Dark and Quiet Skies for Science and Society

Report for review

Online workshop 5-9 October 2020

Protection of existing and future astronomical observatories

Draft Report from the Optical Astronomy WG

N.1 Executive Summary

Ground-based astronomical observations continue to be the drivers of major, high-impact discoveries in astrophysics and basic physics. They are often essential to interpret observations from space-based telescopes. Ground-based optical telescopes can be built at a substantially larger scale and lower cost per unit collecting area than those launched into orbit. And they provide the critical data for planetary defence and key aspects of space situational awareness.

Astronomical research and planetary defence are critically dependent on having a clear view of the heavens, but there is currently great concern amongst astronomers about the increasing impact of human activities, particularly artificial light at night (ALAN). In the past decade alone, the globally averaged rate of increase in artificial sky brightness was 2% per year in terms of both lit area and total radiance, roughly double the rate of world population growth during the same period.

More recently, a new factor impacting the natural night sky integrity has emerged. This impact is from the introduction of energy efficient, white Light-Emitting Diode (LED) technology on large scales. That lighting technology may represent a threat to astronomical observations because of the higher blue content of white LEDs, which scatters more efficiently in the atmosphere, compared to earlier lighting technologies. In addition, there is evidence that the high energy efficiency and relatively low cost of operation of LEDs are fueling elastic demand for the consumption of light, leading to higher overall light emissions.

The International Astronomical Union (IAU) has defined the upper limit of artificial light contribution for a professional site to be considered adequate for true dark-sky observing to be <10 % above the natural background at an elevation of 45° in any azimuthal direction. (Cayrel et al. 1980) The newest professional observatories have been located at remote high mountain sites that are significantly below this limit of artificial light contamination.

The goal of the model regulatory framework proposed in this document is to reduce the current rate of increasing artificial skyglow at major professional observatories by a factor of two or more over the next decade and to achieve a decreasing rate of additional skyglow in the following decade for these sites.

The Working Group strongly advocates an approach of quality lighting design to match the illumination level to need, limiting unnecessary spectral content, and taking more advantage of precise optical control to reduce spill light. A key aspect of site protection is defining near zones with more stringent limits on outdoor lighting levels. Adherence to recommended best practices and to the limits proposed below will accomplish the stated goal of gradually reducing artificial skyglow at professional observatory sites. Major observatories are now typically international consortia, but they are situated in individual countries whose own laws apply to light pollution control. The regulatory framework proposed for COPUOS endorsement provides a model for those national, regional and local governments committed to protecting the invaluable assets of professional observatories within their regions.

Many professional observatories see measurable impact of light domes, the dome-shaped glowing sky area over conurbations, at distances as great as 300 km. The International Commission on Illumination (CIE) provides evidence-based recommendations for illumination levels by usage and environmental zone. Adherence to the minimum required levels and other best practices will greatly reduce urban skyglow. Adaptive lighting technology, allowing lighting levels to be reduced at times of minimal activity is the future path to control of nighttime lighting and reduction in energy costs.

The principles of protection of the near zones around professional observatories are based on best practices of lighting engineering and design adapted to the need for very low artificial skyglow. The near zone is an area within a radius of approximately 30 km, depending on local conditions. The recommended regulatory framework has the following provisions:

1. Exclusive use of luminaires with no light emitted above horizontal;
2. Limiting lamp spectral content in the blue and near-ultraviolet region (below 500nm);
3. Limiting the maintained average illuminance;
4. Implementation of curfews and light-level controls;
5. Defining minimum utilance ratio;
6. Designing and mounting luminaires to minimise direct and reflected light in the direction of observatories.
7. Placing zonal lumens caps on the full area from which ALAN measurably contributes above 30° elevation from the observatory, in the context of a regional lighting master plan.

Observatories on the most remote mountaintops encounter lighting for special use cases in surrounding areas such as open-pit mines, military and border security operations, prisons, and wind farms. These enterprises can have especially high impact because of their short distances. Best practice design and associated regulation can limit uplighting, manage spectral output, and limit total luminous output.

There are strong corollary benefits that incentivise adoption of good lighting practices by host regions that protect internationally significant professional observatories, including sustainability, energy conservation, cost savings, synergy with protection of natural areas, enhancement of nighttime safety, and possible benefits to human health. Both *Fundación Starlight* and the International Dark-Sky Association have established criteria for international recognition of regions that support lighting standards suitable for observatory protection.

N.2 Recommended Practices and Regulatory Framework

N.2.1 For urban areas impacting observatories

1. Follow (and minimize upward deviation to no more than 20% from) the luminance and illuminance levels for road lighting of the appropriate lighting class according to CIE 115*.
2. Whenever possible, dynamically reduce roadway lighting level under low traffic conditions to the appropriate lower lighting class, and down to M6 or even below if the lighting is not immediately needed by any user.
3. Follow (and minimize upward deviation to no more than 20% from) CIE guidance for illumination levels and colour rendition of pedestrian areas by class.
4. Observe (and minimize upward deviation to no more than 20% from) CIE International Standard S 015/E:2005 for illumination of outdoor workplaces, carefully limiting the illuminated area to avoid spill light.
5. Adhere to the zone-appropriate limits by CIE environmental zone for lighting levels, Upward Flux Ratio (UFR) and Upward Light Ratio (ULR), with application of curfew-time reductions in lighting levels.
6. For Zones E2 and E3 impacting observatories, do not exceed the CIE maximum standard permitted luminance levels for building façades and do not exceed ANSI/IES standards for maximum luminances for illuminated signs.
7. Employ adaptive lighting technology in new installations and major renovations to minimise illumination when there is minimal demand.
8. Develop and follow lighting master plans that govern the planning, installation and maintenance of outdoor lighting, especially for urban and suburban areas.
9. Use fully shielded lighting and/or other techniques to assure that no light is directly projected above horizontal. Minimise the impact of unshielded lighting like electronic message boards and older sports lighting by imposition of curfews and limitations by usage zone.
10. Whenever possible, sharply limit any blue and near-ultraviolet (UV) (<500 nm) spectral content of luminaires. Employ sources with the narrowest possible

bandpasses, based on the actual need for colour rendition, and use light sources with the lowest blue-UV content available when colour rendition is necessary.

N.2.2 For observatories and their near zones

1. Each professional observatory with programmes requiring limiting dark-sky data for which regulation of artificial skyglow is critical should obtain a current baseline and well-sampled time series of night-sky brightness measurements.
2. International astronomical organisations are advised to form and support a data repository with consistent formatting to aggregate and make publicly available the sky-monitoring data.
3. Such sky-monitoring data should be collected under uniform protocols with standard calibration in the SI system of dark sky units.
4. All luminaires must provide no direct illumination above horizontal.
5. No architectural lighting, or electronic message displays with light emitted above horizontal be permitted in Zones E0 or E1 adjacent to observatories.
6. The Blue Light Content (percentage of light emitted below 500nm over the total light emitted) should be null**.** The lighting devices should be quasi monochromatic sources with maximum radiant flux (in watts per nm) lying within the 585-605 nm spectral range and having Full Width Half Maximum (FWHM) smaller than 18 nm. If modest color rendition is approved as a necessity, spectra with broader FWHM of ~100 nm can be used.
7. The maintained average illuminance should not be higher than 20% above the minimum maintained average illuminance suggested in technical norms/recommendations published by CIE or IES (i.e. 1.2 times the minimum maintained illuminance prescribed by the norm/recommendation) and this upward deviation must be kept at the lowest possible level by proper lighting design and employing suitable lighting controls.
8. Avoid exceeding luminance or illuminance limits by more than 20% in design in order to accommodate anticipated degradation of performance, and plan on active control and maintenance to achieve nearly constant light output.
9. A maximum possible reduction of the light levels, with a target of at least 66%, should be applied after curfew (or before that time whenever possible). Any lighting installation that is not needed for public safety reasons should be switched off at curfew. For isolated areas or hours of low traffic, sensors should be used to increase the light level as needed when any activity is detected. Without detection, the light level should be set down to 10% or less of the maintained average luminance or illuminance.
10. The utilance ratio should be at least 75%.
11. Luminaires should be designed and mounted to minimise direct and reflected light propagating in the direction of observatories. Approaches include optical beam

forming, directional shielding on the luminaire, and taking advantage of natural shadowing by buildings, landscaping and topological features when possible.

12. Each major professional observatory and controlling governmental body should undertake a modeling exercise to determine the total amount of fully shielded outdoor light allowable so as to slow the rate of growth of artificial skyglow to within the stated goal and to keep the total contribution substantially below the 10% dark site limit defined by the IAU. Local pressure for development, topography, marine layer prevalence and other local factors motivate the need for individual studies rather than a global prescription.
13. Special use cases in remote areas to employ fixtures consistent with the near-zone regulations to the maximum degree possible, consistent with safety and national and local regulations. Direct uplight and colour rendition should be employed if and only if absolutely necessary as required by safety or regulatory requirements.
14. Civilian regulators and military flight planners should exclude the observatory near zones from approved flight paths, and keep those paths as far from observatories as practicable.

N.3 Introduction

N.3.1 The Scientific and Strategic Value of Ground-Based Optical Observatories

In most sciences, discoveries are made as a result of interacting directly with the things being studied, be they molecules or mountains. In astronomy, the objects being studied are too distant for direct experimental interaction, and astronomers instead make their discoveries about the Universe by observing the behaviour of stars and galaxies from afar. In this section, we focus on major professional ground-based observatories with optical/infrared telescopes, typically with primary mirrors with large collecting areas. There are 40 telescopes in the world with mirrors of diameter 3 metres or larger, sited in the U.S., Chile, Spain, South Africa, Russia, China, Australia, and India, constituting a world-wide investment.

Ground-based astronomical observations continue to be the drivers of major, high-impact discoveries in astrophysics and basic physics. They are often essential to interpret observations from space-based telescopes. And they provide the critical data for planetary defence and key aspects of space situational awareness.

The fundamental constituents of the Universe, dark matter and dark energy, are being delineated by current and planned ground-based surveys. One of the primary goals of the Vera Rubin Observatory, an 8.4-meter telescope with a 3-Gigapixel camera now under construction in Chile, is to perform precision cosmological measurements. The distribution and total amount of dark matter will be determined through measurements of the gravitational distortion of the intrinsic shapes of billions of ultra-faint galaxies. The manner in which dark energy alters the rate of expansion of the Universe will be determined by the detection of faint supernovae in the distant Universe. Any skyglow in the night sky from artificial sources compromises the quality of these measurements.

The interplay among conventional matter, dark matter and dark energy is traced by the development and evolution of the massive filamentary condensations called large-scale structure. A probe for tracing the build-up of such filaments is the presence of the simplest atoms — hydrogen. The sightlines to distant quasars skewer the diffuse gas clouds aggregating in the filaments, providing a tomographic probe of their structures. The dense sampling is provided by instruments that couple the telescope focal plane to spectrographs with thousands of optical fibres. Two examples are the Dark Energy Spectroscopic Instrument (DESI) on the Kitt Peak 4-m Mayall Telescope in Arizona and the 4-MOST instrument under construction for the VISTA Telescope at the European Southern Observatory in Chile. Even at the high redshifts of the filaments, the best signals are recorded in the shorter wavelengths of the visible light spectrum. That colour region was particularly dark prior to the introduction of solid-state LED lighting. Now, careful control is needed to avoid the scattered light from blue-rich sources that provide a strong additional source of noise as these observations of the evolving Universe are being conducted.

The past four years have seen the revolution that celestial information can be detected by carriers other than electromagnetic radiation (light, radio, or X-rays). Extraordinarily sensitive laser interferometers can detect the distortion of space by the passage of gravitational waves to an accuracy of a fraction of the diameter of a proton. Identifying the source of these waves requires the coordinated deployment of multiple ground-based telescopes, supporting high-energy detections from specialised orbiting telescopes. Gamma rays and an optical flash were found to originate from the merger of two highly dense neutron stars in a relatively nearby galaxy. Many telescopes were needed to search the large area from which the gravitational wave detection arose, and large telescopes were needed for follow-up, as the source faded rapidly over hours and disappeared in a matter of days. It is expected that such objects will often be observed close to the horizon, where the effects of artificial glare are particularly apparent.

Another critical activity of ground-based observatories is planetary defence, the detection and mitigation of the impact of potentially hazardous asteroids. The search for Near-Earth Objects (NEOs) is driven to progressively fainter limits by the need for ample warning of the hazard of these objects, particularly those of 100m diameter and below, a population not currently well characterized. Orbits for these faint objects must often be determined from observations at low elevations, for which the impact of artificial skyglow is most significant. A similar programmatic requirement applies to the monitoring of space debris, where even the smallest detectable particles can damage valuable space assets. The additional noise added by artificial skyglow can reduce detection efficiency and the ability to maintain orbital parameters.

Astronomical research and planetary defence are thus critically dependent on having a clear view of the heavens, but there is currently great concern amongst astronomers about the increasing impact of human activities, particularly light pollution, on observations made with ground-based optical telescopes.

N.3.2 Impact of Artificial skyglow and Goals for Astronomical Site Protection

The expansion of human activity to even the most remote places, along with the growth in world population and economic development level and the reduction of the cost to provide outdoor lighting have led to exponentially increasing levels of artificial skyglow on average worldwide. This extra light in the sky veils faint celestial sources that provide key scientific information about the origins of the Universe and the origins of life. Protection of access to the dark night sky requires control of the growth of obtrusive lights in the regions hosting major astronomical research telescopes.

Most optical astronomical observations produce either images of the sky in a particular filter waveband (e.g. 400-500 nm) or spectra of individual objects (e.g. stars and galaxies). Either way, the quality of the observation (the 'signal-to-noise ratio') depends on the nature of the observation, the brightness of the object being studied, the exposure time, and three characteristics of the observing site:

1. The transparency of the atmosphere (weather)
2. The 'seeing' (a measure of the blurring imposed by turbulence in the atmosphere)
3. The surface brightness of the night sky

Telescopes are typically built at sites with predominantly good weather, good seeing and dark skies. Artificial skyglow can severely compromise the darkest skies. How much artificially induced skyglow is bad for astronomy? The exposure time needed to reach a given signal-to-noise when observing a faint object is typically proportional to the intensity of the sky background, so if light pollution increases the natural (airglow) surface brightness of the night sky by 1%, this is not a major cause for concern, but if it reaches 10%, the extra exposure time needed will reduce significantly the total amount of time available for observing, meaning that less science can be done with the (expensive) telescope time available and that the faintest objects cannot be observed at all in a reasonable exposure time. A more detailed technical description is found in Appendix 4.

During the past decades, the level of sky brightness increased significantly worldwide (Falchi et al. 2016). In the past decade, the globally averaged rate of increase was 2% per year in terms of both lit area and total radiance, (Kyba et al. 2017) roughly double the rate of world population growth during the same period. This increase is mainly related to three factors: the increase of the global population, economic growth, and the reduction of illumination costs (Tsao et al. 2010).

More recently, a new factor impacting the natural night sky integrity has emerged: the introduction of energy efficient, white light-emitting diode (LED) technology on large scales. That lighting technology may represent a threat to astronomical observations because of the higher blue content of white LED lighting, which scatters more efficiently in the atmosphere, compared to earlier lighting technologies (Aubé, Roby & Kocifaj 2013; Luginbuhl, Boley & Davis 2014). In addition, there is evidence that the high energy efficiency and relatively low cost of operation of white LEDs is fueling elastic demand for the consumption of light (Kyba et al. 2017), leading to higher overall light emissions. On the other hand, significant benefits are derived from the use of modern high quality LED lighting. LED flux can be easily controlled as a function of the time in accordance with the targeted usage. LED luminaires are also generally better focused on the surfaces that require lighting, with less light spill and in most cases with no upward light emissions.

A major increase in ALAN represents a serious problem for world-class ground-based astronomical observatories operating in the optical region of the spectrum (Luginbuhl, Walker & Wainscoat 2009; Aubé 2015). At the best observatory sites around the world, the darkest moonless skies at solar minimum have a natural (mainly airglow) surface brightness at a wavelength ∼550 nm (peak of visible response in green light) of V ∼21.9 mag/arcsec^2 (2.25×10^{-4} cd/m^2; Bará et al. 2020). The International Astronomical Union (IAU) has defined the upper limit of artificial light contribution for a professional site adequate for true dark-sky observing to be <10% at an elevation of 45° in any azimuthal direction. The newest professional observatories have been located at sites that are significantly below this limit of artificial light contamination.

The goal of the model regulatory framework proposed in this document is to reduce the current rate of increasing artificial skyglow at major professional observatories by a factor of two or more over the next decade and to achieve a decreasing rate of additional skyglow in the following decade for these sites.

The goal of the recommended framework covers most of the IAU requirement for site protection, but additional consideration is also needed to reduce the intensity of artificial skyglow as human activity wanes with time during the night, and of control of the colour of the artificial light sources. The Working Group recognises that the dominant *sources* of skyglow in cities may change through the night as sports and commercial lighting reduce, along with vehicle traffic. (Bará et al. 2018) The changing spectra of integrated urban light domes are likely to have different impacts on observing programmes involving imaging and spectroscopy.

N.3.3 Basis of Proposed Model Regulatory Framework

The Optical Astronomy Working Group strongly advocates an approach of quality lighting design to match the illumination level to need, limiting unnecessary spectral content, and taking more advantage of precise optical control to reduce spill light. A key aspect of site protection is defining close-in zones with more stringent limits on outdoor lighting levels. Adherence to recommended best practices and to the limits proposed below will accomplish the stated goal of gradually reducing artificial skyglow at professional observatory sites. The regulatory framework proposed for COPUOS endorsement provides a model for those national, regional and local governments committed to protecting the dark skies of professional observatories within their regions.

Major observatories are now typically funded and operated by international consortia, but they are situated in individual countries whose own laws apply to light pollution control. Some, such as the Observatorio de Roque de los Muchachos (ORM) in La Palma, have been protected by a pioneering law, Ley del Cielo, proposed by the Regional Parliament of the Canary Islands and regulated by law (Law 31/1988, R.D. 243/1992) by the Spanish Government. The government of Chile actively supports such laws in support of the astronomy enterprise (see the Chilean "Norma de Emisión para la Regulación de la Contaminación Lumínica" (1998/2012). International consortia, such as the European Southern Observatory, the Thirty-Meter Telescope International Observatory, the Giant Magellan Telescope Observatory and the South African Large Telescope Observatory, expect that the host countries and regions will commit to keeping the prime natural resource of a dark sky available to the project during its operational lifetime.

A finding at the UN-level that protection of the dark skies at major observatories is necessary to support the mission of the Commission on the Peaceful Uses of Outer Space (COPUOS) will provide a strong impetus for national and local governments to provide such protection. The provision of a model regulatory framework that can be adapted to particular local conditions is the path to implementation.

N.4 Recent History of the impact on the field of astronomy: The search for dark observatory sites away from light pollution of cities and on remote mountain tops

An overview of the development of observatories in the nineteenth and early twentieth centuries to take advantage of dark sky conditions is found in Appendix 4. The story of high-altitude observatories from the 1960s is quite different (HAO 2020). Numerous high-altitude dark sites were established for optical astronomy from 1958, when Kitt Peak in Arizona was founded as the U.S. national observatory. Some eighteen high-altitude optical observatories were built in the four decades from 1960 to 2000, including six in north central and northern Chile, commencing with the Cerro Tololo Inter-American Observatory (CTIO) at 2200 m in 1967. When many of these sites were established over forty years ago, the nearest urban concentrations were small to moderate-size towns with minimal impact on zenith sky brightness and only very modest impact near the horizon. Subsequent population growth and resource development has created measurable artificial light contribution at major professional sites such as those in southern Arizona, California, New Mexico, Texas, north-central Chile, the Canary Islands and southern Spain. Most of those observatories with 4-10-meter-diameter telescopes still fall within the IAU (above) - CIE (below) definition of dark sites, but many of them require strong cooperation from the surrounding population and regulation and enforcement by government entities to maintain that status.

All the world's largest optical telescopes are now at dark, high-altitude sites. Given that the cost of the European Extremely Large Telescope (E-ELT), with first light planned for 2025 on Cerro Armazones in northern Chile (altitude 2817 m), is substantially over one billion euros, comparable to the Thirty Meter Telescope planned for Mauna Kea in Hawaii and the Giant

Magellan Telescope for Las Campanas in Chile, it is understandable that only the very best accessible sites on Earth would be considered. Those sites with nearly untouched dark skies and large-aperture research telescopes are in northern and north central Chile (Cerro Armazones, Cerro Paranal, Cerro Las Campanas, La Silla); in Hawaii (Maunakea and Haleakala observatories), South Africa (SALT, HESS), and Australia (Siding Spring). Other particularly dark sites with small to moderate-aperture research telescopes and potential for development are in central Asia (Mt Maidanak Observatory, Uzbekistan; Mt Gargash, Iranian National Observatory; Hanle Observatory in the Indian Himalayas; Ali Observatory, western Tibet), in Mexico (San Pedro Martir Observatory), and in North Africa (Oukaimeden Observatory in Morocco Atlas Mountains).

In addition, arrays of radio antenna-sized light collecting dishes are deployed in remote locations to capture the faint flashes of blue Cerenkov radiation produced when high-energy gamma rays hit the top of the atmosphere. Such arrays are working in Utah and Arizona in the U.S., in Namibia, and in central Argentina. They require extremely dark sky conditions.

For these remote areas, growing artificial light impacts come from small villages near the mountain sites, major open-pit mining enterprises, wind farms, and other uses of sparsely populated regions. Although yet more remote sites exist, such as Antarctica, the implications for costs, sky coverage, and instrumentation flexibility in these sites make them impractical for the largest-scale astronomical observatories.

N.5 The effect of artificial skyglow on astronomical observations

Artificial light at night (ALAN) is a generic term representing the propagation of a variety of sources of artificial light into the outdoor environment. ALAN includes, but is not limited to, road lighting, exterior sports lighting, lighting of outdoor workplaces, area and landscape functional lighting, floodlighting, façade lighting and lighting for monuments and architectural structures. Besides common exterior lighting installations, festive lighting, light from building interiors passing out through windows, light from transportation and other minor sources of light contribute to ALAN as well.

The sum of all the adverse effects of ALAN is colloquially referred to as 'light pollution' and is more accurately known as 'obtrusive light'. Obtrusive light is 'spill light' or 'stray light' emitted by a lighting installation that falls outside the boundaries of the property for which the lighting installation is designed and because of quantitative or directional attributes, gives rise to annoyance, discomfort, distraction, or a reduction in ability to see or record essential information.

Artificial skyglow is the brightening of the night sky that results from ALAN scattered by the constituents of the atmosphere (gas molecules, aerosols and particulate matter) in the direction of observation. It includes radiation that is emitted directly above horizontal and radiation that is reflected upward from the surface of the Earth. Not all photons are scattered; many go on up into space and leave the Earth, as attested by observations from satellites which show major cities pouring light into space. Artificial skyglow adds sky noise to the astronomical measurement of faint objects, essentially veiling them.

The physics of photon scattering by air molecules shows that the scattering is wavelength-dependent and goes as $1/\lambda^4$, by a process known as Rayleigh scattering. Short wavelength blue photons ($\lambda \sim 450$ nm) scatter about four times more readily than red photons ($\lambda \sim 650$ nm), and ultraviolet ones ($\lambda \sim 350$ nm) do so some ten times more than red. Artificial skyglow close to blue-rich white light sources is therefore strongly weighted towards the blue end of the spectrum, which is also why the daytime sky is blue.

Cayrel et al. (1980) noted that the airglow from natural processes in the atmosphere had emission lines, especially those of atomic oxygen at 557.7, 630.0 and 636.4 nm, and those of atomic sodium at 589.0 and 589.6 nm. The sharp peaks in airglow emission at these wavelengths means that artificial skyglow from lamps that also have emission lines at or near these same wavelengths can be tolerated. In particular, low-pressure sodium street lights, whose production is being phased out, produce more or less monochromatic radiation at 589.0 and 589.6 nm (known as the sodium “D” lines), and scattering from these lamps could be more readily tolerated given that they leave the rest of the electromagnetic spectrum almost unaffected. Cayrel et al. recommended that skyglow equal to the airglow intensity would be acceptable at the sodium D lines, and hence low pressure sodium street lights were the recommended lamp type near astronomical observatories. These sources are no longer available, but the recommendation remains that (nearly) monochromatic sources in the yellow-orange range of wavelengths are the best near observatories.

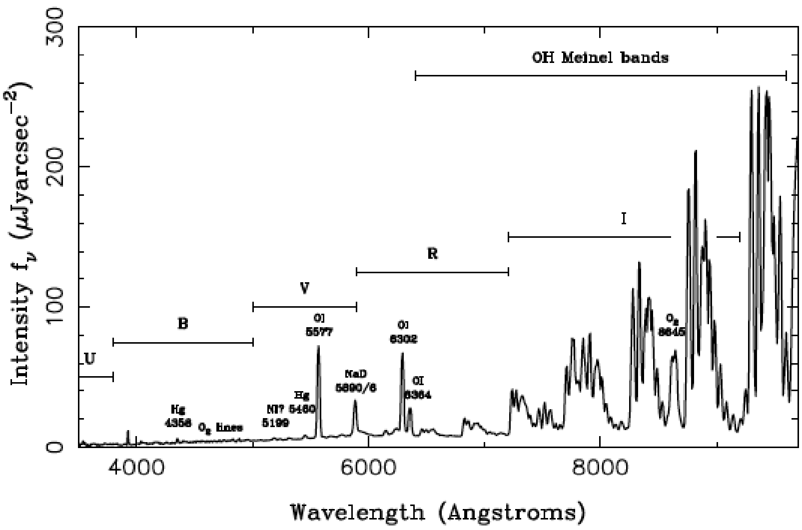

Figure N.1. Night sky spectrum from the William Herschel Telescope on La Palma, Canary Islands in March, 1991. The emission features from Hg and some of the Na are from street lights; the rest of the emission features are natural airglow. (Benn and Ellison 2007)

N.6 Instrumentation and techniques for measuring night-sky brightness at astronomical observatories and trends with time

N.6.1 Sensing night sky brightness

There are two basic approaches to measure and monitor night sky brightness (NSB): upward from the ground, or down from Earth orbit. The former mode involves direct sensing of the radiance of the night sky, while the latter mode predicts the night sky radiance seen from the ground by sensing the upward-directed radiance of light escaping the Earth's atmosphere and applying a model of how light propagates through the atmosphere. Ground-based measurements are model-independent but typically limited geographically and temporally.

Direct measurements of NSB from the ground involve sensors that integrate the flux of light through a known solid angle, within some wavelength range, and over some length of time. These divide into two types: single-channel devices, and multichannel devices. See Appendix 5 for a detailed list of devices and more extensive technical description in a complete version of this abbreviated section.

N.6.1.1 Single-channel devices

Single-channel devices are patterned on photoelectric photometers used by astronomers for almost a century. These devices rely on simple and well-understood physics, require little electric current to operate, and are usually small enough to be easily portable. Their light response is determined in the laboratory, with on-board lookup tables relating measured frequency to light intensity tied to calibrated light sources. Most commercially available devices have their own photometric passbands, which are typically transformed to the Johnson-Cousins *V* filter (547.7nm, FWHM 99.1nm). (Bessell 1990) Researchers have experimented with other filters, but *V* was chosen to match the bulk of existing literature data and the human visual response to light under photopic conditions.

N.6.1.2 Multi-channel devices

Multichannel detectors consist of arrays of light-sensitive elements whose output is multiplexed through one or more signal amplifiers. One commonly encounters cameras capturing two-dimensional images, particularly commercial digital single-lens reflex (DSLR) cameras and mirrorless interchangeable lens cameras (MILC). Some are operated with photometric filters to yield a particular effective passband, while others use Bayer filter mosaics to capture native (pseudo-)true-colour images through the combination of broadband red-, green- and blue-filtered data.

The main advantage these devices have over single-channel devices is the ability to produce two-dimensional images with some amount of both angular and spectral resolution. They are often paired with very wide-angle lenses to capture views with solid angles as large as 2π steradians (a hemisphere) in a single exposure, while others build up multiple-image mosaics with angular offsets between exposures so that the results can later be "stitched" together in software. As a result, these devices provide significantly more spatial information about the angular distribution of NSB than do single-channel devices.

Depending on the pixel scale of the detector, star images may be sufficiently sampled that flux calibration can be performed using spectrophotometric standard stars; other imaging systems make use of lab calibrations from reference light sources and employ integrating spheres for illumination of the camera and lens. Spatial distortion information for particular lens and camera combinations can be used to correct lens aberrations after the fact in software. (Mohar 2015; Kolláth & Dömény 2017)

N.6.1.3 Standardisation of Measurement

For matters requiring a decision process and the influence of stray optical radiation on astronomical observations, it is worthwhile to establish a common standard that is compatible with standards definitions and traceable to SI units. Astronomical photometry-based units (e.g., magnitudes/arcsec^2) do not satisfy such strict criteria. The magnitude per square arcsecond is most often encountered, however, being the native reporting unit of, among other devices, the popular Sky Quality Meter. Transformations between, e.g., magnitude per square arcsecond and the SI candela per square meter have been derived so that astronomical brightnesses in, e.g., *V* magnitudes, can be approximately transformed to photometric values. Noting that the relationship between these quantities depends on the spectral power distribution of the source, Bará et al. (2020) derived the transformation equation and calibrated it using zero-point luminances determined from a variety of skyglow spectra.

From a decomposition of the night sky spectrum, Z. Kolláth et al. (2020a) determined that the 'continuous' component of the natural sky (zodiacal light, scattered starlight and airglow pseudo-continuum) is nearly constant at all visible wavelengths and has a spectral radiance of ∼2 nW m^{-2} sr^{-1} nm^{-1}, or 2 *dsu* (dark sky units). Because of the relatively limited range of broad-band color variations of skyglow under clear, moonless conditions, digital camera-based, three-colour (RGB) radiance measurements in dsu give a usable sky brightness measurement (Z. Kolláth et al. 2020b). The hourly and nightly variations in natural skyglow can be of order 10 %. Therefore, an accuracy of 5 % or better for long-term characterization of an astronomical site is sufficient. High-quality cameras can provide ~2 % accuracy, more than adequate for the task.

Field measurements of NSB are affected by several environmental conditions (weather, air pollution, aerosol levels, variation in natural sky brightness, etc.). Thus it is essential to restrict measurements to nights when conditions are optimal for fieldwork. The necessary conditions to perform a field survey are the following:

- Moon at least ten degrees below the horizon.
- No clouds, fog, high aerosol content, or auroral activity.
- The Sun is at least 18 degrees below the horizon (astronomical twilight).
- Consistent set of spectral bandpasses and altitude-azimuth range.
- No direct light from artificial sources reaching the detector or the camera.
- High Galactic latitude and high ecliptic latitude (if pointed as opposed to all-sky).

These recommendations must be satisfied for long-term surveys to avoid misleading results for trends with time and comparison with other sites.

N.6.1.4 Data modeling

Modeling of observations can assist with their analysis and interpretation. For example, Duriscoe (2013) reported successfully recovering the anthropogenic component of NSB from mosaicked all-sky image data by subtracting 2-D models of natural sources of light. To the extent that construction and application of such models can be automated, they hold the promise of rapidly disentangling natural sources of light in the night sky from artificial sources for the purposes of modeling the angular and temporal evolution of skyglow. For spectrally resolved measurements, it is possible to model the natural components of NSB in wavelength space to subtract and remove them, leaving only the spectrum of artificial light.

N.6.1.5 Remote sensing of night sky brightness

The use of remote sensing platforms (namely, Earth-orbiting satellites) to infer NSB from direct measurements of upward radiance offers a number of attractive qualities. Chief among these is the ability to collect information about NSB from essentially anywhere on Earth, which decouples NSB measurement and monitoring from the deployment of ground-based sensors. Falchi et al. (2016) provided such a global data product. They established the radiance-NSB relationship using many thousands of ground-based NSB measurements. Sánchez de Miguel et al. (2020) recently found a strong correlation between the zenith NSB measured on the ground and orbital radiance measurements at both low and high resolution. They suggested that “it should be possible to create maps of regional sky brightness, or even global sky brightness maps” based on radiance measurements from the newest generation of orbital radiometers.

There are some problems with existing satellite remote sensing platforms. For example, the only instrument that currently achieves nightly global coverage, the Visible Infrared Imaging Radiometer Suite Day-Night Band (VIIRS-DNB; Cao et al. 2014), has no spectral sensitivity shortward of 500 nm. It is therefore effectively blind to the strong peak in white LED light emissions near 450 nm. This limits what can be reliably inferred concerning short-wavelength light sources within the data set. (Bará, Lima and Zamorano 2019) Other problems with current facilities include angular view dependency and effects of varying aerosol concentrations.

N.6.2 Monitoring night sky brightness

In the present context, “monitoring” of NSB refers to its repeated measurement to look for trends on timescales ranging from minutes to years. Monitoring entails the concerns of data handling, transmission and storage, as well as reduction and analysis.

N.6.2.1 Temporal sampling frequency

Monitoring considerations involve the frequency of data collection, both in the temporal and spatial senses. Given the timescales on which the natural NSB is known to vary, sampling frequency is important so as fully to understand the brightness range of the natural night; the same applies to skyglow, which tends to vary in slower and more predictable ways. Bará et al. (2019) studied the distribution of frequencies of variation and conclude:

> *It is clear that no single value of the NSB can be taken as fully representative of the variety of conditions at any given observation site, much like no single air temperature or wind speed could be attributed to it with a claim of completeness. As a matter of fact, the NSB results from the interaction between the light emitted by artificial and natural sources and the changing meteorological conditions, whose combined variability is larger than any of its individual factors.*

Bará et al. further considered whether the NSB sampling rate on a timescale of minutes influences the average indicators using measurement collected in long (e.g., yearly) time periods, concluding that it does not. Recently, Grauer et al. (2019) found evidence for significant variations in the natural NSB background, even near solar minimum, that correlate in time at observing stations separated by thousands of kilometres. This suggests that our knowledge of NSB influences is not complete. Although we have learned much about the contributors to total NSB in any particular direction on the night sky, we are not able accurately to predict it into the future.

N.6.2.2 Examples of trends in night sky brightness near astronomical observatories

A key point to note is that solar activity drives the airglow contribution to natural skyglow to vary during the 11-year solar cycle. Based particularly on data reported by Krisciunas (1997) and Krisciunas et al. (2007), as well as other long-cycle measurements, both Benn and Ellison (2007) and Walker and Schwarz (2007) conclude that the mean *V*-band zenith sky brightness at new moon brightens by ~0.4 - 0.5 mag arcsec^{-2} from solar minimum to solar maximum. The airglow variation corresponds directly to the 10.7 cm solar radio flux variation, while the small auroral contribution can lag by some 2 years. (Roach and Gordon 1973) The most recent solar minimum was in 2008, with another ending currently in 2020.

Sky brightness monitoring for professional observatories continues to be reported in the astronomy literature. Neugent and Massey (2010) compared spectrophotometry for Kitt Peak National Observatory over a two-decade interval, comparing samples from 1988, 1999 and 2009, with azimuthal sampling to gauge the impact of urban growth. Sampling at 30° elevation in the azimuth toward the adjacent city of Tucson, Arizona, was ∼30% brighter than the zenith observation. Corrected for solar activity, the zenith sky brightness in both Johnson-Cousins *B* and *V* bands increased by ∼10% in the first decade interval from an essentially pristine level fainter than 21.9 mag/sq. arcsec, then remained constant for the second decade sample. The Falchi et al. (2016) analysis found that Kitt Peak has an ALAN contribution of 8.4% in *V*-band, consistent with the 10% measurement. Downtown Tucson is ∼66 km along the line-of-sight from the summit of Kitt Peak. The population of the Tucson metropolitan area increased ∼28% over the first decade interval, and another 17% over the second decade. Local governments in the Tucson metropolitan area have strict and somewhat regularly updated outdoor lighting codes for the purpose of protecting southern Arizona observatories and for which local astronomy leadership more actively advocated in the second decade interval. One may conclude that such codes can have an effect in counteracting the effect of population growth in adjacent urban centres on artificial skyglow at observatories.

Walker and Schwarz (2007) reported on a combination of measurement and modeling for Cerro Tololo and Cerro Pachon in north-central Chile. The modeling was based on the population growth of the nearby cities of La Serena/Coquimbo (66 km distant) and Ovalle (59 km) as well as very nearby villages. The corresponding growth of artificial light contribution to zenith *V*-band was modeled to increase from ∼2% in 1992 to ∼9% in 2002. With the introduction of their national regulatory framework and active engagement of astronomy leadership with local governments for implementation, the expectation is that current levels of artificial zenith skyglow are ∼6% for Cerro Tololo and ∼2% for Cerro Pachon. The Falchi et al. (2016) determination for Cerro Tololo was ∼6%. Several sky brightness measurements are reported, based on reduction of scientific imaging data. The scatter is large, and correction would be required for dependences on solar activity and ecliptic latitude (as well as more frequent sampling) to determine whether the improvement at the few percent level has been verified. The two studies discussed here seem to support correlations between skyglow trends at observatories and regional outdoor lighting policies.

Patat (2008) reported six years of monitoring for Cerro Paranal in northern Chile. This intrinsically dark site allowed measurement of trends in sky brightness with solar cycle, and the excitation and variation of atmospheric emission on short timescales and seasonally. The study was based on the sky recorded in images and spectra taken for scientific purposes. The amplitudes of all the natural variations considerably exceed the Falchi et al. (2016) ALAN determination of ∼0.1% from local mines.

N.6.3 Recommendations for Professional Observatories

It is up to the scientific community to monitor and validate the trends in night sky brightness at professional observatories. This task requires a commitment of resources, potentially in equipment and certainly from the technical workforce. Metrics from full-sky pixel histograms can be very effectively interpreted (e.g., Duriscoe 2016), but require relatively high resolution all-sky cameras. Most observatories operate lower resolution all-sky cameras for weather and extinction monitoring; calibration and interpretation of those data streams is possible with effort. Scientific data archives can be mined after the fact for calibrated sky measurements, again requiring effort.

Each professional observatory with programmes requiring limiting dark-sky data for which regulation of artificial skyglow is critical should obtain a current baseline and well-sampled time series of night sky brightness measurements. That information is critical for objective assessment of the efficacy of regulation and for demonstrating to policy makers and implementers that the astronomers value and need their efforts.

One world standard is preferred, using the SI-system calibration in dsu proposed above, and a self-consistent data set is essential for each site. A standardised approach for the conditions of data collection is recommended, under the uniform protocols of N.6.1.3. Use of all-sky monitor data may be made most relevant to astronomy by selection of pixels above a minimum elevation like 20 degrees.

International astronomical organisations are advised to form and support a data repository with consistent formatting to aggregate and make publicly available the sky monitoring data collected.

N.7 Limiting the growth of urban light domes impacting professional observatories

N.7.1 General considerations

Control of urban light domes can be critical to professional observatory operations; for example, island mountain-top sites can be impacted by coastal towns, which are not always shielded by a marine layer. Many older continental sites have seen the substantial growth of nearby urban areas since their founding. The principles of quality outdoor lighting design and active control can be applied to limit the growth of urban light domes that contribute ALAN above 30° from a professional observatory's horizon. That elevation is the practical limit for most limiting observations. Depending on the population, industrial mix, and commitment to quality lighting, the relevant distance can extend to 200 or 300 km. Similar impact is seen from growing urban light domes on natural areas (Koen et al. 2018; Garrett, Donald & Gaston 2019).

This section summarises the fundamental outdoor lighting recommendations for the limitation of skyglow and obtrusive light, primarily as published by the International Commission on Illumination (CIE), the highest scientific authority in the field of light and lighting and a recognised standards body. It contains additional sections relevant specifically to astronomy (N.7.7 and N.7.8). An overview of the summaries of selected CIE Technical Reports and International Standards can be found in Appendix 7, completed by the Terms of Reference of the newest work items carried out in CIE.

Figure N.2. Light domes from Tucson (120 km - 1 million population) and Phoenix (220 km - 4 million population), Arizona, as photographed by M. Pedani in 2008 from the summit of Mt. Graham, site of the world's largest optical telescope.

N.7.2 Road lighting recommendations

Road lighting may be the most familiar and visible to the general public. Luminaire manufacturers and lighting designers have paid serious attention for a long time to efficient distribution of the luminous flux and avoiding excess and stray illumination.

CIE Technical Report 115:2010 introduces a classification system according to the type and operational profile of roads for motorized traffic, pedestrians and low-speed traffic areas, conflict areas, and also for some specific situations. Lighting classes for motorized traffic, based on road surface luminance, range from M1 (the highest class) to M6 (the lowest class), recommending average luminance 2.0 cd m^{-2} for M1 to 0.30 cd m^{-2} for M6. Lighting classes M4 and M3 are most commonly associated with major roads with a transport collecting function while M5 and M6 are the most common lighting classes in residential areas. The quality of lighting for each of the lighting classes is defined by two additional parameters.

Recommendation: Follow (and minimize upward deviation to no more than 20% from) the luminance and illuminance levels for road lighting of the appropriate lighting class according to CIE 115.

An exceptional situation occurs when a particular traffic volume is used as a criterion to provide a lighting system. In those situations – and if no other criterion prevents it – reduction to a lighting level lower than M6 after rush hours may be considered. This is mainly applicable for motorways, which are in general highly predictable and without oncoming traffic, sharp bends or intersections. Systems operating at very low levels cannot be classified as road lighting but as a system of visual guidance. A decision to reduce the lighting level below M6 can be made to satisfy environmental or astronomical site protection arguments. In remote areas and natural reserves, environmental arguments are regarded as even more important than guidance for road users and the lighting can be switched off or decreased to a minimum maintained level.

Recommendation: Whenever possible, dynamically reduce roadway lighting level under low traffic conditions to the appropriate lower lighting class, and down to M6 or even below if the lighting is not immediately needed by any user.

Lighting classes for pedestrians and low speed traffic areas recommend values of both minimum and average horizontal illuminance. Average horizontal illuminance for the highest lighting class P1 is recommended to be 15 lux (lx), and at the other end, 2.0 lx is recommended for the lowest class P6. Minimum horizontal illuminance requirements can be derived from the average as 1/5 of its value. To provide for uniformity, the actual value of the maintained average illuminance may not exceed 1.5 times the value indicated for the class. A high colour rendering contributes to a better facial recognition.

Recommendation: Follow (and minimize upward deviation to no more than 20% from) CIE guidance for illumination levels and colour rendition of pedestrian areas by class.

N.7.3. Recommendations on lighting of outdoor workplaces and area lighting

Lighting of outdoor workplaces is covered by the international standard CIE S 015/E:2005. Lighting quality parameters in terms of the maintained illuminance E_m, overall uniformity U_o, Glare Rating G_{RL} and colour rendering index R_a are recommended for typical workplaces, areas, visual tasks, and activities in a wide range of applications. Regarding safety and security, the recommended maintained illuminance ranges from 5 lx for places with very low risks, up to 50 lx for high risks. To provide appropriate visual conditions, however, these values can be considerably higher, in the most visually demanding applications even up to 300 lx. Such values, which are quite normal in interior lighting, are extremely high outdoors where large areas are to be lit; sometimes it is not an easy task to design lighting systems providing such high values, understanding that these can potentially heavily contribute to skyglow. By careful lighting design it is thus very important to focus the lighting onto clearly demarcated target areas consisting of the task area and surrounding area as specified in the standard. Time management is crucially important here too; many industrial sites and other outdoor workplaces are lit all night even with no users present.

Recommendation: Observe (and minimize upward deviation to no more than 20% from) CIE International Standard S 015/E:2005 for illumination of outdoor workplaces, carefully limiting the illuminated area to avoid spill light.

N.7.4 Limiting the obtrusive light from outdoor lighting installations

Limitation of the effects of obtrusive light from outdoor lighting installations is guided by the Technical Report CIE 150. This document introduces environmental zones as areas where specific activities take place or are planned and where specific requirements for the restriction of obtrusive light are recommended. These zones are defined in Table N.1.

IES-IDA Lighting Zone (IDA 2011)	**IES Environmental Zone** (IES 2014)	**CIE Environmental Lighting Zone** (CIE 2017)	**Description**	**Examples**
LZ0	E1 (Intrinsically Dark Areas)	E0 (Intrinsically Dark)	Parks and similar protected areas where controlling light pollution is a high priority. No artificial light at night is expected in this zone, and its use is often prohibited.	UNESCO Starlight Reserves; IDA International Dark Sky Parks; major astronomical observatories.

LZ1	E1 (Low Ambient Lighting)	E1 (Dark)	Areas where lighting might adversely affect flora and fauna or disturb the character of the area. The vision of human residents and users is adapted to low light levels. Lighting may be used for safety and convenience but it is not necessarily uniform or continuous. After curfew, most lighting should be extinguished or reduced as activity levels decline.	National parks; UK Areas of Outstanding Natural Beauty
LZ2	E2 (Moderate Ambient Lighting)	E2 (Low District Brightness)	Areas of human activity where the vision of human residents and users is adapted to moderate light levels. Lighting may typically be used for safety and convenience but it is not necessarily uniform or continuous. After curfew, lighting may be extinguished or reduced as activity levels decline.	Sparsely inhabited rural areas; villages or relatively dark outer suburban locations

LZ3	E3 (Moderately High Ambient Lighting)	E3 (Medium District Brightness)	Areas of human activity where the vision of human residents and users is adapted to moderately high light levels. Lighting is generally desired for safety, security and/or convenience and it is often uniform and/or continuous. After curfew, lighting may be extinguished or reduced in most areas as activity levels decline.	Small town centres; suburban locations
LZ4	E4 (High Ambient Lighting)	E4 (High District Brightness)	Areas of human activity where the vision of human residents and users is adapted to high light levels. Lighting is generally considered necessary for safety, security and/or convenience and it is mostly uniform and/or continuous. After curfew, lighting may be extinguished or reduced in some areas as activity levels decline.	Town and city centres and other commercial areas with high levels of nighttime activity

Table N.1 Summary of IDA, IES and CIE lighting and environmental zones.

It is recommended that the CIE zones E0 and E1 are assigned to all locations within 100 km of a major optical astronomy observatory regardless of the level of urban development. E2 is recommended to designate locations within 30 km of an operating urban optical astronomy observatory and locations between 100 km and 300 km from a major optical astronomy observatory regardless of the level of urban development.

The CIE 150 stipulates upward ratios differently for luminaires (ULR) and lighting installations (UFR) consisting of at least from 4 luminaires as shown in Table N.2, taking into account environmental zoning of an area.

Upward Light Ratio (ULR) of a luminaire is the proportion of the flux of a luminaire or installation that is emitted, at and above the horizontal, when the luminaire(s) is (are) mounted in its (their) installed position. This is the traditional method to limit skyglow and suitable to compare different single luminaires. ULR however does not take account of the light from the luminaires reflected upwards from the illuminated surfaces.

Upward Flux Ratio (UFR) takes into account both direct and reflected upward components so it is suitable for comparison of whole lighting installations (four or more luminaires) and to assess the lighting design concerning luminaire distribution, geometries of the installation, surfaces reflectance and the area to be lit.

Light Technical Parameter	**Type of installation**	**Environmental Zone**				
		E0	**E1**	**E2**	**E3**	**E4**
Lighting Environment		Intrinsically dark	Dark	Low district brightness	Medium district brightness	High district brightness
Upward Light Ratio (ULR)		0 %	0 %	2.5 %	5 %	15 %
Upward Flux Ratio (UFR)	Road	N/A	2 %	5 %	8 %	12 %
	Amenity	N/A	N/A	6 %	12 %	35 %
	Sports	N/A	N/A	2 %	6 %	15 %

Table N.2. Maximum values of Upward Light Ratio (ULR) of luminaires and Upward Flux Ratio (UFR) of lighting installations

Two sets of limiting values are given, dependent on the levels of lighting already in the area. The more restrictive values are applied after the curfew hour when the spill light should be such that it will not be obtrusive to the majority of recipients. Careful attention needs to be given to the limitation of spill light, including consideration of the type of lighting system to be used, the type of light distribution, their specific location and aiming and the need for fitting of louvres, baffles or shields. The less restrictive values are applied to dark hour activity when the spill light will be perceived as less obtrusive by the local population while they are still awake. Astronomical observations have no such time of night distinction. The limiting values are based on the use of conventional lighting technology, but with good practice being employed through the selection of appropriate lighting levels, appropriate lighting equipment and aiming practices.

Recommendation: Adhere to the zone-appropriate limits by CIE environmental zone for lighting levels, UFR and ULR, with application of curfew-time reductions in lighting levels.

Limitation should be applied also to the effects of over-lit building facades and signs in urban areas outside observatory near zones. In urban lighting it is important to audit and determine appropriately the luminance values that provide visibility. Lighting levels are often increased and can cause negative impacts, such as ratcheting (continuous increase in the lighting levels), glare, rise of energy usage, light pollution and increase in utilisation of lighting. Therefore, some restrictions to the lighting must be made accordingly, ideally following a lighting masterplan (CIE 234).

Recommendation: Local authorities and all legal parties that are involved in planning, implementation and maintenance of lighting installations are encouraged to develop and follow a lighting master plan, especially for urban and suburban areas.

In floodlighting in urban areas outside of the near zones, appropriate lighting techniques might help to significantly reduce light pollution. Wherever possible, light from luminaires should be directed downwards and uplighting should be avoided. If no support for luminaires is available at a higher point than the object of illumination, for example a monument up on a hill, the light beams from luminaires must be narrow enough so that no light is missing the object. If necessary, shields and baffles can be used to fine-restrict the angular beam range. The achieved luminance levels should be aligned with the surroundings to avoid annoyance, glare and significant reflected light. Rigorous adherence to curfew times must take place in this case, too.

CIE 150 recommends maximum permitted values of average surface luminance on building facade L_b and luminance of signage L_s for each of the environmental zones. For building façade luminance, values lower than 0.1 cd m^{-2} are required within zones E0 and E1, 5 cd m^{-2} is limit for the zone E2, 10 cd m^{-2} for E3 and maximum 25 cd m^{-2} is permitted in the zone E4. Allowed sign luminances are higher but their size is usually much smaller. Less than 0.1 cd m^{-2} is required for zone E0, 50 cd m^{-2} for E1, 400 cd m^{-2} for E2, 800 cd m^{-2} for E3 and 1000 cd m^{-2} is the maximum permitted value within the zone E4. These values apply both for pre- and post-curfew except that in Zones 0 and 1 the values shall be zero post curfew. The values for signs do not apply to signs for traffic control purposes.

The Working Group notes that there are other standards for maximum sign luminances that are much more stringent. IES/IDA standards (in the zones corresponding to the CIE zones) call for 0.0 in E0, 20 cd m^{-2} for E1, 40 cd m^{-2} for E2, 80 cd m^{-2} for E3 and 160 cd m^{-2} for E4. (IDA 2019, IES 2019)

Recommendation: For Zones E2 and E3 impacting observatories, do not exceed the CIE maximum standard permitted luminance levels for building façades and do not exceed ANSI/IES standards for maximum luminances for illuminated signs.

N.7.5 Adaptive lighting as a powerful tool to reduce light pollution

The role of adaptive lighting (sometimes called 'smart lighting') is to adapt in a holistic way the whole set of lighting parameters to the needs of users depending on current conditions such as availability and quality of daylight, occupancy pattern, user preferences, etc.,changing both temporally and spatially. Adaptive lighting is capable of exploiting dynamic variation of changes and bringing it to a higher level of utilisation.

Adaptive road lighting incorporating a system of sensing devices and smart controllers is promising for considerable reduction of unnecessary illumination, energy consumption and obtrusive light. The lighting level can be adapted to the actual needs of the users with respect to the nature of their visual tasks and the current conditions in traffic, weather, environment, ambient light of the surroundings, etc. Where the pattern of variation in parameter values is well known (e.g., from records of traffic counts on traffic routes) or where it can be reasonably assumed (e.g., in residential areas) a simple time-based (pre-defined) lighting control scheme may be appropriate. In other situations, an interactive control system linked to real-time data may be preferred. This approach will permit the normal lighting class to be activated in the case of road works, serious accidents, bad weather or poor visibility, while it can also compensate for the excess of luminous flux due to the maintenance factor of the lighting installation. The Technical Committee CIE TC4-62 "Adaptive Road Lighting" started in 2020 to prepare relevant guidelines and recommendations.

When there is no user of lighting present, an additional lowest light level can be defined. Both major roads illuminated to higher levels and streets in large residential areas can be dimmed down to a maintained minimum level necessary to safeguard basic visual functions for safety reasons. The lowest lighting class for pedestrians P6 with 2.0 lx minimum illuminance can be appropriate for this purpose. In such cases, the provided lighting, however, cannot be deemed as road lighting as explained in section N.7.2 above. Adoption of the minimum maintained level approach can lead to huge potential savings. For a case study with standard assumptions, it has been shown that energy saving potential of more than 60% can be achieved for residential areas with M5 and M6 roads only by implementing multi-level lighting control (Gasparovsky et al. 2018). Current lighting technology permits LED luminaires to dim down to 5% of the peak luminous output. In this case, authorities can regulate lighting installations in a way to serve from, e.g., M2 class down to M6 class and even lower when no users are present.

When astronomical observatories are being impacted, full switch-off of some lighting installations can be considered if the safety level remains unaffected and/or other measures will compensate for loss of lighting (e.g., temporal reduction of speed limit by means of interoperating smart traffic systems), and if lighting is switched on again once sensors detect oncoming vehicles or persons. This special case can be also combined with non-lighting measures such as retro-reflective signage, special road lane painting and so on, ensuring the maintenance of road safety levels.

Adaptive lighting is just beginning to permeate lighting applications, and time is required for adaptive lighting to be applied habitually. There is strong evidence that a combination of appropriate lighting class selection, use of the right luminous distribution and the implementation of adaptive lighting control can significantly decrease the level of obtrusive light beginning from the existing over-illuminated areas and coming to new installations that are required to be designed.

Recommendation: Employ adaptive lighting technology in new installations and major renovations to minimise illumination when there is minimal demand.

N.7.7 Fully shielded luminaires

Fully shielded luminaires are important in an urban setting to control the stray light most damaging to nearby observatories emitted above horizontal, and should be employed whenever possible. Urban nighttime activity, however, draws many exceptions to the general restriction. LED advertising message boards send 15-30% of their luminous output above horizontal. Neon and internally illuminated signs have little directional control. Older "decorative" lighting of tall structures like skyscrapers and bridges can be aimed upward. Low-quality sports lighting often has an upward component, particularly if there is inadequate mast height.

Two mitigations are possible in the case of these de facto exceptions. The immediate one is the imposition of curfews. Sports lighting should be employed only when the field is engaged. This approach may require a change in community attitudes for tighter control of the times of lighting athletic fields in public parks, for example, hence community support. Lighted advertising and decorative structure lighting should be switched off at curfew time, typically midnight. On-site signage should be turned off no later than one hour after close of business if that is later than the curfew.

In the longer term, any replacements of lighting installations should be made consistent with full shielding. Externally illuminated billboards should have fully shielded luminaires, top-mounted. Modern sports lighting, with proper beam formation and full shielding can be implemented to avoid trespass into surrounding areas as well as into the night sky. Sufficient mast height in sports stadia is required to avoid upward tilt; bearing the increase in marginal cost is a consequence of commitment to limiting artificial glare.

Consumer demand and regulatory pressure can combine to reduce the luminance of digital message boards and other lighted signs. Current technology puts limits on the dynamic range of brightness of LED message boards, such that clear visibility during the day at >5000 cd/m^2 cannot then accommodate appropriate low lighting levels at night. Incentives for running digital message boards at dark sky acceptable 100 cd m^{-2} instead of the currently claimed technological limit of >300 could include a later beginning of curfew.

Recommendation: Use fully shielded lighting or other techniques to assure that no light is directly projected above horizontal. Minimise the impact of unshielded lighting like electronic message boards and older sports lighting by imposition of curfews and limitations by usage zone.

N.7.8 Limitations on spectral content for illumination, particularly in blue and UV

Although monochromatic sources are the best for astronomy, urban living places greater demand on colour rendition. As discussed in N.5 above, the artificial sky brightness is inversely proportional to the fourth power of the wavelength of the emitted light. Therefore, it is always recommended to use red or amber (or very warm) light instead of blue (or cool) sources of lights. At far away distances from the observatory, lighting technology requirements can be less restrictive because of the atmospheric extinction that also favors the removal of short wavelengths (blue). Thus, lighting sources with limited emission below 550nm can be used (CIE 150, 2017). Most LEDs with high colour temperatures and Metal Halide (MH) lamps strongly emit in blue, causing severe damage to astronomical observation.

Previous studies (Luginbuhl et al. 2014) have shown that LEDs with high colour temperatures and MH lamps produce a sky brightness 8 times higher than monochromatic Low Pressure Sodium (LPS) vapor lamps and 3 times higher than nearly monochromatic High Pressure Sodium (HPS) vapour lamps. Due to the high content in blue light of such lighting technologies, the artificial sky brightness resulting from these sources is visible at distances greater than 300km (Luginbuhl et al. 2014). LED light sources with colour temperatures (CCT) of 2200K, 2700K and 3000K show low to moderate blue radiant flux (no more than 15% in the latter one, with respect to the integrated radiant flux over the human visible spectrum, 380 - 780nm) but their effects are still significant.

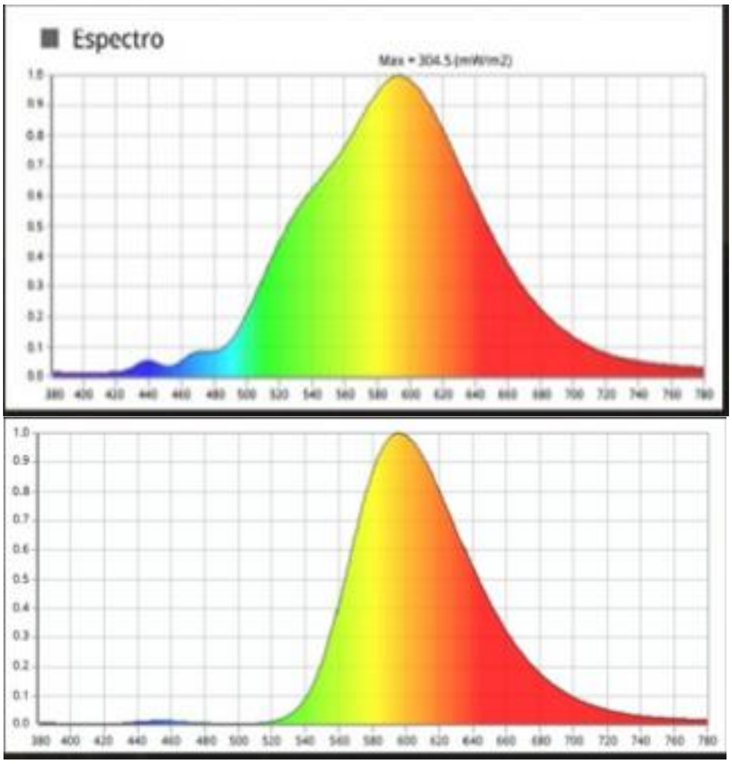

Figure N.3 Upper - “ultra-warm LED” spectral output; Lower - PC amber LED.

The light pollution effect of these LED sources has been modeled through the software used to calculate the New World Atlas of Light Pollution (Falchi et al. 2016) with spectral weighting (Aubé et al. 2014). Figure N.4 shows the Star Light Index (SLI) maps (Aubé et al. 2014) which is a comparison at constant lumens based on the scotopic response of human vision. The results can be seen in Figure N.4 for colour temperatures of 2200K, 2700K and 3000K respectively. The 2200K CCT LEDs, also known as “ultra-warm LEDs” have an integrated radiant flux in the blue (between 380nm and 499nm) of less than 8% of the total emitted radiant flux in the visible range of the human eye (between 380nm and 780nm). Even though this effect is relevant in terms of blue emission reduction, the propagation effect is not that different from the 2700K and 3000K LED lamps. Note that LED sources with CCT 2700K and 3000K comply with many recommendations and even regulations, like the Chilean Norma Lumínica (S.D. N043/2012 Ministry of Environment). The results shown in Figure N.4 indicate that the reduction in blue light percentage of those LED sources (between a 5% to 15% of the spectral emission at wavelengths between 380nm and 780nm) does not generate a significant reduction in the artificial sky brightness.

On the other hand, Figure N.4 also shows the effect of using PC amber LED type (phosphor-converted amber LED) in the propagation of light pollution, using the model of Falchi et al. (2016). The difference is clearly seen between the light pollution generated with PC amber LED and with LED sources of 2200K, 2700K and 3000K (Figure N.4). The spectral response of a PC amber LED does not have emissions below 500nm, significantly reducing the atmospheric scattering. As shown in Figure N.4, only at the centre of large urban areas would the increase in artificial sky brightness be between 5.12 to 10.2 (colour red), indicating that the Milky Way would not be visible. This result confirms that in the vicinity of optical observatories, the best options are sources with around 1% of emission in the range 380 - 499 nm, with respect to the visible spectrum. It should be noted that these calculations have been performed with PC amber as one of the first available LED technologies with minimum blue light content, a solution that is currently being replaced by more efficient options.

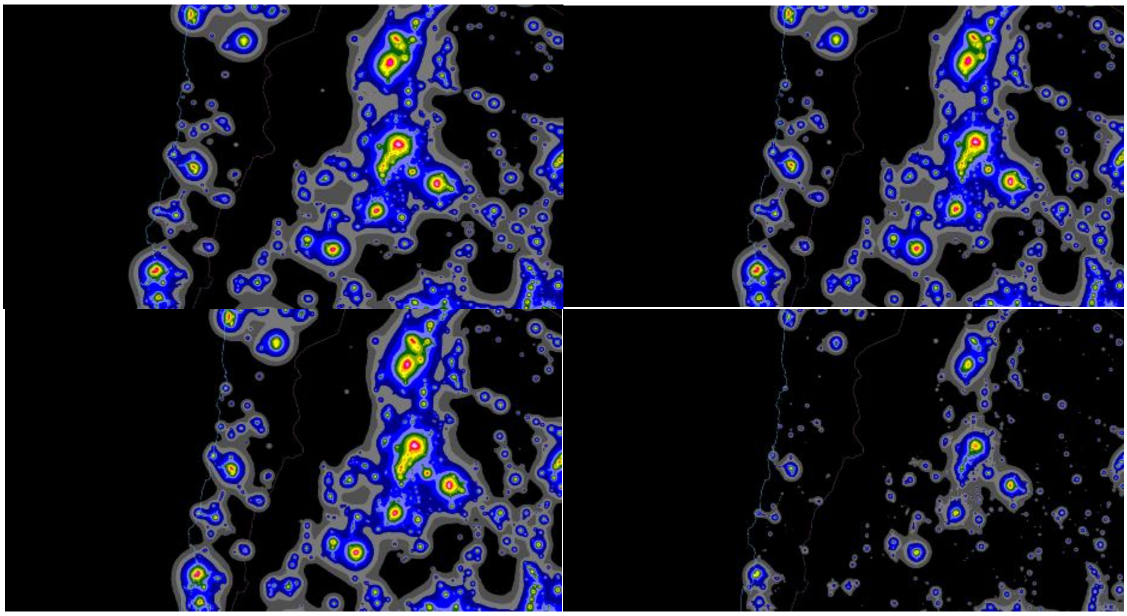

Figure N.4. Comparatively modeled La Serena - Antofagasta Star Light Index (SLI) from Falchi et al. (2016) algorithm for different colour temperature LEDs. The SLI shows how heavily the night sky will be polluted in the scotopic band (i.e., for a dark-adapted eye) using different lamp types and assuming a constant installed lumen and angular emission function. The step from one colour to the next is a doubling of the sky brightness, starting at a fractional contribution to the natural brightness of 0.01 to 0.02. Upper left: 2200 K; upper right: 2700 K; lower left: 3000 K; lower right: PC Amber.

Recommendation: Whenever possible, sharply limit any blue and near-ultraviolet (UV) (<500 nm) spectral content of luminaires. Employ sources with the narrowest possible bandpasses, based on the actual need for colour rendition, and use light sources with the lowest blue-UV content available when colour rendition is necessary.

N.7.9 Conclusions and outlook

Obtrusive light, due to its complexity and novelty, is still separately addressed within different disciplines, e.g. ecology, astronomy, and illuminating engineering. Furthermore, the lighting research community and industry use different methods for the assessment of lighting installations. Lighting technology currently offers technical solutions for efficient, controllable and environmentally friendly lighting. Therefore, knowledge is highly fragmented, and it is sometimes difficult to compare and translate outcomes from and between different fields. Joint effort of CIE, IAU and other interested organisations is recommended to find a common language and to improve the balance between lighting needs and obtrusions.

N.8 Model regulations to protect dark skies in the immediate areas around professional observatories

N.8.1 Introduction

The near zones around professional observatories can be a mix of CIE Zones E0, E1 and potentially E2. The physical radius is approximately 30 km, depending on topology and state of development. Regions that implement protection for such zones meet the criteria for certification as unique Dark Sky Places, as defined by both *Fundacion Starlight* and the International Dark-Sky Association. Appendix 6 provides details. The Working Group advocates that the need for any artificial light at all must be demonstrated to be approved in the E0 and E1 zones in immediate proximity to the observatory, and the need for colour rendition must also be demonstrated even into adjacent Zones E2; otherwise very narrow bandpass sources are required.

Many regions located nearby major observatories have implemented measures to mitigate the negative impact of ALAN on the astronomical research capabilities. Interventions involving the adoption of modern lighting technologies and design practices are expected to yield the greatest positive environmental consequences (Duriscoe, Luginbuhl & Elvidge 2013). Countries vary on whether the ordinances are applied through the framework of environmental law or land use zoning.

One example is the Observatorio Roque de los Muchachos in Canary Island (Spain), which benefited from an efficient national protection law (*Ley del cielo*) with many successful approaches to limit the threat to the night sky integrity of the Island of La Palma. As for many other cases worldwide, a number of criteria have been defined to protect the night sky as efficiently as possible. The recommended regulatory framework has the following provisions:

1. Exclusive use of luminaires with no light above horizontal;
2. Limiting lamp spectral content in the blue and near ultraviolet region (< 500nm);
3. Limiting the maintained average luminance or illuminance;
4. Implementation of curfews and light-level controls;
5. Defining minimum utilance ratio;
6. Designing and mounting luminaires to minimise direct and reflected light in the direction of observatories.
7. Placing zonal lumens caps on the full area from which ALAN measurably contributes above 30 deg elevation from the observatory, in the context of a regional lighting master plan.

The Working Group discusses each of these criteria in the following sections to establish best practices to protect professional astronomical observatories from the effects of light pollution originating in the immediate surroundings. The focus on areas within a radius of 30 km leads to specific measures when compared to areas located farther. As an example, the blue and UV contents of the light spectra are very important elements to restrict for sources located nearby because of the higher scattering efficiency in the short wavelength, but this factor may be less important for farther sources because of the atmospheric extinction that is higher in the same spectral range. To identify the optimal measures for each criteria, the Working Group takes into account the successful experiments in many regions of the world but more specifically from the Canary Islands case, and also considers the latest advances in light pollution modeling.

N.8.2 Exclusive use of luminaires with no light above horizontal

It has been demonstrated that full shielding is a very efficient way to reduce the artificial skyglow (Cinzano and Diaz Castro 2000, Luginbuhl et al. 2009, Duriscoe et al. 2013, Schroer and Holker 2014, Aubé 2016). The first element to avoid is any emission of light above the horizontal plane. This is particularly important when the observer is located at a higher altitude than the source and especially when no obstacles can block the light propagation toward the observer. Obstacles are generally associated with buildings, trees and hills. This blocking effect will be treated in Section N.8.7.

According to Aubé et al. (2018), removing the upward emissions can reduce the sky radiance by a factor of around 2. This is actually a conservative value because that result was obtained assuming a constant luminous flux, but in reality, when the Upward Light Ratio (ULR) is reduced, the flux can also be reduced if one wants to keep the same illuminance on the ground level. This result was obtained without obstacles blocking, because in the case of the studied observatory (Halaekala), light pole heights are higher than houses in the nearby city of Kahului (pop. 26,337). This small city located 30 km away from the observatory is responsible for 96% of the sky brightness when looking toward Honolulu at 20 degrees elevation. This latter result clearly shows why the light emissions from the immediate areas around an observatory are the most important to control.

Recommendation: All luminaires must provide no direct illumination above horizontal.

One implementation is that the luminaires are fully shielded with flat glass and without any tilt angle.

Recommendation: No architectural lighting, or electronic message displays with light emitted above horizontal be permitted in Zones E0 or E1 adjacent to observatories.

N.8.3 Limiting the lamps' spectral content in the blue region

Blue light content (BLC) is defined by the IAU as the percentage of light emitted below 500nm over the total light emitted. Blue light can be more harmful than other wavelengths to the living organism but also to the sky brightness as it impacts astronomical observations. Prior to the introduction of LED lighting, the blue/UV region of the spectrum was naturally dark; now that spectral region is under threat.

Recommendation: The BLC should be null. The lighting devices should be quasi monochromatic sources with maximum radiant flux (in watts per nm) lying within the 585-605 nm spectral range and having Full Width Half Maximum (FWHM) smaller than 18 nm. If modest color rendition is approved as a necessity, spectra with broader FWHM of 110 nm can be used.

As an example, the Spanish *Ley de Cielo* offers more detailed specifications: The maximum radiant flux peak should also lie between 585 and 605 nm. Its spectral content cannot have more than 0.6% of the radiant flux below 440 nm, less than 1.5% below 500 nm, less than 7%, below 550nm, and at least 90% of the radiant flux must lie between 550 and 700 nm. Moreover, any blue light peak should be lower than 2 % of the maximum radiant flux. Most PC amber LEDs comply with these requirements. Those light sources with spectral bandwidth up to 110nm have the advantage of having a colour rendering index[1] higher than 40.

N.8.4 Limiting the maintained average illuminance

Recommendation: The maintained average illuminance should not be higher than 20% above the minimum maintained average illuminance suggested in technical norms/recommendations published by CIE or IES (i.e. 1.2 times the minimum maintained illuminance prescribed by the norm/recommendation) and this upward deviation must be kept at the lowest possible level by proper lighting design and employing suitable lighting controls.

As an example, in North America, the American National Standard Practice for Design and Maintenance of Roadway and Parking Facility Lighting RP-8 document, the Illuminating Engineering Society (IES) suggests, for a local road and a pavement class R3, a minimum maintained average illuminance of 9 lux. In such a case, the installed maintained average illuminance should not be higher than 10.8 lux (1.2 × 9).

Recommendation: Avoid exceeding luminance or illuminance limits by more than 20% in design in order to accommodate anticipated degradation of performance, and plan on active control and maintenance to achieve nearly constant light output.

[1] C**olour rendering index** (**CRI**) is a quantitative measure of the ability of a light source to reveal the **colors** of various objects faithfully in comparison with an ideal or natural light source.

If necessary, the frequency of maintenance interventions on the lighting installation can be increased to reach that goal, although the claimed low depreciation of LED luminous output should also contribute. Active control can also dim initial output to desired levels.

N.8.5 Implementing curfews and light level controls

Curfew is time during which stricter requirements (for the control of obtrusive light) will apply. This is often a condition of use of lighting applied by a government controlling authority, usually the local government. A typical curfew start time is midnight and end time at dawn, but varies by locality.

Recommendations: A maximum possible reduction of the light levels, with a target of at least 66%, should be applied after curfew (or before that time whenever possible). Any lighting installation that is not needed for public safety reasons should be switched off at curfew. For isolated areas or hours of low traffic, sensors should be used to increase the light level as needed when any activity is detected. Without detection, the light level should be set down to 10% or less of the maintained average luminance or illuminance.

N.8.6 Defining minimum utilance ratio

Utilance (*U*) of an installation is the ratio of the luminous flux received by a defined reference surface to the sum of the individual output fluxes of the luminaires of the installation. The reference surface should include surrounding areas as established in norms. The value of the quantity *U* tells us how much light is projected where it is needed; the rest is useless and therefore contributes unnecessarily to light pollution.

Recommendation: Utilance should be higher than 75% ($U > 0.75$), but any higher value is better.

N.8.7 Luminaires to minimise light propagating toward observatories

Recommendation: Luminaires should be designed and mounted to minimise direct and reflected light propagating in the direction of observatories. Approaches include optical beam forming, directional shielding on the luminaire, and taking advantage of natural shadowing by buildings and topological features wherever possible.

It has been shown by Aubé (2015) that blocking the direct view to a luminaire can significantly drop the sky brightness observed from that luminaire. This is because the light cannot escape the lighting area without experiencing at least one reflection off a built (or natural) surface. This advantage must be realised in the context of minimizing the overall luminous intensity requirement for the whole installation.

N.8.8 Lumen Caps

The restrictions on individual fixtures are critical, as defined in the sections above. To slow, stop, and reverse the rate of increase of artificial skyglow, a regional lighting master plan is needed as well. While CIE prescriptions for lighting control by installation in near zones E0 and E1 and possibly E2 are likely to be adequate, ALAN impacting the skyglow as seen from the observatory above elevation 30 degrees may originate from towns and cities within a radius of hundreds of km. The elevation limit is a practical one above which most limiting observations are conducted. Control of the total artificial skyglow therefore requires integral limits by zone, based on usage, topography, and pressure for development. Falchi and Bará (2020) make the case for the importance of integral limits as well as per-fixture limits, and describe a linear modeling approach relating key indicators to the integrated limits.

Recommendation: Each major professional observatory and controlling governmental body undertake a modeling exercise to determine the total amount of fully shielded outdoor light allowable to slow the rate of growth of artificial skyglow to within the stated goal and to keep the total contribution substantially below the 10% dark site limit. Local pressure for development, topography, marine layer prevalence and other local factors motivate the need for individual studies rather than a global prescription.

N.9 Special cases

Observatories in remote locations can encounter enterprises with outdoor lighting needs and regulations that can be more difficult to adapt to dark sky conformity, e.g.,open-pit mines, military and national border security operations, prisons, wind farms, and airports.

Modern quality lighting design can be applied to 24/7 pit mining operations very effectively to preserve operational safety while significantly reducing stray light. Monochromatic sources can be extensively used; when and where colour rendition is required (e.g., to distinguish oil from blood), an additional bank of broader band lighting can be switched on, then switched off when the operation is complete. Beam-forming can limit the amount of up-light resulting from operations when full shielding is not possible, for example, in the headlamps of large mining vehicles that traverse steeply sloped roads. Matching the illumination level to the task with appropriate contrast to dark night surroundings greatly reduces the total light levels of the operation.

Military bases, prisons, and border security operations often require lighting large areas for nighttime operations. These lighting installations can nevertheless be fully shielded and observe the minimum maintained average illuminance + 20% criterion as recommended above for observatory near-zone protection.

Wind farms, transmission line towers, broadcast antennas and any tall structures in aircraft approach paths are typically required to be lit with warning lights. Mitigations near observatory sites can include monochromatic sources (red) and physical shielding for the small solid angle subtended by an observatory with a direct sightline.

Airports have strict requirements for safe operations. Nevertheless, apron work areas can have fully shielded fixtures and illuminance levels appropriate for night-time work without over-lighting. Rotating beacons can be blanked out for the narrow azimuth that contains any direct sightline.

Aircraft wingtip lighting is comparable in apparent brightness to that of the brightest stars. The Working Group recommends that civilian regulators and military flight planners exclude the observatory near zones from approved flight paths, and keep those paths as far from observatories as practicable.

N.10 Incentives for compliance

Although it is often possible to enact high-quality outdoor lighting policies in various jurisdictions, anecdotally we find many instances in which those policies essentially fail in their intent to bring regulatory solutions to the problem of light pollution. Most often the failures result from inadequate implementation and enforcement of laws and norms relating to outdoor lighting. Governments may enact good outdoor lighting policies for the right reasons, but those policies may not have the intended effect either because they are enforced inconsistently (or not at all), or because there is inadequate public support for the policies to sustain a strong and effective enforcement regime. Well-intended outdoor lighting policies can therefore fail to obtain improvements to either lighting or night-time conditions. However, rather than simply proscribing bad behaviours through statute or rulemaking, better results with respect to the protection of night sky quality may be obtained through incentivisation of good behaviours. The notion of “incentives” should broadly cover both subjects: both the path to arrive at enactment and the enforcement side after enactment is achieved. We consider several factors that may incentivize voluntary compliance, especially in cases where the social and/or political will to enforce or to concentrate on the protection of local observatories does not yet exist. A discussion of the relationship between ALAN and human health is found in the bio-environment report.

N.10.1 Sustainability, valuing limits on light pollution, cost savings

N.10.1.1 Sustainability

The notion of sustainable living is usually thought of in relation to reducing the consumption of non-renewable resources, increasing renewability, and limiting the generation of waste. As a result, it tends to be targeted toward improving energy efficiency in order to lower dependence on fossil fuels and limit the emission of climate-altering carbon gases to the atmosphere. However, it can be argued that the drive to improve the energy efficiency of outdoor lighting in the name of reducing the carbon footprint of lighting has resulted in significant increases in ALAN emission into the nighttime environment (Kyba et al. 2017), in effect exchanging one environmental harm for another. The reduction of light pollution is therefore an environmental goal of comparable value to actions taken to achieve more environmentally just and sustainable societies. (Hölker et al. 2010) A truly 'sustainable' world would achieve an appropriate balance between legitimate human needs for ALAN and the deleterious effects of outdoor light at night.

N.10.1.2 Valuing limits on light pollution

Light pollution is a manifestation of waste: artificial skyglow is literally light that benefited no one, whether emitted directly into the night sky or reflected from the ground. Eliminating wasted light therefore saves electricity as it reduces light pollution. The benefits of reducing light pollution in this fashion have been offset somewhat by the arrival on the global market of highly energy-efficient solid-state lighting such as LED.

Prior to the introduction of energy-efficient solid-state lighting (SSL), electricity used to power outdoor lighting accounted for about 1.5% of global power consumption. (Brown 2006) Now, an economic 'rebound effect' implied by remote sensing of night lights, attributable to cheap and widely available LED lighting, has the potential to offset most or all of the expected environmental benefit of the transition away from older technologies. It has been argued that the low cost of operating modern lighting calls for a new definition of 'efficiency' that considers primarily the total cost of light including its impact rather than simply its electricity cost of production. (Kyba, Hänel & Hölker 2014) Although the world usage of light is typically quantified in units such as watts of electric power consumption, regulation of light per capita is a better framework to address this problem of consumption of a commodity with environmental consequences. Policies can be formulated in ways that meet development needs, protect public safety, and provide property owners with reasonable use of outdoor ALAN on their own properties while capping the total light emission in a region in a way that is equitable.

Absent regulation of outdoor light use to curb consumption, solid-state lighting threatens the same negative externalities that accompanied earlier technologies in terms of light pollution. When these externalities are considered as part of the total cost of SSL retrofits, their apparent benefits to society appear to fade. For example, one study of a municipal SSL retrofit effort in the United States found a ten-year rate of return of -146.2% compared to +118.2% when the costs associated with avoided carbon emissions and health outcomes related to ALAN exposure are ignored. (Jones 2018)

N.10.1.3 Reduced costs of providing public lighting

In many parts of the world, the provision of lighting in public spaces is taken as a critical infrastructure component to be provided by governments; in certain areas, like the rural U.S, local governments tend to contract the provision of public lighting to private vendors such as electric utilities. Solid-state lighting (SSL) technology has greatly reduced the cost of providing outdoor lighting. Governments could bank the savings, but available evidence suggests in many cases the difference funds the purchase and installation of new lighting. (Kyba et al. 2017) It is also thought that in many cases, public lighting levels are excessive even in relation to IES/CIE-recommended minima. Lowering lighting levels in the transition from older lighting technologies to SSL can avoid over-lighting while delivering both expected cost savings and expected environmental benefits.

An example of a case where an SSL retrofit resulted in a reduction of light emission is in the city of Tucson, U.S. During the transition from legacy high-pressure sodium technology to 3000K white LED, the city reduced the light emission of the street lighting system by about 60%, resulting in an operational cost savings of USD 2.16 M per year. (Barentine et al. 2018) In addition, the municipality has prolonged the life of its white LED lighting products by routinely operating them below the maximum possible power draw; it realises further electricity savings by actively dimming most of the city's ∼19,500 street lights during the night hours.

N.10.2 Synergy with protection of natural areas

Protected natural areas sometimes host astronomical observatories. Examples include Observatoire Mont-Mégantic in the Mont-Mégantic International Dark Sky Reserve in Québec, Canada; Mt. John Observatory in the Aoraki Mackenzie International Dark Sky Reserve, New Zealand; and AURA Observatory in the Gabriela Mistral International Dark Sky Sanctuary, Chile. The long-term viability of these sites for conducting ground-based astronomical observations is in part secured by the landscape-level legal protections associated with the sites' international dark-sky designations. Support for these protections, and the land-use restrictions with which they are generally associated, is often related to the economic benefits associated with 'astrotourism', a form of tourism in which visitors come to view and enjoy dark night skies. (Collison & Poe 2013). This form of sustainable tourism can support rural economies, particularly in areas where previous industries based on non-renewable resource extraction have wound down. (Mitchell & Gallaway 2019)

N.10.3 Quality lighting enhancing night-time safety

Besides its ancillary benefits to the protection of the nocturnal environment, the notion of 'quality' lighting is intended to improve conditions at night for safe transit and use of outdoor spaces by the public. The goal of quality lighting is to improve visibility while minimizing environmental impact and the cost of operation. While there is scant unambiguous scientific evidence to date to support the conjecture, we hypothesize that the same lighting design that is best for minimizing light pollution is also most conducive to public safety by carefully targeting the use of ALAN to outdoor task performance at night, thereby reducing wasted light.

A significant limiting factor in drawing clear and unqualified conclusions about the interaction of outdoor lighting and crime and road safety is that carefully controlled studies involving both are notoriously difficult to design, conduct, and interpret. As a result, many of the claims about outdoor lighting and its impact on public safety -- for better or worse -- may be fundamentally wrong. (Marchant 2017; 2019) The lack of conclusive studies makes developing evidence-based policy and setting minimum illumination levels particularly challenging. More information is found in Appendix 8.

Appendix 1. Table of Contents

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Appendix 4. History of light pollution impacts on astronomy

A4.1. History of the impact on the field of astronomy: nineteenth century urban observatories and their fate in the twentieth century electric light era

In Europe and in North America, many astronomical observatories were established or expanded during the nineteenth century. This was a century of great advances in telescope design, with achromatic refractors being the dominant and preferred technology from the 1820s when Fraunhofer's 24-cm aperture Dorpat telescope was installed at the Tartu Observatory in what is now Estonia (in 1824). The 15-inch (38-cm) Harvard refractor in Cambridge Mass. followed in 1847 and many others since, culminating in the Yerkes Observatory 40-inch refractor of 1897.

The great majority of these nineteenth-century observatories were in or near major cities and hence in an urban environment, which in many cases was having electric street lighting installed before the end of the century. Examples of major urban observatories established during or before the 19th century are the Royal Greenwich Observatory; the Paris Observatory; Allegheny Observatory in Pittsburgh, Ohio; Potsdam Astrophysical Observatory and many more. A survey indicates that 43 astronomical observatories were established in the nineteenth century, mainly in large cities of Europe and North America. Thirty-four of these were established in the second half of the nineteenth century. Just ten major observatories were operational in the world in the late 18th century. A useful list is found at Observatories (2020).

The statistics show a tremendous growth in observatory and telescope numbers from the mid-19th century onwards, concurrent with the beginnings of the new science of astrophysics from the 1860s. Nearly all these new institutions were in major cities, and ironically many were being established from the 1880s, just as the first electric street lighting was also being installed. The result was a catastrophic conflict between the requirements of astronomers for dark skies and the rush to illuminate cities with the new marvel of electric lighting, ostensibly to enhance safety and enable cities to commercial activities late into the night.

Today none of the urban observatories established before 1900 are still used for astronomical research observations. Light pollution put an end to that. Some are still the office headquarters for astronomers to analyse data or develop instrumentation (for example the Paris Observatory, the Royal Observatory Edinburgh). Some have been converted to museums or facilities for public outreach enabling the public to look through old telescopes (such as the Royal Observatory, Greenwich;, the Kuffner Observatory, Vienna and the Yerkes Observatory in Wisconsin). Others have closed altogether or moved to a better site, such as the Berlin Observatory (established 1830, moved to Babelsberg, Potsdam in 1906) and the Melbourne Observatory, established in 1862 and closed in 1945.

Only a few 19th century observatories which were sited on remote mountain tops are still used for research. Pic du Midi Observatory was established in 1878 at an altitude of 2877 m in the French Pyrenees and continues to be a world-class observational site for astronomical research. In 2013 the International Dark-Sky Association (IDA) gave accreditation to the surrounding Pic du Midi International Dark Sky Reserve which gives protection to the site from light pollution. The other famous mountain-top observatory still undertaking research is the Lick Observatory, which opened in 1881 on Mt Hamilton (altitude 1283 m) in California. It is now severely affected by light pollution from San Jose and the rest of Silicon Valley, and its future is in jeopardy.

A4.2. History of the impact on the field of astronomy: The search for dark observatory sites away from light pollution of cities and on remote mountain tops

Charles Piazzi Smyth (1819-1900), the Astronomer Royal for Scotland, was the father of mountain-top astronomy. In 1856 he was funded by the British Admiralty to lead an expedition to Tenerife, where he established a temporary observing site on Alta Vista at 3300 m altitude, on the eastern slopes of the 3700-m high Teide. Here he used small telescopes to observe the diffraction rings and Airy disk[2] of star images which are only seen in very steady air. He also observed the separation of close double stars such as alpha Piscium, an observation which was impossible from low altitude sites such as Edinburgh (Smyth, 1858, 1863).

By the end of the nineteenth century, it was realised that mountain-top observatories provided significant benefits for astronomy. At first the benefit was from sharper images arising from more steady air. However, in the twentieth century the additional benefit that came from darker skies away from light pollution was realised. As discussed above, mountain observatories were established at Pic du Midi (2877 m) in France in 1878 and on Mt Hamilton (1283 m) in California in 1881. These were the first two permanent astronomical observatories that enjoyed very dark skies at high altitude.

Mt Wilson Observatory was perhaps the most famous of the new mountain observatories of the early twentieth century. It was established from 1904 by George Ellery Hale on the San Gabriel Mountains near Pasadena, about 30 km north-east of downtown Los Angeles and

[2] The diffraction rings and Airy disk of a point-like star are an artefact of the wave nature of light on entering an aperture such as a telescope. In turbulent air at low altitude observatories these fine features are normally washed out in a blurred image.

only 10 km from central Pasadena (as the crow flies). It was the site for the famous 60-inch reflecting telescope of 1908 and 100-inch Hooker reflector of 1917. Mt Wilson was operated by the Carnegie Institution, but after 80 years of research, the light pollution made it no longer a viable site. The research observations were closed from 1984, although Georgia State University still runs an array of smaller telescopes on Mt Wilson.

Mt Wilson Observatory is probably the most successful optical observatory in the history of astronomy, and was made famous by the pioneering achievements of Edwin Hubble observing faint galaxies in the 1920s. These were observations that greatly benefitted from dark skies. In fact the first electric street lights in Los Angeles were installed in March 1916, but it is a reasonable assumption that the skies above Mt Wilson would have remained dark for most of the 1920s and even 1930s.

Perhaps surprisingly, the drive to establish further high altitude observatories at dark sites did not immediately follow the successful development of the Mt. Wilson Observatory outside of Los Angeles, California in the early 1900s. Probably two world wars and the economic depression of the early 1930s delayed their introduction in the first half of the twentieth century. Another major mountain-top observatory in the first half of the twentieth century was the Palomar Observatory at 1712 m on Palomar Mountain, which was established in 1936. It is about 100 km northeast of San Diego in California, and the site of the famous 200-inch (5-m) Hale telescope. It is also 150 km southeast of Los Angeles, so today is affected by light pollution, with the artificial light contribution in excess of 60% of the natural sky background when the two urban areas are not blanketed by marine layers (from Falchi et al. 2016). The Swiss also built the Sphinx Observatory on the Jungfraujoch at 3700 m in 1937. It was an ideal site for ultraviolet astronomy. These were the only mountain observatories of the first half of the twentieth century.

A4.3. The effect of artificial skyglow on astronomical observations

skyglow from ALAN arises from the scattering of light particles, or photons, by air molecules and aerosols, after they have been emitted from streetlights or other artificial light sources. Scattering is simply the change in direction of a photon as a result of its interaction with an air molecule, normally oxygen or nitrogen, or aerosol like a water droplet or dust particle.

The immediate result of scattering is a brightening of the night sky from artificial light at night. Not all photons are scattered – many go on up into space and leave the Earth, as attested by observations from satellites which show major cities pouring light into space. A bright night sky or skyglow affects astronomical observations because inevitably every observation of an astronomical object, be it star, nebula, galaxy or quasar also records skyglow photons mixed together with those from the object under study. The task of the astronomer is to interpret just the photons emitted by the astronomical body. In principle, a knowledge of the skyglow intensity should allow its contribution to be subtracted from the raw observation. In practice, there are difficulties in doing that.

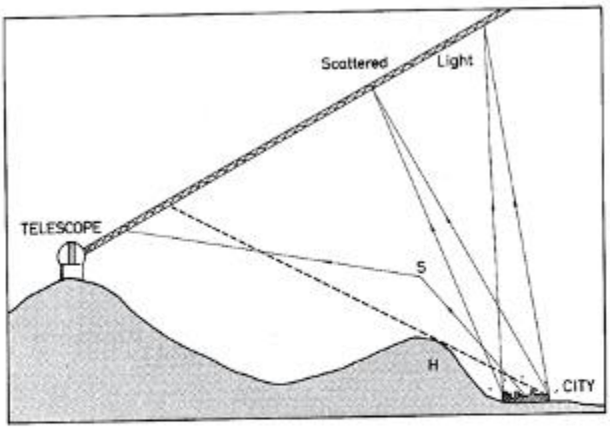

Fig. A2.1. Mechanism of sky illumination from artificial lights. Light emitted by the city can reach the telescope either by direct scattering involving air molecules and aerosols located in the telescope field of view, or by multiple scattering in indirect paths such as that shown via the point S. Note that the hill H protects part of the telescope beam from direct illumination. Figure courtesy of Cayrel et al. (1979).

There are two ways of interpreting the effect of skyglow on astronomy. One approach is to consider that every observation requires a certain minimum contrast in order reliably to detect and deduce information about the astronomical source. The contrast *C* is just the ratio of the object's detected flux or surface brightness to that of the skyglow, or

$C = S_* / S_{SG}$

where S_* is the recorded surface brightness of the astronomical image and S_{SG} that of the skyglow recorded in the same image area (including natural airglow). If we consider an observatory A where the skyglow is twice as bright as at observatory B, the contrast for a given object seen from A will be halved which may make the contrast too low for detection or for analysis. Observatory A will therefore have access to fewer objects than B. If the type of object is uniformly distributed throughout space, then a simple analysis shows that an increase of skyglow by a factor of 2.5 reduces the number of accessible objects by a factor of four.

A more concise relationship between the brightening of limiting magnitude and artificial skyglow is sometimes expressed by the equation

$$\Delta m = -2.5 log(a + 1)$$

where *a* is the ratio of artificial skyglow to natural airglow. This is sometimes referred to as the skyglow formula.

A second analysis considers the noise in any physical measurement. Every measurement of a physical quantity has an uncertainty as a result of noise. In the case of astronomy, the noise is from the statistical uncertainty that the number of photons collected represents a true measure of an object's brightness. Both S_* and S_{SG} have noise. Our raw measurement is of $R = (S_* + S_{SG})$ and the noise is the combined noise from both sources. If S_{SG} is subtracted from R, then the remaining noise is still that of R and includes the skyglow noise. So our measurement of S_* is adversely affected with an extra dose of noise, even though the skyglow signal has been subtracted.

The report of Cayrel et al. (1980) noted that the natural airglow had emission lines, especially those of atomic oxygen at 557.7, 630.0 and 636.4 nm, and those of atomic sodium at 589.0 and 589.6 nm. The sharp peaks in airglow at these wavelengths meant that any artificial skyglow from lamps that also have emission lines at these same wavelengths can be tolerated. In particular, low pressure sodium street lights produce more or less monochromatic radiation at 589.0 and 589.6 nm (known as the Na D lines), and these meant that scattering from these lamps could be more readily tolerated, given that they leave the rest of the electromagnetic spectrum almost unaffected. Cayrel et al. recommended that skyglow equal to the airglow would be acceptable at the D lines, and hence low pressure sodium street lights were the recommended lamp type near astronomical observatories. These sources are no longer available, but the recommendation remains that (nearly) monochromatic sources are the best near observatories.

The physics of photon scattering by air molecules shows that the scattering is wavelength-dependent and goes as $1/\lambda^4$ a process known as Rayleigh scattering. Short wavelength blue photons (λ ∼450 nm) scatter about four times more readily than red photons (λ ∼650 nm), and ultraviolet ones (λ ∼350 nm) do so some ten times more than in the red. skyglow is therefore strongly weighted towards the blue end of the spectrum, which is also why the daytime sky is blue. This fact also strongly favours nearly monochromatic lights near 600 nm for street lighting, as their orange colour scatters relatively little compared to emissions from bluer lamps.

Finally we note that the brightness of skyglow at an observatory depends on the distance r to a town and its population P. Treanor (1973) has modeled this with the formula

$$S_{SG} / S_{AG} = (A/r + B/r^2) exp(-kr)$$

where A, B and k are constants, with estimated best values being $A = 1.8 \times 10^{-5} P$, $B = 13.6 \times 10^{-5} P$ and $k = 0.026$ km^{-1}.

On the other hand Walker (1977) fitted a slightly different formula and obtained with $C = 0.01 P$. In either case, the polluting skyglow declines rapidly with distance r and is proportional to the population *P* and hence to the number of streetlights, assumed to be low pressure sodium.

Appendix 5. Instrumentation and techniques for measuring night sky brightness and sky background in astronomical observatories and trends with time

A5.1 Sensing night sky brightness

There are two basic approaches to measure and monitor night sky brightness (NSB): look upward from the ground, or look down from Earth orbit. The former mode involves direct sensing of the radiance of the night sky, while the latter mode predicts the night sky radiance seen from the ground by sensing the upward-directed radiance of light escaping the Earth's atmosphere and applying a model of how light propagates through the atmosphere.[3] Ground-based measurements are model-independent but typically limited geographically and temporally. We focus here largely on the ground-based approach, but briefly comment on new capabilities for remotely sensing NSB.

Direct measurements of NSB from the ground involve sensors that integrate the flux of light through a known solid angle, within some wavelength range, and over some length of time. These divide into two types: single-channel devices, and multichannel devices. Table A1 summarises a variety of both types of device.

Instrument	**Manufacturer**	**Type**	**Sensor(s)**	**Bandpass**	**Reference**
Sky Quality Meter (SQM)	Unihedron (Canada)	Single-channel; wide- (SQM) and narrow-field (SQM-L)	TSL237 light-to-frequency (LTF) converter	Native (modified Johnson-Cousins *V*)	Cinzano (2005, 2007)
Telescope Encoder and Sky Sensor WiFi (TESS-W)	Universidad Complutense de Madrid (Spain)	Single-channel	TSL237 LTF	Native (modified Johnson-Cousins *V* with enhanced red response)	Zamorano et al. (2017)

[3] This approach was taken by Falchi et al. (2016) in predicting average zenith brightnesses around the world from satellite remote sensing data based on a model described by Duriscoe (2013). Although their model was calibrated with thousands of sky brightness measurements, anecdotally the predictions are often in error by as much as 20%. One reason for this may be that the model assumed a flat Earth with no topography, while we know that topography can screen out anthropogenic light from distant sources, even at the zenith; however, see the recent work of Sánchez de Miguel et al. (2020) addressing scattered light in the Earth's atmosphere.

Digital single-lens reflex (DSLR) + fisheye lens	Various	Multi-channel	Complementary metal-oxide semiconductor (CMOS)	Broadband RGB	Hoot (2007)
Astronomical camera + lens or telescope	Various	Multi-channel	CMOS or charge-coupled device (CCD)	Various	Duriscoe et al. (2007); Falchi (2010); Aceituno et al. (2011)

Table A1. Summary of several devices for measuring the brightness of the night sky.

A5.1.1. Single-channel devices

Single-channel devices are patterned on photoelectric photometers used by astronomers for almost a century. These devices rely on simple and well-understood physics, require little electric current to operate, and are usually small enough to be easily portable. They typically employ light-to- frequency (LTF) converters whose output is a signal pulse stream, the frequency of which is linearly proportional to received light intensity. Their light response is determined in the laboratory, with on-board lookup tables relating measured frequency to light intensity tied to calibrated light sources. Since the response of LTF converters is also sensitive to the ambient operating temperature, sensing of the air temperature is required to properly correct the measured frequency. This is usually done on board the measurement device.

Most commercially available devices have their own photometric passbands modeled on Johnson-Cousins *V*. Researchers have experimented with other filters, but V was chosen to match the bulk of existing literature data and the human visual response to light under photopic conditions. Infrared blocking filters are often used in combination with the quantum efficiency profile of the semiconductor material of the LTF to achieve the desired effective passband. Optics such as lenses may be used to constrain the opening angle defining the device’s angular field of view. Although single-channel device measurements indicate only the brightness of the night sky averaged across a fairly large acceptance angle, some authors report creating crude two-dimensional maps of NSB by interpolating spot measurements from these devices. (Zamorano et al. 2014)

Single-channel devices have a number of advantages, including ease of use; portability; a physically simple sensing mechanism; temperature compensation; good repeatability; rapid capture and display of data; and relatively long historical basis. However, their use also involves certain drawbacks. In order to sense a sufficient amount of yield a measurable signal, they must integrate light over a fairly large solid angle. They yield no valuable spatial resolution in most applications, making them generally unsuitable for monitoring the behaviour of light domes near the horizon. Lastly, there are differences among commercially available devices in terms of photometric passbands that complicate comparison of results among different device types.

A5.1.2. Multi-channel devices

Multichannel detectors consist of arrays of light-sensitive elements whose output is multiplexed through one or more signal amplifiers. The ideal example is a spectroradiometer, which provides a complete set of information about the wavelength-dependent brightness of the night sky in any given direction. However, the current generation of such devices is too slow for capturing time- resolved NSB data, and they tend to be prohibitively expensive. One more commonly encounters cameras capturing two-dimensional images, particularly commercial digital single-lens reflex (DSLR) cameras and mirrorless interchangeable lens cameras (MILC). Some are operated with photometric filters to yield a particular effective passband, while others use Bayer filter mosaics to capture native (pseudo-)true-colour images through the combination of broadband red-, green- and blue-filtered data.

The main advantage these devices have over single-channel devices is the ability to produce two- dimensional images with some amount of both angular and spectral resolution. They are often paired with very wide angle lenses to capture views with solid angles as large as 2π steradians (180º) in a single exposure, while others build up multiple-image mosaics with angular offsets between exposures so that the results can later be “stitched” together in software. As a result, these devices provide significantly more spatial information about the distribution of NSB than do single-channel devices.

Depending on the pixel scale of the detector, star images may be sufficiently sampled that flux calibration can be performed using spectrophotometric standard stars; other imaging systems make use of lab calibrations from reference light sources and employ integrating spheres for illumination of the camera and lens. Spatial distortion information for particular lens and camera combinations can be used to correct lens aberrations after the fact in software. (Mohar 2015; Kolláth & Dömény 2017)

Multichannel devices have certain drawbacks. Due to sensor size and pixel scale, they generally have limited angular resolution. When imagers are used with fisheye lenses to capture all-sky data in single exposures, significant spatial distortions are induced near the horizon. Their multi-spectral functionality is usually limited to a few broad passbands. And, lastly, there is as yet no standard, SI-traceable reporting unit for night sky measurements.

A5.1.3. Colour considerations

An adjunct issue to the brightness of the night sky is its spectral power distribution (SPD). As the preceding discussion suggests, the sensed NSB is the result of integrating, with respect to wavelength, the convolution of the SPD of the night sky with the spectral bandpass of the measuring device. The SPD of the night sky is a complex function of the various physical processes from which it results; it is further modulated by wavelength-dependent scattering during the transit of night sky light through the Earth's atmosphere. Measurements of NSB in both radiometric and photometric units are therefore strongly dependent on the night sky's spectrum. (Bará et al. 2020) Because most devices used to sense NSB have relatively large spectral bandpasses, the response of those instruments interact with the night sky SPD in complex ways and call for careful consideration when interpreting measurements. (Sánchez de Miguel et al. 2017)

Some reports (e.g., Jechow et al. 2019, 2020) indicate the use of metrics such as the correlated colour temperature (CCT) of the night sky as a means of characterizing its spectral qualities. While CCT is an appropriate representation of the spectra of thermal sources, its utility diminishes as the SPDs of sources become increasingly non-thermal. Since many NSB components, such as airglow and aurorae, have decidedly non-thermal SPDs, the use of CCT alone is unlikely to give reliable colour information about the night sky.

A5.1.4. Data modeling

Modeling of observations can assist with their analysis and interpretation. For example, Duriscoe (2013) reported successfully recovering the anthropogenic component of NSB from mosaicked all-sky image data by subtracting 2-D models of natural sources of light. To the extent that construction and application of such models can be automated, they hold the promise of rapidly disentangling natural sources of light in the night sky from artificial sources for the purposes of modeling the angular and temporal evolution of skyglow.

For spectrally resolved measurements, it is possible to model the natural components of NSB in wavelength space to subtract and remove them, leaving behind only the spectrum of artificial light sources. From a decomposition of the night sky spectrum, Kolláth et al. (2020) determined that the 'continuous' component of the natural sky (zodiacal light, scattered starlight and airglow pseudo-continuum) is nearly constant at all visible wavelengths and has a spectral radiance of $\sim$2 nW m^{-2} sr^{-1} nm^{-1}.

There are a handful of additional approaches to the modeling NSB that add other inputs to the direct sensing of light. A recent example, provided by Kolláth & Kolláth (2020), used raw backscatter data from a laser ceilometer to provide inputs to Monte Carlo simulations of sky radiances measured simultaneously from the ground using calibrated cameras. The authors applied this technique to infer the vertical structure of the radiance distribution of the night sky.

A5.1.5. Remote sensing of night sky brightness

The use of remote sensing platforms (namely, Earth-orbiting satellites) to infer NSB from direct measurements of upward radiance offers a number of attractive qualities. Chief among these is the ability to collect information about NSB from essentially anywhere on Earth, which decouples NSB measurement and monitoring from the deployment of ground-based sensors. Falchi et al. (2016) provided such a global data product. They calibrated the radiance-NSB relationship using many thousands of ground-based NSB measurements, but their predictions are sometimes inaccurate. This may be the result of models assuming a flat Earth, and which therefore do not take into account the screening effect of topography, or due to the fact that locally variable atmospheric turbidity can induce scattering effects for which models can't account.

Diffuse light around cities in remote sensing imagery from Earth orbit was long thought to result from a combination of sensing artifacts and low spatial resolution, (L.Imhoff et al. 1997; Li & Zhou 2017) but it is now recognised as a real signal corresponding to light scattered in the atmosphere. Kocifaj & Bará (2020) showed that certain aerosol properties, such as the particle size number distribution, can be successfully retrieved from orbital radiometry of the angular radiance distribution of the scattered light near cities. Sánchez de Miguel et al. (2020) recently found a strong correlation between the zenith NSB measured on the ground and orbital radiance measurements at both low and high resolution. They suggested that "it should be possible to create maps of regional sky brightness, or even global sky brightness maps" based on radiance measurements from the newest generation of orbital radiometers.

However, there are other problems with existing satellite remote sensing platforms. For example, VIIRS-DNB has no spectral sensitivity shortward of 500 nm, so the instrument is effectively blind to the strong peak in white LED light emissions near 450 nm. This limits what can be reliably inferred concerning short-wavelength light sources within the data set. (Bará, Lima and Zamorano 2019)

A5.1.6. Night sky brightness measurement units

NSB measurements found in the literature are reported in several different, and sometimes con- fusing, units. Although one occasionally finds illuminances reported in SI units like microlux, the majority of measurements are given in luminance (surface brightness) terms. As a further compli- cation, measurements can be either radiometric or photometric depending on whether they refer broadly to the entire visible spectrum or instead are weighted by the spectral response of the human eye, respectively.

Some units characterizing NSB in luminance and radiance terms are as follows:

- **Candela per square metre** (cd m^{-2}), a linear, SI unit informally called the “nit”. The unit is based on the SI unit of luminous intensity (candela) and the SI unit of area (metre). The CGS equivalent is the **stilb** (1 stilb = 10^4 nits).
- **Lambert** (L), a linear, non-SI unit defined as π^{-1} cd cm^{-2} (= 3183 cd m^{-2}).
- **S_{10}(vis)**, a linear, non-SI unit defined as the surface brightness of 10th *V* magnitudes per square degree.
- **Magnitude per square arcsecond** (mag $arcsec^{-2}$, or mpsa), a logarithmic, non-SI unit defined such that if an area on the sky contained only exactly one magnitude *N* star in each square arcsecond, the sky brightness would be *N* mag $arcsec^{-2}$.
- **Night Sky Unit (NSU)**, a linear, non-SI unit representing the average zenith NSB away from the ecliptic assuming quiescent airglow conditions and the absence of skyglow (∼0.2 mcd m^{-2} in the *V* band). It is sometimes called a “Natural Sky Unit” or a “sky”.
- **Dark Sky Unit (DSU)**, a linear, non-SI unit (but traceable to SI units) representing a band-averaged spectral radiance in which 1 DSU = 1 W m^{-2} sr^{-1} m^{-1}. (Kolláth et al. 2020)

Of these, the magnitude per square arcsecond is most often encountered, being the native report- ing unit of, among other devices, the popular Sky Quality Meter. Transformations between, e.g., magnitude per square arcsecond and the SI candela per square meter have been derived so that astronomical brightnesses in, e.g., *V* magnitudes can be approximately transformed to photometric values. Noting that the relationship between these quantities depends on the spectral power distribution of the source, Bará et al. (2020) derived the transformation equation and calibrated it using zero-point luminances determined from a variety of skyglow spectra.

A5.2 Monitoring night sky brightness

In the present context, “monitoring” of NSB refers to its repeated measurement to look for trends on timescales ranging from minutes to years. Monitors, like sensing devices, fall into two general categories: those that function autonomously, and those whose operation requires human attendants.

Autonomous monitors are sensing devices fitted into weatherproof housings with their own electric power supplies and, optionally, network connections. Some of them save their measurements to on-board memory, while others relay them to another location for storage via a local network or the Internet. At present, autonomous monitors tend to be single-channel devices with few requirements for field calibration. Attempts to construct autonomous all-sky imagers have tended to leverage existing facilities marketed to amateur astronomers as cloud sensors; other, purpose-built devices, such as the ASTMON system (Aceituno et al. 2011), are intended as fully robotic instruments whose data acquisition and reduction are automated and which function as permanent monitors.

Attended monitors may function automatically, but require a human operator for their setup and maintenance. This is usually because the monitoring device is not permanently installed and lacks equipment to make it durable in the natural environment. The operator may also direct details of the data collection protocol (e.g., manually switching slides in a rotating filter wheel). An example of this is the Road Runner system, in which a single-channel sensing device is mounted to the roof of an automobile and collects NSB data continuously while the vehicle is driven. (Rosa Infantes 2011) Another example is the U.S. National Park Service Night Sky Team (NPS NST) imaging method: its camera, situated on an automatic 'go-to' mount, executes an imaging programme automatically, but it must be transported to each measurement site and set up by NPS NST staff. (Duriscoe et al. 2007) There is also considerable human effort required to reduce, analyse, and report the resulting data.

Monitoring entails the concerns of data handling, transmission and storage, as well as reduction and analysis. Some autonomous monitors log NSB data to on-board storage media, which must be periodically retrieved and copied by human attendants. Other systems, such as TESS-W, make use of wireless networking and transmission of measurements to a central storage location via the Internet, leaving them vulnerable to network interruptions;[4] unless the data are separately captured and stored on the local network, they are simply lost. There are also concerns about data reporting formats, although some effort has been put into designing and promoting a protocol for recording and reporting NSB data.[5]

A5.2.1. Temporal sampling frequency

Other monitoring considerations involve the frequency of data collection, both in the temporal and spatial senses. Given the timescales on which the natural NSB is known to vary, sampling frequency is important so as to fully understand the brightness range of the natural night; the same applies to skyglow, which tends to vary in slower and more predictable ways. The presence of skyglow can 'stabilise' NSB if it significantly exceeds natural sources of light in the night sky in terms of radiance, as in many bigger cities. In such cases, only weak variations exist from night to night once the anthropogenic signal overwhelms the natural signal. This situation makes it such that NSB monitors typically perform best in urban environments, while potentially giving ambiguous information in naturally dark locations.

Various approaches to visualizing NSB time-series data are suggested in the literature. Perhaps the most common method is the NSB densitogram, commonly referred to as a

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[4] A May 2020 examination of the 199 nodes of the TESS-W network listed on https://tess.dashboards.stars4all.eu/d/ tess latest measures/s4a-photometer-network-latest-measures?orgId=1 indicated that 81 (41%) returned no data in the past 24 hours.

[5] See Kyba & Lolkema (2012) for details. See also "Definition of the community standard for skyglow observations" (white paper, 2013), available on https://www.darksky.org/wp-content/uploads/bsk-pdf-manager/47 skyglow DEFINITIONS.PDF.

‘jellyfish plot’. In this representation, the NSB is plotted against the local time, and each pixel is colour-coded to represent the number of observations in a time series that fall into that particular (time, NSB) bin. It is a convenient way to both compress a lengthy time series into a single plot as well as to quickly discern between typical and atypical NSB conditions.

This kind of data visualisation helps inform efforts to characterize night sky quality at a given location and follow its evolution in time. For example, Bará et al. (2019) suggest that a well-sampled jellyfish plot can be used to extract meaningful sky quality metrics. However, the authors conclude:

> *It is clear that no single value of the NSB can be taken as fully representative of the variety of conditions at any given observation site, much like no single air temperature or wind speed could be attributed to it with a claim of completeness. As a matter of fact, the NSB results from the interaction between the light emitted by artificial and natural sources and the changing meteorological conditions, whose combined variability is larger than any of its individual factors.*

There have been some limited efforts made to apply, e.g., Fourier analysis techniques to time-domain measurements of NSB. For example, Puschnig et al. (2019) used fast Fourier transform frequency analysis of nightly mean NSB measurements made using a network of Sky Quality Meters in Austria. From this analysis they concluded that the circalunar periodicity of NSB, of biological importance to a number of nocturnal species, essentially disappears for maintained zenith brightnesses higher than about 16.5 mag arcsec^{-2} ($\sim$32 mcd m^{-2}).

Bará et al. (2019) further considered whether the NSB sampling rate on a timescale of minutes influences the average indicators using measurement collected in long (e.g., yearly) time periods, concluding that it does not. Resampling a series of zenith brightnesses obtained with Sky Quality Meters in one-minute readings to sampling intervals of five and ten minutes, they found that the the maximum absolute difference of the full width at half-maximum (FWHM) of the darkest peak in a histogram of time-series NSB values was < 0.0009 mag arcsec^{-2} for a five-minute sampling interval and < 0.0017 mag arcsec^{-2} for a ten-minute sampling interval. These values are well below the measured precision of the SQM ($\lesssim$ 5%).

However, the question of which temporal NSB sampling frequencies are sufficient to yield a sense of the typical night sky quality is not well formed because there is yet no general agreement as to what we mean by ‘typical’. If this were clearly and definitively decided, a simple analysis would easily reveal the optimal sampling parameters to yield the desired metric.

A5.2.2. Spatial sampling frequency

Characterizing the typical NSB across a large geographic area demands consideration of the proper spatial sampling frequency in order to ensure uniform results, especially with respect to acceptable measurement uncertainties. To date there is one published study on this subject by Bará (2017), based on data from Falchi et al. (2016). Bará found that a useful rule of thumb is that one measurement per square kilometre is sufficient to constrain the zenith NSB at any point in a sampled region to a precision of ±0.1 V mag arcsec^{-2} rms. However, the author notes that "exact reconstruction of the zenithal night sky brightness maps from samples taken at the Nyquist rate seems to be considerably more demanding."

Appendix 6 Certification programmes with international recognition

A6.1 The Starlight Foundation and International Certification System

A6.1.1 Background

"The sky, our common and universal heritage, is an integral part of the environment perceived by humanity. Humankind has always observed the sky either to interpret it or to understand the physical laws that govern the universe"[6].

Astronomy has had an undeniable influence within science development and has contributed to many technological advances that defined human progress throughout history. Ground-based observatories are exceptional windows for the observation of the universe, and they have provided the vast majority of our knowledge of astronomy. However, present technical requirements restrict suitable areas to very specific and limited locations offering good conditions for the development of advanced astronomy, and of optical and infrared astronomy in particular.

The Starlight Initiative was born with the "Declaration in defence of the Night Sky and the Right to Starlight" (2007), in which, representatives of IAC, UNESCO, UNWTO, IAU, UNEP-CMS, CE, SCBD, COE, MAB and Ramsar-Convention launched this international movement in defence of the night sky , promoting the dissemination of astronomy and sustainable, high-quality tourism in those places where the night sky is cared for. The Starlight sites are scenarios that incorporate the preservation and observation of the night sky as a part of the natural, scenic, cultural and scientific heritage; and encourage "Star Tourism", and promoting infrastructure, products, activities and training of specialised guides in sustainable tourism.

[6] Explanatory Note concerning the Proclamation of 2009 as International Year of Astronomy (33rd session of the UNESCO General Conference).

The Starlight Foundation (in Spanish it is known as *Fundación Starlight*) is a legal non profit entity created in 2009 by the Institute of Astrophysics of the Canary Islands and the consulting Corporación 5 as the body in charge of the Starlight Initiative, providing human resources and means for its development and promotion. This followed on from the First International Starlight Conference held in la Palma in 2007. The conference had the slogan 'Starlight, a Common Heritage' (Ed. Marín & Jafari, 2007), and explored the need to protect the night sky on our planet from different perspectives and to find ways for its enjoyment by society. The objective of this meeting was to spread the idea of the defence of the night sky among the population, considering it as an outstanding, universal cultural value and a vital asset to promote and develop astrotourism.

A6.1.2 Windows to the Universe: preserving of the sky quality of astronomical sites[7]

The **eighth clause of the Starlight Declaration specifically concerned astronomical observatories**. It reads: '*Areas suitable for unimpaired astronomical observation constitute an asset in short supply on our planet, and their conservation represents a minimum effort in comparison with the benefits they contribute to our know-how and to scientific and technological development. The protection of sky quality in these singular places must be given priority in regional, national, and international scientific and environmental policies. The measures and provisions must be made to safeguard clear skies and to protect such spaces from the harmful effects of light, radio-electric emissions, and air pollution*.'

In addition to the very best astronomical sites, there are many other valuable locations that must also be identified and preserved. These other sites are excellent for many aspects of astronomical research, and are also valuable for educational and outreach activities.

The defence of astronomical sky quality, as well as the establishment of measures and regulations to avoid its possible deterioration, is the basic function of the application of the **Starlight Reserve concept to the best sites for astronomical observation.** Involvement of people, through education and distribution of information on astronomy and its benefits, is key to achieving conservation of the sky for astronomy and science.

The Starlight Reserve@[4] concept was established in the UNESCO World Heritage Centre, Paris (October 2007), *Astronomy and World Heritage*. The criteria were well determined in the *International Seminar and World Heritage* (London) and at *the World Heritage Committee* (Quebec), in 2008. The concept was presented in the II Starlight Conference that was held in Fuerteventura (2009). The Starlight Reserve is a protected natural area where a commitment to protecting the quality of the night sky and access to starlight is established. Its function is to preserve the quality of the night sky and the different associated values, whether cultural, scientific, astronomical, or the natural landscape.

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[7] Concept Starlight Reserve@
https://www.fundacionstarlight.org/cmsAdmin/uploads/o_1bi3lj80lkvjqpqjdn8675rlb.pdf

Several specific types of Starlight Reserves have been identified and defined. To date they cover the following categories: Starlight Heritage Sites, **Starlight Astronomy Sites**, Starlight Natural Sites, Starlight Landscapes, Starlight Oases-human habitats, and mixed Starlight Sites. See list in https://www.fundacionstarlight.org/en/section/list-of-starlight-reserves/290.html

A6.1.3 Case studies-ICOMOS-IAU Thematic Study (2009)[8]

There are only a few places on the planet where we find this unique combination of environmental and natural circumstances: well conserved spaces with very little alteration to natural starlight. These exceptional sites, including their natural components, can be considered as "landscapes of science and knowledge". As we would have expected, the world's largest contemporary observatories, true scientific monuments, are located in these places and are, to a greater or lesser extent, historical sources of native astronomical culture. The case of Hawaii, the Canaries and northern Chile are for an ensemble of discrete sites that, within this context, have outstanding universal significance as a group.

This is the first Thematic Study in any field of science heritage. It is elaborated using examples of properties, including some already on the World Heritage List or national Tentative Lists. The ICOMOS-IAU Global Thematic Study on Astronomical Heritage was presented to UNESCO's World Heritage Committee at its meeting in Brasilia at the end of July 2010. Its endorsement by the meeting means that it may be used as the basis for developing specific guidelines for UNESCO member states on the inscription of astronomical properties.

A6.2 The International Dark-Sky Association and accreditation of International Dark Sky Places

The International Dark-Sky Association (IDA) is a non-governmental organisation founded in Tucson, U.S., in 1988, and whose mission is to preserve and protect the nighttime environment and our heritage of dark skies through environmentally responsible outdoor lighting. IDA's public outreach efforts increase public attention to the issue of artificial light at night and its effects, and it provides solutions and reliable, fact-based education throughout the world.

In 2001, IDA initiated its International Dark Sky Places programme to encourage communities, parks and protected areas around the world to preserve and protect dark sites through responsible lighting policies and public education. Sites are accredited by the programme in recognition of efforts made by locals toward the achievement of these goals. International Dark Sky Places in several categories are recognised, including International Dark Sky Parks, International Dark Sky Reserves, International Dark Sky Communities, and

[8] https://starlight2007.net/index_option_com_content_view_article_id_171_itemid_159_lang_en.html

International Dark Sky Sanctuaries and Urban Night Sky Places. At the time of writing, there are over 140 accredited International Dark Sky Places worldwide.

Ground-based astronomical observatories conducting scientific research tend to be located in some of the most remote and naturally darkest places on Earth. Certification of these facilities is therefore best served by accreditation as IDA International Dark Sky Sanctuaries, described as “public or private lands possessing an exceptional or distinguished quality of starry nights and nocturnal environment, and that is specifically protected for its scientific, natural, or educational value, its cultural heritage, and/or public enjoyment.” (IDA 2018) These sites are “typically situated in a very remote location with few (if any) nearby threats” to the quality of their dark night skies. The key eligibility criterion for International Dark Sky Sanctuary status is that the “night sky brightness at the zenith is routinely equal to or darker than 21.5 magnitudes per square arcsecond in the visual band and where significant light domes are not present toward the local horizon in any direction.”[9] Furthermore, eligible sites must implement quality outdoor lighting management plans; ensure that all site lighting conforms to the lighting plan within ten years of accreditation; maintain an ongoing programme to measure and monitor the brightness of the night sky; and engage the public in the local area and beyond in a programme of education and outreach on the fragility of night skies over such sites and the value of natural nighttime darkness.

An example of the application of this programme category to an astronomical observatory site is the Gabriela Mistral International Dark Sky Sanctuary. The world’s first accredited International Dark Sky Sanctuary, the site is owned and operated by the Associated Universities for Research in Astronomy, the sole representative of 40 U.S. universities and four international affiliates who operate cutting-edge professional astronomy facilities at a near pristine, 36,000-hectare site in the Elqui Valley of northern Chile. AURA’s land title makes certain demands including a limitation of activities solely to the support of astronomical research. Between this restriction and the requirements of proper conditions for making extremely precise scientific measurements, dark night skies over the site have been preserved for decades. In addition to its value to astronomy, the site serves as crucial habitat for a number of sensitive and/or endangered species.

Appendix 7 Overview of CIE publications and works on lighting recommendations and obtrusive light

At the international level, recommendations for various lighting applications are developed and provided by the International Commission on Illumination (CIE). The CIE has a strong technical, scientific and cultural foundation and is an independent non-profit organisation. The CIE is recognised by the CIPM, the International Organisation for Standardisation (ISO) and the IEC as a standardisation body across its scope , publishing international standards for

[9] These conditions correspond approximately to a zenith luminance of 250 µcd m^{-2} and a naked-eye limiting magnitude of +6.7.

basic research on light and lighting. Many national and regional regulations and norms are based on or refer to CIE publications, these being:Technical Reports, International Standards, Technical Notes, and Position Statements.

This annex gives an overview of CIE publications with outdoor lighting recommendations which are the most relevant in relation to the limitation of adverse effects of ALAN as unnecessary spill light and skyglow. Current CIE work items in the field are mentioned in this annex, too.

A7.1. Overview of selected CIE publications on lighting recommendations

CIE 115:2010 'Lighting of Roads for Motor and Pedestrian Traffic' presents a structured model developed for the selection of the appropriate lighting classes (M, C, or P) for roads for motorised traffic, conflict areas and areas for pedestrians. This model is based on the luminance or illuminance concept, taking into account the different parameters relevant for the given visual tasks. Applying for example time dependent variables like traffic volume or weather conditions, the model offers the possibility to use adaptive lighting systems. This Technical Report highlights the importance of power consumption and environmental aspects in road lighting which with improved performance of luminaires and control gears make it possible to introduce adaptive lighting.

CIE 236:2019 'Lighting for Pedestrians: A Summary of Empirical Data' concerns lighting for roads where pedestrians are the primary road user. Lighting guides recommend certain criteria for design such as target illuminances. The bases of these recommendations are, however, largely unstated or were not published in international magazines and got lost. The aim of this report is therefore to provide a summary of credible, empirical evidence of the effects of changes in lighting on the visual impressions and visual performance of pedestrians, as a basis for future revisions to design standards.

CIE S 015/E:2005 'Lighting of Outdoor Workplaces' specifies requirements for lighting of tasks in most outdoor work places and their associated areas in terms of quantity and quality of illumination. In addition recommendations are given for good lighting practice. All usual visual tasks are considered. The standard gives detailed information on lighting design criteria. Fifteen tables specify the lighting requirements for various areas, tasks and activities.

CIE 083:2019 'Guide for the Lighting of Sports Events for Colour Television and Film Systems, 3rd Edition' provides quality aspects to be fulfilled for colour television and colour film in sports lighting applications including vertical illuminance, uniformity of horizontal illuminance, flicker, colour temperature and colour rendering of the lighting together with lighting requirements on the surrounding spectator areas. New Technical Report on general requirements for sports lighting is being prepared by the Technical Committee CIE TC4-57 'Guide for Sports Lighting'.

CIE 234:2019 ‘A Guide to Urban Lighting Masterplanning’ is providing guidance about the objectives and underlying principles relating to the lighting aspects of the urban nightscape. It deals with the visual, organisational, environmental, and technical elements of these aspects of urban planning. This guide identifies the lighting planning criteria that should be considered when initiatives are being taken in relation to new or existing lighting in urban areas or newly planned conurbations. Guidance is provided to both the functional and expressive aspects of lighting. This publication is intended to support those decision makers who are required to initiate, promote, and manage the night-time image of their city and who require a masterplan to provide a sound basis for long term lighting developments.

CIE 094-1993 ‘Guide for Floodlighting’ aims to provide information on how to use exterior lighting for the decoration of the night-time urban landscape. Of the many applications of lighting in an urban environment, this guide deals with those having a purely aesthetic and decorative purpose. Such lighting can be used every night, as is often the case in the lighting of monuments, public art, commercial buildings, or used only periodically on the occasion of a festival or public gathering. The lighting of natural sites, parks, and gardens is also dealt within this guide. This guide provides tools for the exterior lighting designer and ideas for the town architect. For those who have to make the decisions on expenditure, this guide explains the possibilities of combining outdoor beautification with economical and energy friendly decorative lighting. Update of this publication is currently dealt in the Technical Committee CIE TC4-59 ‘Guide for Lighting Urban Elements’.

A7.2. Overview of CIE publications on obtrusive light

CIE 001-1980 ‘Guidelines for minimizing urban skyglow near astronomical observatories’ has been prepared jointly with IAU. Purpose of this publication is to stimulate collective action that minimises the degradation of the astronomical environment near cities. The problem and its solutions are stated in a manner that provides a basis for understanding, cooperation, and action by astronomers, lighting engineers and public authorities. The report explains the effect of man-made skyglow, the degree of glow likely to be produced by lighting near an observatory, the level above which skyglow should not be allowed to rise, and how it can be contained by good lighting practice and public ordinances.

CIE 126-1997 ‘Guidelines for minimizing skyglow’ gives general guidance for lighting designers and policy makers on the reduction of the skyglow. The report discusses briefly the theoretical aspects of skyglow and it gives recommendations about maximum permissible values for lighting installations in relation to the needs of astronomical observations - casual sky viewing included. These values must be regarded as limiting values. Lighting designers should do all possible to meet the lowest specifications for the design unless the specific installation requires relaxation. Other uses of the open air areas at night will usually result in less stringent skyglow requirements. Practical implementation of the general guidance is left to National Regulations.

CIE 150:2017 'Guide on the Limitation of the Effects of Obtrusive Light from Outdoor Lighting Installations, 2nd Edition' is intended to help formulate guidelines for assessing the environmental impacts of outdoor lighting and to give recommended limits for relevant lighting parameters to contain the obtrusive effects of outdoor lighting within tolerable levels. As the obtrusive effects of outdoor lighting are best controlled initially by appropriate design, the guidance given is primarily applicable to new installations; however, some advice is also provided on remedial measures which may be taken for existing installations. This guide refers to the potentially adverse effects of outdoor lighting on both natural and man-made environments for people in most aspects of daily life, from residents, sightseers, transport users to environmentalists and astronomers.

A7.3. Current CIE works related to obtrusive light problems

TC 4-58 'Obtrusive Light from Colourful and Dynamic Lighting and its Limitation' aims to provide guidelines for the implementation and usage of colourful and dynamic lighting in outdoor applications aiming at limitation of obtrusive light with respect to astronomical observations, humans and night-time environment. To develop metrics for obtrusive light from colourful and dynamic lighting systems and to propose suitable methods for limitation or prevention of obtrusive light from such systems.

TC 4-61 'Artificial Lighting and its Impact on the Natural Environment' deals with effects of artificial lighting on the natural environment, including impacts on flora and fauna and aims to provide guidance on ways to minimise these effects. This would be accomplished by making recommendations on light levels, spectral distributions, and other specific considerations of a broad range of organisms as well as specific habitats.

TC 4-62 'Adaptive Road Lighting' aims to analyze needs, specify recommendations, develop methodology and promote application of adaptive road lighting based on various conditions and input data from field sensors and interconnected systems with respect and tailored to specific requirements of different user groups and user patterns.

DR 4-53 'Environmental Aspects of Obtrusive Light from Outdoor Lighting Installations' aims to analyze contents of current CIE publications and progress in current Technical Committees dealing with obtrusive light problems and to suggest concerted actions in order to harmonise development of new CIE publications in the field. This reportership also aims to identify potential gaps in research and recommendations and to prepare new work items to fill-in these gaps. As a result of this activity, a new Technical Committee on measurement of obtrusive light is in preparation.

A7.4. CIE Research Topics with relevance to obtrusive light problems

Light and lighting technologies are essential to modern daily life, touching on its every aspect. These technologies require well-founded knowledge, both fundamental and applied, to ensure that they can be used with confidence in their safety and quality. CIE publications provide that confidence. They are based on the strongest available scientific evidence and follow a rigorous review and ballot process. To develop consensus-based documents fit for the future requires that scientists engage now in building the knowledge base that will support them.

The current priority research topics of the CIE that need immediate attention by the research community in support of developments in lighting technology and application can be found on the CIE website, http://cie.co.at/research-strategy. Topics that relate to human capabilities and ecological systems, whether fundamental or applied, would all benefit from also addressing diversity and inclusion dimensions. Publications in the peer-reviewed literature on these topics will provide the basis for the next generation of CIE technical reports and standards.

Some of the current research topics that have some relevance to the effects, management and/or measurement of obtrusive light are:

a. Recommendations for Healthful Lighting and Non-Visual Effects of Light
b. Integrated Glare Metric for Various Lighting Applications
c. Adaptive, Intelligent and Dynamic Lighting
d. Support for Tailored Lighting Recommendations
e. Metrology for Advanced Photometric and Radiometric Devices

Appendix 8 Challenges of relating safety to nighttime lighting

Among the causes of light pollution is the popular belief that the use of outdoor light at night necessarily improves road and traffic safety and discourages or prevents the perpetration of both violent and property crimes. While under certain circumstances the careful application of outdoor lighting may improve nighttime safety, this belief is otherwise not grounded in peer-reviewed scientific evidence. Some studies find evidence for a positive correlation in which crime or road collisions decrease after application of lighting treatments, (Bullough, Donnell & Rea 2013; Wanvik 2009a) while others find either a negative correlation, (Morrow & Hutton 2000) none at all, (Marchant 2004; Sullivan & Flannagan 2002; Marchant 2011) or equivocal results. (Wanvik 2009b) A few authors turn the question around and ask whether reducing outdoor lighting in areas prone to either crime or road collisions leads to poorer outcomes, finding little or no such evidence. (Steinbach et al. 2015)

Among the practical barriers to a clear determination of the effect of outdoor lighting on public safety is an inability to model whatever underlying mechanism may exist. Jackett and Frith (2013) note that “no well-established dose-response relationship to lighting parameters exists from which one can deduce benchmark levels of lighting for safety.” One consequence, as Fotios and Gibbons (2018) write, is that “recommendations for the amount of light [for drivers and pedestrians] do not appear to be well-founded in robust empirical evidence, or at least do not tend to reveal the nature of any evidence."

A separate issue regarding road traffic is whether automotive lighting itself is a source of objectionable light pollution, specifically in relation to its utility as a means of ensuring public safety. There is little research to date on the overall contribution of automobile lights to light pollution, although early work suggests that the impact is non-trivial. (Lyytimäki, Tapio & Assmuth 2012; Bará et al. 2018; Gaston & Holt 2018) Also, researchers are only beginning to contemplate the implications for the need for future installations of roadway lighting as the result of the introduction of autonomous (self-driving) vehicles. (Stone, Santoni de Sio & Vermaas 2019)