analysis, then the measurement conditions before and after a lighting conversion might not be directly comparable (*51*). This is also true for comparisons between different instruments. Satellite observations are particularly affected by this issue. For example, the main source of orbital ALAN data, with global coverage and nightly temporal cadence, is insensitive to light with wavelengths shorter than 500 nm (*52*). Space-based measurements are also influenced by the emission angle of ground-based light sources. Ground-based measurements have shown that zenithal observations can differ substantially from those obtained at low elevation angles (*53*, *54*). The lower signal-to-noise ratio of measurements taken in low-light environments makes them less reliable than locations with high levels of light pollution, and complex corrections because of natural night airglow are required (*55*). Portable instruments, such as cameras or drones, can be easily maintained, but permanently installed devices are susceptible to meteorological conditions, such as rain and snow. Solar radiation during the daytime has been shown to affect the optics of instruments, causing an aging effect that influences nighttime measurements (*56*).

There is a wide range of instrumental and environmental influences that affect light pollution measurements, which must be considered during data processing. The wide range of techniques can be advantageous for tackling different research goals, but the lack of measurement standards contributes to difficulty in comparing results and the need for complex interpretations. Yet, measurements made consistently with well-designed protocols over long periods of time can yield information of distinct value to light pollution researchers and dark-sky activists alike. Provided that data are obtained with care and the instrumental limitations are understood, light pollution measurements can be confidently applied to situations involving urban planning, land management, natural resource conservation, and more.

Using data more comprehensively

There is great potential for extracting more information from measurement data than is typical at present, for example, through long-term observations of NSB, which are scarce and generally only consist of zenith radiance data. Monitoring networks routinely operate single-channel optical instruments to gather time series of zenith radiance for trend analysis (*57*). However, such data contain more information than is inferred from simple trend statistics. Exploiting more of the information content of zenith radiance measurements has been demonstrated in nighttime monitoring of atmospheric aerosols using differential photometry (*58*). Zenith radiances obtained in rough or irregular terrain, from two measuring stations separated in elevation, have been used to characterize the turbidity of the atmospheric layer between the stations. Conventional measurements, when taken under suitable configurations or spatial arrangements, can therefore provide additional information about the nighttime environment (*58*).

Aerosols—tiny particles suspended in the air—are a large source of uncertainty in quantifying the impacts of ALAN. Several measuring techniques and tools for retrieving aerosol properties have been developed to determine the aerosol optical depth (AOD), a parameter used in, for example, modeling the influence of ground-based light sources. Multiple techniques are in use to determine AOD, but only a few of them are applicable at night, and most are difficult for inexperienced experimentalists to use. One method useful for light pollution measurements relies on an empirical relationship between the zenith brightness and AOD; it can be implemented with low-cost optical devices during moonless nights (*21*).

Simple measurement techniques are preferable for use in monitoring programs at many locations. As discussed above, local atmosphere data are highly advantageous to interpret light pollution measurements, but the instrumentation for measuring atmospheric conditions is not present at most sites. For example, ceilometers—devices that use lasers or other light sources to determine the height of a cloud ceiling or cloud base—can provide useful information on local atmospheric conditions that can be used as inputs for light pollution analyses and skyglow modeling (*59*). When systematically used, measurements of cloud base altitude and backscatter from aerosols provide complementary information to light pollution data.

Spectral data are usually required to characterize light sources (*60*) and to quantify light field distributions for a broad range of atmospheric conditions (*61*). Such measurements are rarely available. Ground-based spectral measurements are infrequent (*62*) because optical systems with the required sensitivity are expensive. Space-based spectral measurements require highly sensitive detectors with high spectral and spatial resolutions. Orbital remote sensing of ALAN mostly uses the Day-Night Band—part of the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument aboard the Suomi spacecraft (*16*)—which can be used to map directional outputs from cities for a range of zenith viewing angles (*63*). The collective effect of the whole-city lights (i.e., its cumulative angular emission pattern) is a required input for, for example, ecological light pollution measurements or forecast approaches, but is difficult to determine experimentally. Exploitation of satellite data for this purpose is a challenge for both experimentalists and theorists. VIIRS does not have a multispectral capability with both sufficient sensitivity and panchromatic response in the optical range. Multiple-angle remote sensing could be used for extended diagnosis of the atmosphere and artificial lights (*53*).

Conclusion and outlook

Experiments and theoretical studies are equally useful to investigate light pollution because they provide complementary information about the nighttime environment. Field experiments can never be performed under fully controlled conditions; the data gathered by optical systems are therefore not free of errors or the effects of other physical phenomena. Measurements are only possible in discrete locations because data acquisition in an arbitrary spatial pattern is impractical. Theoretical studies are required to address these issues. Models are also useful in determining the isolated effect of single parameters on the light field, improving our understanding of their impacts on the measured quantities. However, the models are accurate only within the limitations of the theories used. Experimental data and theoretical models are complementary, providing incomplete information if isolated from each other. Theories can fill data gaps, whereas experimental data are necessary to test the theories.

The development of new models and experimental techniques should go hand in hand because the outcome of one drives progress in the other and can generate new applications. Understanding the processes of light emission and propagation allows for more-specialized field experiments that more fully use the information content of nighttime light measurements. For example, the polarization of light at night is largely unexplored in light pollution research.

Light pollution has drawn increasing attention from the scientific community in recent decades, and we expect that trend to continue. There is a need for more-accurate devices, data acquisition, and study management—all activities that have high technical demands. As the number and diversity of instruments available for field light pollution measurements continue to increase, we question whether a technical standard for absolute calibration of their data can be achieved. Given the need for more global collaboration in the interdisciplinary field of light pollution research, we feel that standardization of measurement protocols will be necessary.

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