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Towards an International Dark Sky Place: Challenges of
Measuring and Modelling Light Pollution

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Abstract

The present thesis discusses various methods for measuring and simulating light pollution for International Dark Sky Place certification. The thesis goes on to discuss the limitations of these measurement methods and the general problems that can arise during measurements, including meteorological influences, especially clouds. Given the absence of a universally applicable measurement method or apparatus, a multitude of diverse methodologies and instruments must be employed to ensure the attainment of reliable values. Despite the considerable progress made in the field, current simulations still lack the capability to accurately replicate the meteorological influences caused by clouds. These measurements are being carried out for the Nature Park Weißbach and the municipality of Weißbach near Lofer, as they are attempting to obtain DarkSky certification as an International Dark Sky Park and as an International Dark Sky Community. Although measurements on the scale of a master's thesis are not necessary for certification as a community, the measurements required for certification as an International Dark Sky Park, which were carried out in this thesis, show that the Weißbach Nature Park achieves the threshold value of a night sky brightness of 21.20 mag/arcsec². Therefore, it can be certified as an International Dark Sky Park.

Kurzfassung

In dieser Arbeit wird auf verschiedene Messmethoden eingegangen um Lichtverschmutzung zu messen und zu simulieren für eine International Dark Sky Place Zertifizierung. Des Weiteren wird auch auf die Limitierung dieser Messmethoden und die allgemeinen Probleme, die bei den Messungen stattfinden können (wie Meteorologische Einflüsse, besonders mit Wolken) eingegangen. Dadurch, dass es keine universelle Messmethode und kein universelles Messgerät gibt, müssen auf viele verschiedene Messmethoden und -instrumente zurückgegriffen werden, um vertretbare Werte liefern zu können. Selbst Simulationen sind noch nicht auf dem Stand, um meteorologische Einflüsse durch Wolken exakt wiederspiegeln zu können. Diese Messungen werden für den Naturpark Weißbach und die Gemeinde Weißbach bei Lofer durchgeführt, da diese versuchen eine Zertifizierung von DarkSky zu erlangen als International Dark Sky Park und als International Dark Sky Community. Für die Zertifizierung als Community sind Messungen im aufwand einer Masterarbeit nicht nötig, aber die Messungen die für die Zertifizierung als International Dark Sky Park benötigt werden, und in dieser Arbeit gemacht wurden, zeigen, dass der Naturpark Weißbach den Schwellwert einer Nachthimmelshelligkeit von $21.20 \text{ mag/arcsec}^2$ erreicht und sich somit als International Dark Sky Park zertifizieren lassen kann.

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1. Introduction

In 2001, Cinzano et al. (2001) published the first World Atlas of artificial night sky brightness. Utilising data from the US Air Force Defence Meteorological Satellite Program (DMSP) Operational Linescan System (OLS), or DMSP-OLS for short, from 1996-1997, it was determined that in excess of 99% of the population of the United States and Europe and approximately two-thirds of the global population reside under a light-polluted night sky. For approximately two-thirds of the population of the United States, for about half of the people living in Europe, and for about one-fifth of the world's population, it is no longer possible to see the Milky Way with the naked eye. Furthermore, approximately 40% of the population of the United States, one-sixth of the European population, and one-tenth of the global population are no longer able to adapt their eyes to the night-time environment due to the excessive light pollution.

In 2016, Falchi et al. (2016) published the new world atlas of artificial night sky brightness. The creation of the new world atlas was achieved by utilising data from the Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band (DNB), newly developed precision charge-coupled device (CCD) brightness measurements, and a novel Database of Sky Quality Meter (SQM). The result indicated that light pollution had worsened within a 15-year period. It is estimated that approximately 83% of the global population and more than 99% of the population residing in the United States and Europe live under a light-polluted night sky. For approximately 80% of North Americans, 60% of Europeans and one-third of the global population, viewing the Milky Way with the naked eye has become impossible due to the prevalence of light pollution. In addition, it is noteworthy that 23% of the world's total land surfaces, encompassing the areas between 75°N and 60°S, is characterised by light pollution. Moreover, 88% of Europeans and nearly half of the United States population experience nights that are subject to this type of disturbance. Furthermore, it has been posited that Singapore is the nation with the most light pollution, and as a consequence, the entire population lives under such a bright night sky that their eyes are unable to fully adapt to the night.

A comparison of the data sets from Cinzano et al. (2001) and Falchi et al. (2016) reveals a significant increase in global light pollution, from approximately 67% to 83%, over a period of 15 years.

In 2023, Kyba et al. (2023) published findings showing that night sky brightness increased significantly on an annual basis between 2011 and 2022. The Globe and Night project analysed a total of 51,351 observations of stellar visibility made by citizen scientists during this period. The global increase in night sky brightness was found to be 9.6% per year on average, with this ranging between 7-10% per year depending on the region (6.5% per year in Europe, 10.4% per year in North America and 7.7% per year in the rest of the world). The findings of this study demonstrate the significance of ground-based observations and measurements, thereby underscoring the limitations of reliance on satellite-only

1. Introduction

data. Satellite data estimates for the period 2012-2016 predicted only a 2.2% annual increase in global night sky brightness, while ground-based measurements show a global annual increase of 9.6%. This finding indicates that satellite data alone is inadequate, as the capability of satellites to detect light is limited to wavelengths greater than 500 nm. It has been demonstrated that light with shorter wavelengths scatters more effectively in the atmosphere, thereby contributing more significantly to skyglow. Furthermore, white LEDs exhibit emission peaks between 400-500 nm, which are undetectable by satellites. Moreover, the majority of satellite radiometers exhibit little to no sensitivity to light emitted towards the horizon, where horizontal light contributes significantly to skyglow due to its extended atmospheric path length. Additionally, it has been posited that the transition to LED lighting may result in alterations to the spectral characteristics, with different implications for satellite observations and human perception. When LEDs maintain the same luminance, the spectral shift towards shorter-wavelength light causes the radiance observed by the satellite to decrease, while skyglow as seen by humans could actually increase.

This limitation of satellites compared to ground-based measurements is also mentioned in the work of Wallner et al. (2023). In this study, the temporal trend of artificial light at night in the 47 nature parks in Austria is analysed using VIIRS satellite data from 2012 to 2022. The evaluation demonstrated that these nature parks exhibited an average enhancement of approximately 42% in radiance over the decade, which is more than double the $\sim 18\%$ increase observed across Austria's entire territory. Furthermore, the statistical analysis demonstrated that changes below $\pm 10\%$ cannot be reliably attributed to actual changes in artificial lighting due to atmospheric variations and measurement uncertainties. The study employed a range of sophisticated analytical techniques, including polynomial trendline analysis and extensive statistical modelling, to account for atmospheric effects, seasonal variations, and limitations in satellite measurement. The validity of the approach was established by utilising ground-based SQM data to derive realistic uncertainty estimates. As in Kyba et al. (2023), Wallner et al. (2023) also address the limitation of VIIRS in that wavelengths below 500 nm are not recorded, potentially missing light sources that emit large amounts of radiation in shorter wavelengths, particularly neutral-white LEDs. Consequently, trends may be underestimated or overestimated, depending on the evolution of lighting technology. Furthermore, it is mentioned that VIIRS data are filtered for moonless and cloud-free conditions; however, atmospheric parameters still highly influence detected radiance, increasing data scatter and decreasing reliability. Moreover, it is noted that satellite measurements are susceptible to variation depending on observation angles and times, which can result in inconsistencies in the identification of ground-based light sources. It is therefore recommended that a separate ground-based light measurement network be established for particularly dark areas or areas that require protection, such as nature parks, for the purpose of conducting more detailed analytical research. Satellite data provides invaluable broad-scale monitoring capabilities; however, ground-based measurements are imperative for conducting precise, detailed analyses of light pollution trends, particularly in areas designated as dark sky where the signals are less pronounced and more vulnerable to various sources of uncertainty.

In order to protect places from light pollution, such as nature parks in Austria mentioned in Wallner et al. (2023), or to counteract light pollution in general, DarkSky International (DarkSky) launched the International Dark Sky Places (IDSP) programme

in 2001. The IDSP programme has assisted in the establishment of over 230 Dark Sky Places globally, a measure aimed at counteracting light pollution and promoting the conservation of the natural night sky (DarkSky International, 2025c). The preservation of the nocturnal firmament is but one of the reasons why Dark Sky Places are of such significance. Furthermore, the impact of light pollution on a variety of factors is widely documented, including wildlife (e.g. Mahdi (2024), Levy et al. (2025), Deitsch et al. (2025)), ecosystems (e.g. Fonvielle et al. (2025), Ceppi et al. (2025), Easton et al. (2024)), human health (e.g. Salomon et al. (2025), Li et al. (2025), Salceda (2024)), and of course astronomical observations (e.g. Green et al. (2022), Falchi et al. (2022), Kocifaj et al. (2021)). Consequently, there is a concerted effort to raise awareness of light pollution among the inhabitants of Dark Sky Places, with the objective of informing them of the issue and its implications. To date, Austria has only one Dark Sky Place, namely the International Dark Sky Park Attersee-Traunsee¹. The number of designated Dark Sky Places in Austria is set to increase, with the Nature Park Weißbach and the municipality of Weißbach bei Lofer, both located in the province of Salzburg, poised to join the ranks.

This Master's thesis aims to achieve the following objectives:

- to provide an overview of the effects that light pollution can have on animals, the environment, humans and astronomy
- to carry out measurements and simulations for the Weißbach Nature Park to obtain Dark Sky Place certification, using various measurement methods
- to identify problems and limitations associated with measuring devices and methods
- to highlight meteorological parameters and their associated issues, especially clouds
- to identify ways to improve the scientific accuracy of measurements and simulations
- to identify measuring devices and methods that other locations can use to obtain Dark Sky Place certification

¹<https://www.sternenpark-attersee-traunsee.at/>

2. Light Pollution and Dark Sky Places

2.1. Light Pollution

In Falchi et al. (2016), light pollution is defined as a modification of the natural nocturnal lighting conditions caused by anthropogenic light sources. In natural conditions, the presence of night-time lighting is determined by celestial light sources, including the moon, natural atmospheric emissions (i.e. airglow), stars and the Milky Way, as well as zodiacal light. The introduction of artificial lighting has been demonstrated to disrupt these natural conditions. Consequently, the term 'light pollution' has emerged as a descriptor for the adverse effects of artificial light on both natural environments and human beings. In more specific terms, the phenomenon of light pollution can be conceptualised as a by-product of industrial civilisation, which engenders alterations to the intrinsic patterns of light and darkness within ecosystems. This change has profound implications, given that almost all living creatures have evolved according to a natural rhythm of day and night. It has been estimated that approximately 30% of all vertebrates and more than 60% of all invertebrates worldwide are nocturnal (Hölker et al. (2010a)).

Longcore and Rich (2004) proposed a distinction between two primary categories of light pollution: astronomical and ecological light pollution (cf. Figure 2.1).

The phenomenon of 'astronomical light pollution' has been defined as the impairment of human vision of the night sky, whereby stars and other celestial bodies are overshadowed by direct or reflected light shining upwards. This phenomenon, which has been observed to occur on a widespread scale, involves the collective contribution of hundreds of thousands of individual light sources, resulting in an enhancement of illumination within the night sky. The phenomenon of light being reflected back from the sky is referred to as 'sky glow'. The term 'ecological light pollution' is defined as the presence of artificial light that disrupts the natural cycles of light and darkness within ecological systems. The emphasis of this concept is directed towards the impact on biological systems as opposed to the observation of celestial phenomena. It is important to note that although shielded lights can reduce astronomical light pollution, they still cause ecological light pollution.

Longcore and Rich (2004) and Hölker et al. (2010a) propose a tripartite classification system for the constituent elements of ecological light pollution:

- **Direct glare**, which is defined as the brightness of light sources that are directly visible to organisms.
- **Chronically elevated illumination**, which is defined as a sustained increase in the ambient light intensity in the environment.
- **Temporary, unexpected fluctuations in illumination**, i.e. sudden changes in light conditions, have been shown to disorient organisms.

2. Light Pollution and Dark Sky Places

The phenomenon of light pollution has its origins in a variety of sources, including terrestrial, freshwater and marine environments. In urban and terrestrial environments, sources of light include sky glow from cities, street lighting, illuminated buildings and towers, commercial advertising, factories, car parks, airports, security lighting, natural gas flaring, skybeams, illuminated sports venues, vehicle lighting and car headlights. In the marine environment, the presence of artificial light is attributable to various anthropogenic sources, including ships, lighthouses, fishing vessels that utilise light to attract fish, gas flares on offshore oil and gas platforms, cruise ships, and even lights on underwater research vessels.



Figure 2.1.: Illustration of both astronomical and ecological light pollution. (Longcore and Rich, 2004)
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2.2. Case Studies on the Impacts of Light Pollution

Given the multitude of studies on the effects of light pollution (e.g. Hölker et al. (2010b), Gaston et al. (2013), Kyba et al. (2017), Maroni et al. (2018), Abdussamad and Dissi Gambo (2019), Windred et al. (2024)), this chapter will examine studies that may have an impact on animals and the environment found in nature parks (e.g. in Austria) (with the exception of the study by Easton et al. (2024)).

2.2.1. Wildlife

Case Study: "Evaluation of Metabolic and Haematological Impacts of Light-at-Night Exposure on Adult Male Wistar Rats under Sleep Restriction Condition", by Mahdi (2024)

Mahdi (2024) investigation focused on the metabolic and haematological effects of nocturnal light exposure on adult male Wistar rats under conditions of sleep restriction. Contrary to the methodologies employed in other studies (e.g. Mustonen et al. (2002), Dauchy et al. (2010), Maroni et al. (2018)), constant light protocols were not utilised, in which rats are typically exposed to light for 12 hours during their 12-hour dark phase. In accordance with the study's parameters, the rats were exposed to an illuminance of approximately 750 lux for a duration of 5 hours during the initial 5 hours of the scotophase, which constitutes the dark phase of the 24-hour cycle. The implementation of this exposure protocol is indicative of the mean duration of human nocturnal light exposure, which, according to Abdussamad and Dissi Gambo (2019), is approximately 5 hours. This is more congruent with the conditions experienced by wild animals in environments that are subject to elevated levels of light pollution.

Despite the comparatively reduced exposure period, the results indicated the presence of significant metabolic disorders. The rats that were exposed to light-at-night (LAN) gained significantly more body weight than the control animals despite having a lower food intake. This indicates that their energy consumption was reduced rather than their energy intake being increased.

Furthermore, the results indicated that fasting blood sugar levels were significantly elevated in animals exposed to LAN, suggesting an impairment in glucose regulation. In addition, the proportion of monocytes was found to be significantly higher in the LAN group, suggesting mild systemic inflammation.

It is notable that the weight disparities became statistically significant after the fifth of six weeks, indicating cumulative and time-dependent effects of artificial light at night (ALAN) on the subjects. This finding suggests that LAN exposure, associated with melatonin suppression and a reduction in metabolic rate, may predispose individuals to obesity, diabetes mellitus and adverse cardiovascular events.

Case Study: "Light alters calling-song characteristics in crickets", by Levy et al. (2025)

Levy et al. (2025) investigated the hypothesis that lifelong exposure to constant light exerts an influence not only on the timing of cricket stridulation, but also on the acoustic properties of the song itself.

The results of the study demonstrated significant differences in song characteristics between male *Gryllus bimaculatus* crickets raised under normal light-dark cycles (12 hours light : 12 hours dark) and those raised under constant light (40 lux) from egg to adulthood. It was found that, compared to the males in the control group, those exposed to constant light produced significantly shorter chirps, with compressed intervals between syllables. The proportion of syllables per stridulation also varied significantly: The results demonstrated that 75% of the control males produced 4-syllable stridulations. In contrast, the males exposed to constant light conditions exhibited an almost equal distribution between 3- and 4-syllable stridulations. These changes are biologically significant because female crickets

2. Light Pollution and Dark Sky Places

possess neural circuits that are tuned to specific intervals between syllables (between 15 and 25 ms), while males under constant light conditions produced intervals averaging only 11.71 ms. Preliminary experiments on female mate selection confirmed that females preferred the songs of males in the control group to those of males under constant light conditions.

Evidence has been presented which indicates that ALAN exerts influence not only on the timing of animal communication, but also on the quality of their signals. This, in turn, has a direct impact on mate selection and possibly reproductive success.

Case Study: "Butterflies at porch lights: Exploring nocturnal light visitation in butterflies using community science data from iNaturalist", by Deitsch et al. (2025)

Conventionally, ALAN research on insects has primarily concentrated on nocturnal species. However, Deitsch et al. (2025) utilised community science data from iNaturalist to examine light visits by diurnal butterflies. The 384 verified observations of butterflies at artificial light sources in the United States and Canada were compiled by the researchers, representing 107 species from all six North American butterfly families.

The frequency of light visits exhibited significant variation across different taxa: The Lycaenidae (blues) were most frequently observed at light sources, while the Papilionidae (swallowtails) were observed least frequently. The analysis revealed that habitat preference emerged as the most significant predictor of light attraction. In contrast to the initial predictions, species inhabiting closed habitats (i.e. forests) exhibited a significantly higher frequency of visits to light sources in comparison to species inhabiting open habitats. It is hypothesised that the enhanced ambient brightness in open habitats serves to diminish the contrast of artificial light sources. Alternatively, forest butterflies may erroneously interpret artificial light sources as sunspots or gaps in the canopy, which they naturally seek out for thermoregulatory purposes and mating.

From the perspective of conservation biology, 56 threatened species of butterfly have documented relatives that have been observed at light sources. This finding suggests that ALAN may be underestimated as a threat to butterfly populations, in addition to the effects of habitat loss and exposure to pesticides.

2.2.2. Ecosystems

Case Study: "Skyglow increases cyanobacteria abundance and organic matter cycling in lakes", by Fonvielle et al. (2025)

Fonvielle et al. (2025) conducted the most extensive study to date on the effects of light pollution on aquatic ecosystems, utilising 15 large enclosures at Lake Stechlin in Germany. Throughout the duration of a month, the enclosures were subjected to three distinct conditions: a control condition (no additional light), a low light pollution condition (0.06 lux), and a high light pollution condition (6 lux).

The presence of cyanobacteria and aerobic anoxygenic phototrophic bacteria was found to increase by up to 32 times under the influence of skyglow, with bacterial growth rates being up to 2.99 times higher in the presence of high levels of skyglow. The treatment had an effect on 13% of the identified metabolites, with the majority of the increased compounds being bioavailable substances derived from algae. Furthermore, the disruption of day-night fluctuations in metabolites was found to be 53–65% lower in the presence of

light pollution, thereby indicating a disruption of circadian rhythms as opposed to a direct stimulation of photosynthesis.

Network analysis revealed a decline in interactions between bacterial species, with competitive interactions decreasing from 26% to 17%, suggesting a reduction in resource constraints. It is noteworthy that the effects were 2 to 3.5 times stronger during nocturnal hours, and even a low level of skyglow of 0.06 lux triggered significant changes. It is hypothesised that skyglow exerts its effect on cyanobacteria via non-photosynthetic circadian regulatory pathways rather than through direct photosynthesis.

Given the annual increase in global light pollution of approximately 10%, there is a growing concern that an increasing number of lakes may be susceptible to an escalation in cyanobacteria, which could lead to an elevated risk of harmful algal blooms.

Case Study: "Artificial night light intensity modulates herbivory and phytochemistry in European beech", by Ceppi et al. (2025)

In a 43-night field experiment, Ceppi et al. (2025) investigated the impact of varying LED street lighting intensities on European beech trees and their herbivores at two Swiss forest sites. Four light conditions were tested: a dark control group, 21 lux (30% intensity), 35 lux (50%) and 70 lux (100%). The study established that higher light intensities resulted in significant alterations to leaf morphology.

Trees under 100% and 50% light intensity exhibited leaf development that was 30–35% larger and possessed a marginally diminished specific leaf area in comparison to the control group. The observed effects manifested in a manner that was distinct across the two experimental sites. Of the 218 metabolites detected, 18 exhibited a significant response to the light treatments, with flavonols demonstrating the greatest response. A significant proportion of metabolites demonstrated reactions even at an intensity of 30%, with patterns frequently exhibiting non-linear characteristics. It has been established that flavonol concentrations typically peak at an intensity of 50%, subsequently decreasing at 100%.

In the context of an examination of herbivory, it was observed that the presence of light of the highest intensity appeared to have a negative impact on the likelihood of infestation by herbivorous organisms. This phenomenon was concomitant with a decline in the levels of certain flavonols and an amino fatty acid, which typically function as feeding stimulants for herbivorous organisms.

This finding indicates that dimming could be a viable strategy for mitigating the ecological impacts of ALAN. However, even substantial dimming (up to 30%) can elicit discernible phytochemical alterations. It is recommended that artificial light should be used solely when absolutely necessary and at the lowest intensity required to achieve the desired task.

Case Study: "Evaluating ecological risk in artificial habitat failure: A systematic review and risk assessment considering noise and light pollution in the marine environment", by Easton et al. (2024)

The utilisation of artificial reefs has seen a marked increase on a global scale for the purposes of habitat restoration and fisheries enhancement. However, it is notable that only 42% of these reefs achieve their designated conservation objectives. Easton et al. (2024) conducted a systematic review of 72 articles on marine fish and invertebrates in

2. Light Pollution and Dark Sky Places

order to investigate how light and noise pollution from nearby ports and cities affect reef functionality.

The findings of the study demonstrated that light pollution exerted a detrimental effect in 78% of cases, including 36% mortality in fish studies, while noise pollution affected 75% of cases, primarily causing temporary behavioural changes. In light of the findings, a risk assessment matrix was formulated, integrating consequence and probability ratings on a scale ranging from 1 to 16. Fish exposed to ALAN received the highest risk rating (16), whereas invertebrates scored lower (6). In the context of noise exposure, fish have been observed to be affected by high-frequency sounds, with ratings of 9, in conjunction with other combinations, reaching 6. A series of mitigation strategies is proposed, including the utilisation of red or yellow lighting in lieu of white or blue lighting, increasing the distance from sources of pollution, reducing light intensity, and imposing limitations on the duration of noise.

2.2.3. Human Health

Case Study: "Artificial light exposure at night: A hidden risk factor for type 2 diabetes", by Salomon et al. (2025)

Salomon et al. (2025) investigated the influence of ALAN on the risk of developing type 2 diabetes mellitus (T2DM), highlighting an often overlooked environmental factor. While established risk factors for T2DM include lifestyle factors such as diet and physical activity, exposure to light at night – especially blue light – has been demonstrated to disrupt the circadian rhythm by suppressing melatonin production (cf. Figure 2.2). This, in turn, can lead to impaired insulin sensitivity, altered glucose metabolism and increased appetite. The present investigation is founded upon a seminal study by Windred et al. (2024), which analysed data from 84,790 participants in the UK Biobank using approximately 13 million hours of light sensor data.

The findings indicated that with each 10-lux increase in night-time light exposure, there was a 30% elevated risk of developing T2DM, and that individuals in the highest exposure quartile exhibited a 50% higher risk compared to those in the lowest quartile. It is important to emphasise that circadian rhythms regulate the sleep-wake cycle and metabolic processes. Artificial light during the night disrupts this balance, leading to circadian misalignment. This is associated with obesity, cardiovascular disease and T2DM. Notwithstanding the existence of substantial evidence, this issue persists in being overlooked in public health discourse, with healthcare professionals not routinely evaluating patients' light exposure when assessing diabetes risk.

It has been hypothesised that a reduction in night-time light exposure could serve as an effective diabetes prevention strategy, particularly in urban areas where levels of light pollution are high.

Case Study: "Light Pollution and Oxidative Stress: Effects on Retina and Human Health", by Salceda (2024)

Salceda (2024) examines the impact of light pollution, particularly blue light (400–500 nm), on the retina and overall human health. The increased use of LED technology and electronic displays has led to a significant increase in exposure to blue light, which constitutes approximately 25% of solar radiation and 30% of emissions from electronic

2.2. Case Studies on the Impacts of Light Pollution

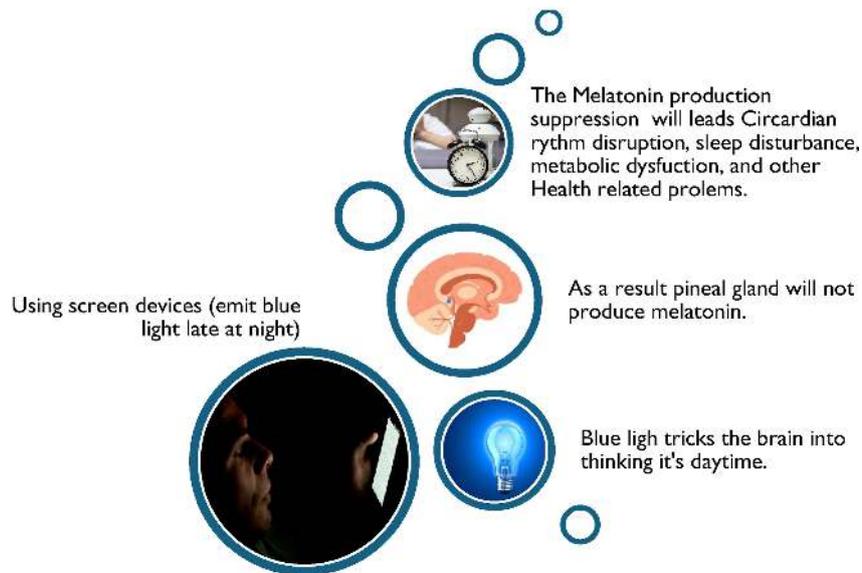


Figure 2.2.: This diagrammatic representation aims to demonstrate the deleterious effect on the circadian rhythm and T2DM as consequences of ALAN exposure. (Salomon et al., 2025)
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devices. The study identifies three key areas of concern.

Firstly, with regard to retinal effects, the absorption of blue light by chromophores leads to the generation of reactive oxygen species (ROS), which in turn cause oxidative stress. During the process of phototransduction within the retina, light exposure triggers the conversion of 11-cis-retinal to all-trans-retinal. Excessive exposure has been demonstrated to lead to lipofuscin accumulation, which, in turn, produces ROS and triggers cell death pathways. The retinal pigment epithelium (RPE) is particularly vulnerable, and damage to it is associated with age-related macular degeneration (AMD)—the leading cause of blindness in industrialised countries. It is particularly concerning for children, as their retinas absorb over 65% of blue light at 460 nm.

Secondly, with regard to the subject of circadian disruption, intrinsically photosensitive retinal ganglion cells containing melanopsin (which exhibit peak sensitivity at 460 nm) have been demonstrated to regulate melatonin secretion and circadian rhythms. Disruption to these cycles has been linked to increased rates of diabetes, depression, cancer, cardiovascular disease, and obesity, particularly among individuals who work night shifts.

Thirdly, with regard to cutaneous effects, blue light has been demonstrated to penetrate more deeply into skin tissue than UV radiation, thus contributing to cutaneous ageing, DNA damage, and potentially cutaneous cancer in long-term animal studies.

Case Study: "Comprehensive Assessment of Real-Life 24-h Light Exposure Pattern in Children and Young Adults: Intensity, Timing and Rhythm", by Li et al. (2025)

Li et al. (2025) investigated 24-hour light exposure patterns in 831 school-age children (7–11 years) and 344 young adults (over 18 years) in China using portable light sensors worn continuously for 5–7 days. The modern lifestyle has undergone a shift in light exposure,

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deviating from natural patterns. This deviation is attributed to a decrease in daylight hours due to an increase in indoor activities, and a concomitant rise in ALAN. This shift has been linked to the emergence of circadian rhythm disorders and associated health complications.

It is revealed that children experienced significantly higher daytime light levels than young adults, with nearly all children meeting the recommended minimum of 250 lx compared to only 40% of young adults. However, night-time light exposure proved problematic for both groups. It was established that children were exposed to higher levels than young adults before bedtime and during sleep. Furthermore, it was determined that 73% of children exceeded the recommended maximum of 1 lux compared to 32% of young adults. Children also exhibited more stable daily light rhythms, presumably attributable to the structured school and family routines to which they were subject. In addition, both groups demonstrated higher levels of exposure during weekdays compared to weekends.

Young adults' diminished daytime exposure is ascribed to subsequent circadian rhythm disruption, the absence of formal guidelines regarding outdoor activity and the prevalence of indoor pursuits. Conversely, children's heightened night-time exposure was attributed to the completion of educational assignments under artificial lighting.

2.2.4. Astronomy

Case Study: "The growing threat of light pollution to ground-based observatories.", by Green et al. (2022)

Green et al. (2022) present a thorough review of the rising threat to ground-based astronomical observatories from light pollution. Many observatories constructed decades ago in proximity to smaller towns have now been subjected to considerable levels of light pollution as a result of urban expansion, while even remote locations are at risk of being impacted by mining, military activities and infrastructure development.

The measurement and quantification of light pollution is a subject under investigation. In the field of astronomy, the measurement of light pollution is typically accomplished through the utilisation of the Johnson V bandpass filter. This filter has been shown to closely approximate the photopic (light-adapted) visual response of humans. However, the scotopic response is more relevant for assessing the impact on visual astronomy and human vision adapted to darkness. As demonstrated in Figure 2.3, the scotopic response exhibits a peak at shorter wavelengths in comparison to the photopic response. This phenomenon elucidates the disproportionate impact of blue-rich light sources, such as white LEDs, on the perceived brightness of the night sky in contrast to yellow light sources, including high-pressure sodium vapour lamps.

The physics of light propagation is examined on the basis of four key relationships:

- The brightness of the sky, which is directly proportional to the illuminance
- Direct emissions upwards, which have a 40 to 150 times greater impact than the same luminous flux downwards
- The effect of light propagation increases approximately with the inverse 2.5 power of distance, and

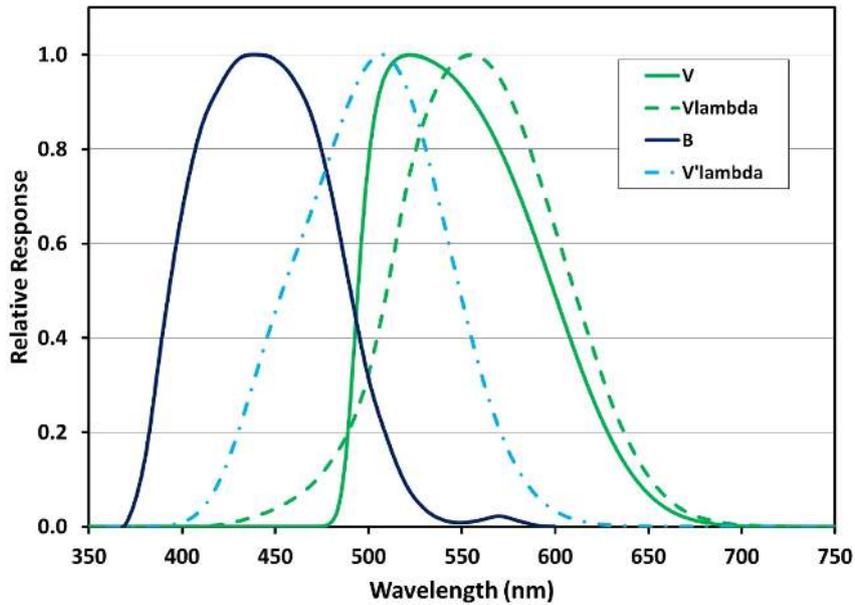


Figure 2.3.: The graph demonstrates the spectral sensitivity of the Johnson V and B passbands, as well as the light-adapted (photopic – V-lambda) and dark-adapted (scotopic V'-lambda) sensitivity of the human eye. (Green et al., 2022)

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- White LEDs have a 1.6 to 2.8 times greater visual impact on sky glow than yellow light sources such as high-pressure sodium lamps.

Another aspect described is field measurement methods, with particular reference to the method employed by the U.S. National Park Service to create all-sky images. In these cases, natural components are modelled and removed in order to isolate artificial influences. The Sky Quality Index (SQI), a metric developed by the National Park Service, integrates various factors to assess the quality of the night sky. These factors include the natural sky, the visibility of the Milky Way, the effects on scotopic vision, and the number of visible stars. The SQI ranges from 0 to 100, with higher values indicating better night sky conditions. It has been observed that even locations more than 100 km away from large cities experience a significant deterioration in sky quality.

With respect to existing large observatories, it is noted that natural fluctuations complicate the establishment of baseline values. The New World Atlas was the basis for the identification of locations with virtually untouched conditions, including Paranal, Sutherland and San Pedro Martir. It became evident that the International Astronomical Union (IAU) threshold of 10% had already been exceeded at many large observatories. Projections indicate the likelihood of a 20-30% growth over the coming decade in the absence of countermeasures. A comprehensive overview of global regulatory frameworks is provided, with a focus on the elements that are shared across different regions. These elements include fully shielded luminaires, radial protection zones, lumen limitations, spectral management, and night-time quiet hours. Two detailed case studies demonstrate the efficacy of measures to reduce light pollution:

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- **Flagstaff, Arizona**

Flagstaff achieved a 10% reduction in sky brightness through the implementation of its 1989 lighting regulations, in conjunction with the sustained commitment of observatories to local planning.

- **Maunakea, Hawaii**

In the vicinity of Maunakea, despite the presence of a population approaching 200,000 inhabitants, stringent regulatory measures have been implemented mandating the use of filtered LEDs and the implementation of comprehensive shielding measures, thereby ensuring the preservation of an exceptionally dark sky.

As demonstrated in Figure 2.4, Flagstaff has committed itself to the preservation of the natural night sky. In Figure 2.4, an analysis is conducted of all-sky images between Flagstaff and Cheyenne, Wyoming. The two cities have shown similar population trends; nevertheless, Flagstaff has clearly taken the initiative to mitigate light pollution.

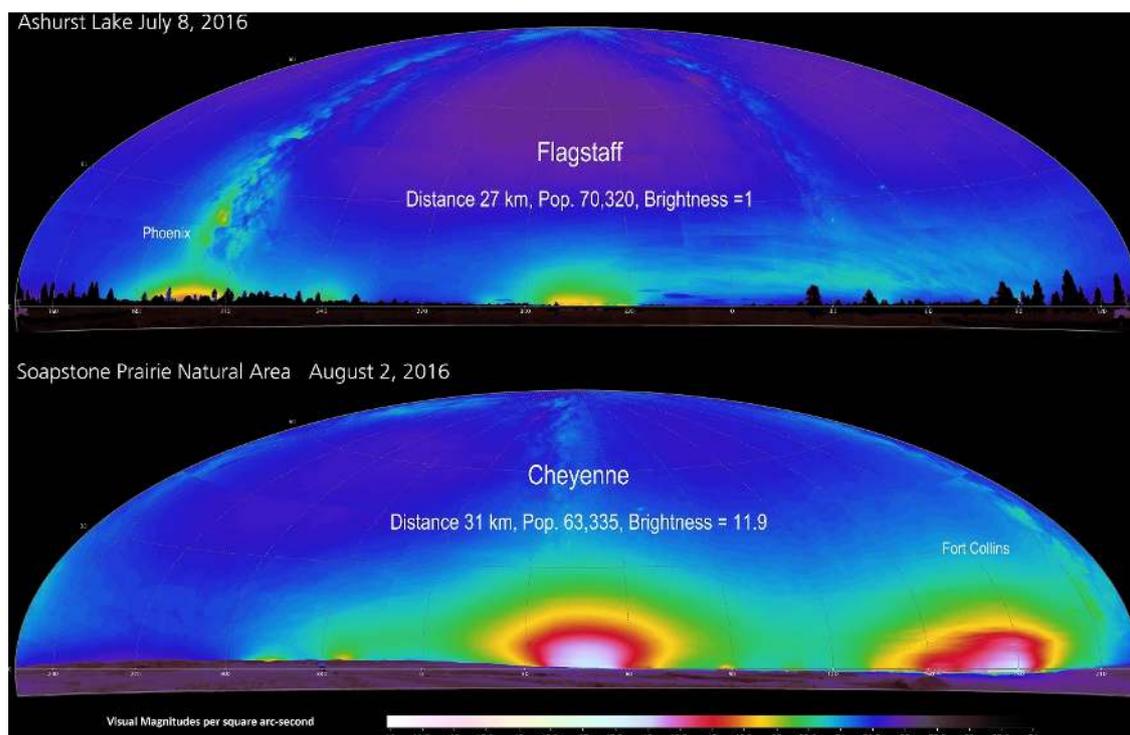


Figure 2.4.: Comparison of all-sky images captured by the U.S. National Park Service. The images were taken 27 km outside of Flagstaff, AZ (upper) and 31 km outside of Cheyenne, WY. (Green et al., 2022). Reprint with permission.

Case Study: "Light pollution indicators for all the major astronomical observatories.", by Falchi et al. (2022)

A comprehensive assessment of light pollution at all 28 major astronomical observatories worldwide was conducted by Falchi et al. (2022). The study calculated five complementary indicators in the Johnson V band:

- Zenith radiance
- Average radiance across the entire sky
- Average radiance 30° above the horizon
- Average radiation in the first 10° above the horizon
- Horizontal irradiance as an environmental indicator

An analytical point spread function was developed for each indicator, and their results were calibrated using over 20,000 ground-based sky brightness measurements.

The results obtained demonstrate significant variations between the locations. It is worth noting that only six to seven observatories remain below a 1% increase from the assumed natural background at the zenith, while two-thirds have already exceeded the critical threshold of 10% for acceptable light pollution levels at 30° above the horizon, as set by the IAU. Among the darkest professional sites are Paranal (the South African Astronomical Observatory) and the Australian Astronomical Observatory, while heavily urbanised sites such as Lick, Mount Wilson and Beijing show significant signs of deterioration.

A particularly valuable aspect of the methodology is its ability to identify specific sources of pollution. For instance, it was determined that the street lighting along Ruta 5 in Chile constitutes more than half of the artificial light pollution affecting the La Silla and Las Campanas observatories. This finding indicates that the implementation of targeted mitigation measures has the potential to yield substantial enhancements. A similar phenomenon was observed at the Tokyo Atacama Observatory, where 38% of its zenith pollution was attributed to ALMA, underscoring the potential for unintentional interference from astronomical facilities on neighbouring sites.

Case Study: "The proliferation of space objects is a rapidly increasing source of artificial night sky brightness.", by Kocifaj et al. (2021)

Kocifaj et al. (2021) investigated a previously overlooked source of light pollution: the diffuse sky brightness caused by sunlight reflecting off thousands of artificial satellites and debris fragments orbiting the Earth.

The number of operational satellites in orbit in January 2021 was approximately 3,372. This is expected to increase by more than an order of magnitude in the 2020s due to the deployment of mega-constellations. This will result in tens of thousands of debris fragments. Unlike the well-known problem of satellite streaks in telescope images, this diffuse effect manifests as an overall increase in background brightness, which can be detected by low-resolution instruments such as the Sky Quality Meter, as well as by the naked human eye. Neither of these can resolve individual objects, but instead integrate their combined light into a diffuse glow.

A theoretical model has been developed to quantify this contribution by combining three key components:

- The size distribution of space objects ranging from micrometres to tens of metres.
- Their altitude profiles ranging from a few hundred kilometres to geostationary orbit at an altitude of almost 36,000 km.

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- Their reflective properties characterised by an assumed average albedo value of 0.5.

Using catalogued object data from the 1990s, and taking into account the 4.5-fold increase in tracked objects since then, it is estimated that space objects currently contribute 16–21 $\mu\text{cd}/\text{m}^2$ to zenith sky brightness. Current growth trends suggest that this value could reach 25 $\mu\text{cd}/\text{m}^2$ by 2030.

This contribution is significant, representing approximately 10% of natural sky brightness, typically around 200 $\mu\text{cd}/\text{m}^2$ or 22.0 mag/arcsec² in the Johnson V band. This 10% threshold exactly corresponds to the maximum permissible level of light pollution for astronomical observatories set by the IAU in 1979. It should be emphasised that these estimates represent lower limits as not all space objects have been discovered and catalogued yet, meaning the actual contribution is likely to be higher.

2.3. Dark Sky Places

The night sky and the nocturnal environment are valuable natural, cultural and historical resources that merit protection. The objective of International Dark Sky Places is to protect ecologically sensitive areas and our universal heritage in the starry night sky. These locations are dedicated to the preservation of the natural night sky and the mitigation of light pollution. The Dark Sky Places certification is issued by Dark Sky International (Dark Sky) via the International Dark Sky Places (IDSP) programme. The programme was initiated in 2001 following the recognition of Flagstaff, Arizona, USA, for its outdoor lighting policy and retrofitting efforts. The IDSP programme has been developed to encourage communities and protected areas to emulate Flagstaff's example, with a view to promoting the adoption of better lighting through the implementation of effective public policy. Subsequent to this, the IDSP programme has certified over 200 locations in 22 countries. The programme's scope encompasses an area of 160,000 km² spanning six continents, with an increasing number of Dark Sky Places being recognised on an annual basis (DarkSky International (2025c)).

According to DarkSky International (2025b), there are five different certificates for Dark Sky Places from the IDSP programme from 2018, each with specific standards and criteria:

- **Urban Night Sky Places:**

An Urban Night Sky Place is defined as a city park, open space or observation site located in proximity to a substantial urban area, the design and planning of which actively promote an authentic night-time experience despite the presence of significant artificial lighting. It is acknowledged that these places are characterised by unique features, which precludes their classification within any other category. Nevertheless, commendation is merited for the endeavours undertaken to raise awareness of the benefits of appropriate outdoor lighting. This ensures public safety whilst concomitantly minimising potential harm to the natural night-time environment.

- **International Dark Sky Communities:**

A Dark Sky Community is defined as a city, town or other legally constituted community that has demonstrated exceptional commitment to preserving the night sky. This commitment is evidenced by the implementation and enforcement of high-quality outdoor lighting regulations, the education of the public about dark

skies, and the support of citizens' efforts to preserve dark skies. The concept of 'Dark Sky Communities' signifies the commitment of these localities to the promotion of responsible lighting practices and the safeguarding of nocturnal environments. They serve as exemplary models for neighbouring communities, setting an example for the wider region to emulate.

- **International Dark Sky Parks:**

A Certified Dark Sky Park is a natural protected area distinguished by exceptional or outstanding starry nights and a nocturnal environment. Such areas are specially protected due to their scientific, natural, educational, cultural heritage and/or public enjoyment value. The land in question can be under either public or private ownership, provided that the landowner(s) consent to the right of perpetual, uninterrupted public access to particular areas incorporated within the Dark Sky Park designation.

- **International Dark Sky Reserves:**

The designation of a Dark Sky Reserve refers to a public or private area that has been distinguished by its exceptional or outstanding quality of starry nights and nocturnal environment. Such areas are protected due to their scientific, natural, educational, cultural heritage and/or public importance. The concept of reserves encompasses two distinct components, namely a core area that fulfils minimum standards for sky quality and natural darkness, in conjunction with a buffer area that facilitates the conservation of the dark sky within the designated core area. The formation of reserves is achieved through a collaborative effort among multiple land managers who recognise the inherent value of the natural night environment. This recognition is formalised through the implementation of regulatory frameworks and long-term planning strategies.

- **International Dark Sky Sanctuaries:**

A Dark Sky Sanctuary is defined as a public or private area distinguished by its exceptional or outstanding nocturnal environment, which is protected on the basis of its scientific, natural, educational, cultural heritage or public enjoyment value. A sanctuary, in contrast to a Dark Sky Park or Reserve, is characterised by its location in highly isolated regions, where the quality of the dark night sky remains largely unimpacted by environmental influences. Additionally, it does not fulfil the criteria necessary for designation as a park or reserve. The geographical isolation of designated Dark Sky sanctuaries imposes considerable limitations on public outreach opportunities. The primary purpose of designation is therefore to raise awareness of these ecologically sensitive areas and to promote their long-term conservation.

The subsequent subchapters will address the general process of obtaining certification for a Dark Sky Place, followed by a concise overview of the guidelines for International Dark Sky Parks and International Dark Sky Communities. These are mandatory for the certification of the Nature Park Weißbach and the municipality of Weißbach bei Lofer.

2.3.1. Application Process for Dark Sky Places

It is important to note that, due to the divergent requirements for the various types of Dark Sky Places, the entire application process takes an average of one to three years. It is not possible to establish a universal template for the application process, as each location

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is unique and is subject to its own specific circumstances. Nevertheless, the application process can be divided into three phases:

- **Phase 1: Initial inquiry** (Average duration: 45 days)
- **Phase 2: Formal application** (Average duration: 1-3 years, depending on certification type)
- **Phase 3: Final review and certification** (Average duration: 90-150 days)

Phase 1: Initial inquiry

The process commences with meticulous preparation and research. It is imperative that applicants familiarise themselves with the guidelines specific to their certification category, as each Dark Sky Place certification category is subject to a distinct set of rules and requirements. The subsequent stage in the process is the submission of a pre-application inquiry form. This form must contain detailed information about the proposed site, as well as an explanation of the motivation for the area's potential designation as an International Dark Sky Place. Subsequently, a review of the submission is conducted by DarkSky staff, with the purpose of determining whether the proposed site meets the eligibility criteria. Following this assessment, guidance is provided for the subsequent steps to be taken. (DarkSky International (2025d)) Should the proposed site successfully pass the initial eligibility check, applicants are required to pay a one-time fee in order to formally initiate the application process. (DarkSky International (2025a))

Phase 2: Formal application

Following the successful completion of the eligibility assessment and the payment of the application fee by applicants, they will be provided with comprehensive guidance on the development of their certification documents by a DarkSky staff member. It is essential that applicants devise a Lighting Management Plan that meticulously delineates the methodology for the governance of outdoor lighting with a view to the preservation of nocturnal skies. In order to ascertain the levels of darkness at the proposed site, it is necessary to conduct a thorough night sky quality survey. In addition, it is essential to conduct a comprehensive inventory of all existing lighting fixtures. Moreover, the development of educational and outreach programmes is imperative to engage the public in the significance of dark sky conservation. In this context, a universal template is not applicable, as each site is characterised by distinct conditions and challenges.

Phase 3: Final review and certification

Upon completion and submission of all documentation pertaining to the application, a comprehensive review of said documentation will be conducted by DarkSky staff. During this period, reviewers may request further information or propose modifications for the application, with the objective of ensuring that all requirements are met. Following the successful approval of a Dark Sky Place, an official announcement is published by DarkSky, which celebrates the new certification and features quotes from key partners involved in the application process, as well as DarkSky staff. It is also important to note that the certification is not permanent. Dark Sky Places are subject to regular reviews by Dark

Sky staff, who assess their adherence to commitments regarding the protection of the dark sky. This encompasses ongoing outreach initiatives, night sky monitoring, public access programmes, and adherence to lighting requirements. In the event of non-compliance with the requisite standards by a Dark Sky Place, the certification shall be revoked. (DarkSky International (2025d))

Figure 2.5 also contains a concise overview of the three distinct phases of the IDSP application process.

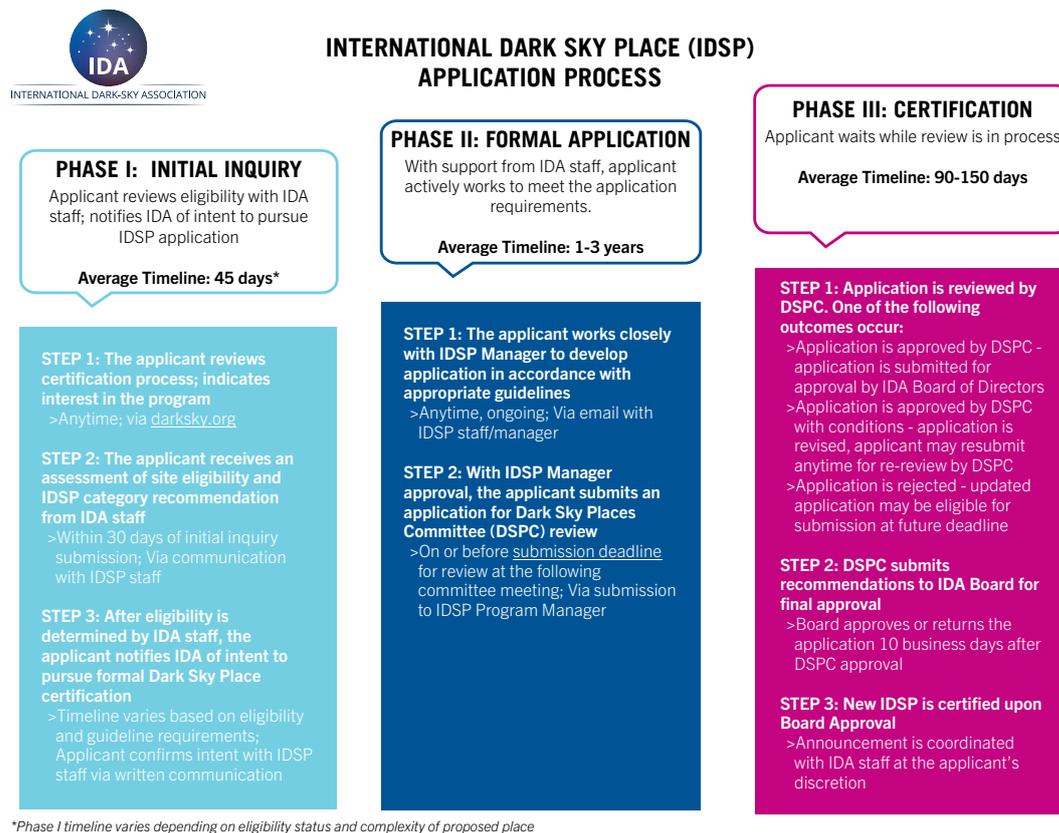


Figure 2.5.: A graphic from DarkSky International (2025d) that provides a concise overview of the three phases of the application process for an International Dark Sky Place.

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2.3.2. Guidelines for International Dark Sky Parks

This subsection provides a brief overview of the most essential elements of the guidelines for International Dark Sky Parks from September 2023. The complete guidelines can be found in the Appendix in chapter A.2 DarkSky International (2023b).

The designation of an area as an International Dark Sky Park (IDSP) is predicated on the presence of a distinctive and exceptional quality of starry nights and a nocturnal

2. *Light Pollution and Dark Sky Places*

environment. This land is subject to specific protection measures in consideration of its scientific, natural, educational and/or culturally significant characteristics, and for the advantage of the general public. These lands may be owned by either the public or private entities, with the proviso that landowners consent to the provision of permanent, ongoing public access to designated areas. The programme's objectives are threefold: firstly, to identify areas of public land that require attention; secondly, to restore these areas; and thirdly, to protect them. The programme focuses on national and state parks, as well as accessible private lands, with a strong commitment to the preservation of dark skies. The promotion of eco- and astrotourism is an additional objective, as is the protection of the natural night-time environment for the purposes of public enjoyment and professional astronomy. Furthermore, there is a need to encourage conservation professionals to recognise dark skies as valuable resources in need of proactive protection. In addition to these objectives, it is essential to provide national and international recognition for participating parks, and to encourage parks to become environmental leaders by communicating the importance of dark skies to the public and surrounding communities.

Achieving IDSP designation is indicative of a park's commitment to safeguarding dark skies, while concomitantly fostering awareness among park administration, personnel, guests and the local community. The designation confers several privileges upon designated parks. Firstly, they are permitted to display the DarkSky logo in official publications and promotional materials. Secondly, the logo may be used by commercial enterprises and other groups within the community to identify the park area. Thirdly, DarkSky is obliged to promote and highlight ongoing park efforts through dedicated pages on their website. The park managing agency will also be able to identify DarkSky as a partner in their efforts to conserve the natural environment.

All protected public lands are eligible. Private lands are also eligible if the owners consent to regular public access at night in perpetuity. Parks must provide an opportunity for public night-time access, either supervised or unsupervised; however, a portion of designated land or limited night-time hours may suffice. These requirements may be adjusted if endangered wildlife or sensitive archaeological sites are involved. Public access may incur a nominal entry fee, but cannot be contingent on the compulsory paid use of other products or services. There are no minimum or maximum land area requirements, though larger parks exceeding 1,000 km² may designate smaller areas with special permission and justification. Most importantly, parks must offer an exceptional dark sky experience compared to the surrounding area.

The minimum requirements for all parks are as follows:

1. A quality, comprehensive Lighting Management Plan (LMP) that meets minimum standards.
2. Typical night-time conditions, with the Milky Way readily visible and minimal glare, where light domes are dim and restricted (corresponding to 21.2 magnitudes per square arcsecond).
3. The park's pledge to preserving dark skies is evidenced by the implementation of several measures, including:

- Recognition in management documents.
 - Two-thirds of lighting is compliant at application.
 - A plan for 90% compliance within 5 years and 100% within 10 years.
 - An ongoing measurement programme.
4. Description of current and future threats to dark skies.
 5. Evidence of leadership through at least one restoration project involving lighting demonstrations, external partners or municipal cooperation.
 6. Present dedication to public education.
 7. Incorporating dark skies/natural darkness into interpretation and outreach programmes.
 8. Dedicated programming at least four times per year.
 9. Appropriate public signage indicating IDSP designation.
 10. Annual reports documenting activities and progress, submitted by 1. October.

The Lighting Management Plan is a written policy approved by the park management team. It contains minimum provisions that meet or exceed applicable agency policies, and it conforms to all laws. The use of outdoor lighting must be prescribed only when strictly necessary for public safety purposes. All fixtures exceeding 500 initial lamp lumens must be fully shielded and fitted with appropriate timers and motion sensors. However, lighting under 500 lumens may remain unshielded for special purposes such as historical preservation, on condition that this is stated in the LMP. Motion-activated lighting with a duration of under five minutes is exempt from other requirements. Lighting must minimise short-wavelength emissions by restricting the correlated colour temperature to 3,000 K or less, limiting the spectral power below 550 nm to 25%, or maintaining the scotopic-to-photopic ratio below 1.3. Visitor activities involving the introduction of artificial light must be regulated, including the imposition of reasonable limits on camping equipment and recreational vehicle lighting, and the prohibition of inappropriate light painting and searchlights. Illuminated signs must only operate during associated activities; display single colours on black backgrounds; maintain luminance below 100 cd/m²; and limit surface area to 18.6 m². The plan must also govern temporary lighting installations to ensure adherence to the LMP for the shortest possible duration.

A lighting inventory is a formal audit of all artificial outdoor lighting in a park that is used to determine LMP compliance rates and identify equipment that requires retrofitting or replacement. A complete inventory is required for IDSP status and must accompany a plan to bring park lighting into compliance with the LMP. When collecting data, numerous fixtures may be grouped by facility or area. It is important to note whether the fixtures are fully shielded or special-purpose fixtures with a lumens output of less than 500, as well as the lighting application for each fixture or group. Daytime photographs or manufacturer diagrams may be included with the inventory. Inoperable fixtures must be included in the inventory, but only those that are physically disconnected from power

2. *Light Pollution and Dark Sky Places*

supplies count as compliant when calculating LMP compliance rates. For comprehensive tracking and planning purposes, the inventory should clearly document the location, fixture type, shielding status, operational status, special purpose designation, application and LMP conformance status of each fixture.

In circumstances where a park lacks the necessary resources to submit a successful application for designation as an International Dark Sky Park, a provisional status may be granted. The Provisional Status is recognised as a means of acknowledging the park's ongoing efforts towards achieving IDSP designation. It is also intended to serve as a bargaining position to facilitate the implementation of essential lighting upgrades or retrofits. This status is subject to expiration after a period of three years, during which time parks may submit applications for full status at any point. Material submitted for the purpose of removing provisional status may be an addendum to the initial application, provided it includes current assessments of sky quality, goals, outreach, and programs listed in the original application. In order to be granted provisional status, parks are required to meet four criteria. Firstly, they must have a Lighting Management Plan that has been approved by the relevant park management. Secondly, they must satisfy the minimum sky quality criteria. Thirdly, they are required to complete an inventory of outdoor lighting owned by either the park or concessionaires. Finally, they must demonstrate that appropriate outreach efforts have been undertaken. Applicants seeking provisional status are required to submit a nomination package to DarkSky, encompassing documented intent to create and support a DSP, initial sky quality measurements, a Lighting Management Plan, and an action plan outlining how the aspiring park will meet minimum requirements.

2.3.3. Guidelines for International Dark Sky Communities

This subsection provides a brief overview of the most essential elements of the guidelines for International Dark Sky Communities from September 2023. The complete guidelines can be found in the Appendix in chapter A.3 DarkSky International (2023a).

An International Dark Sky Community (IDSC) is defined as a town, city, municipality, or other similar political entity that has demonstrated a remarkable commitment to the preservation of the night sky through the implementation and enforcement of quality lighting policies, the promotion of dark-sky education, and the active support of the dark skies ideal by its citizens. The programme's objective is twofold: firstly, to identify communities that demonstrate exceptional commitment to and success in pursuing dark sky preservation and restoration, and secondly, to concurrently promote the adoption of quality outdoor lighting. The enhancement of outdoor night-time quality of life for residents and visitors is a fundamental objective. Furthermore, provisions are to be made for the safeguarding of human health, nocturnal habitats, and the public's right to enjoy the night sky. Moreover, it is imperative to acknowledge the necessity of providing recognition at local, national, and international levels for such communities. Ultimately, it is recommended that communities be encouraged to identify dark skies as both a valuable asset and a worthy aspiration.

Achieving IDSC designation serves to recognise the efforts made by the community to protect the night sky and its dependent nocturnal environment. The designation serves to enhance awareness of dark sky matters among community residents and visitors. The

International Dark Sky Community logo may be used in official publications and on signs at entrances or within the community. Moreover, it has been determined that other groups within the community are permitted to utilise this logo for the purpose of identifying the area. DarkSky is committed to the promotion of ongoing community initiatives aimed at safeguarding the integrity of night skies. DarkSky will also be responsible for maintaining pages that identify and describe all IDSCs on its website.

It is imperative for the community to possess a certain degree of legal organisation that is officially recognised by external entities. This could manifest in the form of a town, city, municipality, or other legally constituted community, such as urban neighbourhoods and subdivisions. However, it is not obligatory for the community to be an incorporated entity. The eligibility criteria for unincorporated communities to attain IDSC status are contingent upon the implementation of public policy that is in alignment with the stipulated minimum requirements, which are legally binding within the territorial boundaries of the community.

The minimum requirements for all communities are as follows:

1. Comprehensive outdoor lighting regulations that establish:
 - Mandatory full shielding for all fixtures exceeding 1,000 initial lamp lumens.
 - Controls on blue-rich light emissions, with a maximum colour temperature of 3,000 K or a comparable standard.
 - Caps on total unshielded light output across the community.
 - Measures to prevent excessive illumination; levels are kept within 10% of the industry recommendations.
 - Standards for future public lighting requiring dimming capabilities or time-based controls.
 - Sign lighting parameters (maximum 100 nits (100 cd/m²) brightness, business-hours operation, 18.6 m² size cap).
 - Conditional exemptions for sports facilities meeting strict criteria.
 - Retrofit timeline requiring full compliance within 10 years.
2. Commitment by the community to dark skies shown through:
 - Public lighting that meets policy standards or has a 5-year compliance roadmap.
 - Active promotion through community communications, educational materials and funding.
3. Broad support from community organisations.
4. Public awareness initiatives including at least one approach:
 - Hosting a minimum of two annual educational events about night sky preservation.
 - Distributing dark sky information alongside regular community communications.

2. *Light Pollution and Dark Sky Places*

5. Measurable implementation results via completed projects following the lighting standards or comparable proof of effectiveness.
6. Ongoing monitoring system for tracking sky brightness changes over time.
7. Visible designation markers at community entry points or prominent civic locations.

In circumstances where a community lacks the necessary resources to submit a successful application for designation as an International Dark Sky Community, a provisional status may be granted. This provisional designation acknowledges the community's ongoing endeavours to attain full IDSC recognition, whilst concurrently providing the institutional support required to secure funding, implement lighting retrofits, or undertake other essential preparations. The provisional period extends for a maximum of three years, thereby affording communities the necessary flexibility to achieve full designation at a time that is convenient to them during this designated period. It is possible for communities to upgrade their status by submitting either a complete new application or supplementary documentation. This documentation must demonstrate how previously unmet requirements have been addressed. It should also include updated evidence of lighting policies, community engagement activities, and overall progress. In order to be considered for this provisional designation, it is necessary for communities to demonstrate the presence of four fundamental elements. Firstly, there must be formal adoption of a lighting management policy by the relevant local government authority. Secondly, there must be verification that current sky conditions meet the programme's stipulated standards. Thirdly, a complete audit of existing outdoor lighting infrastructure must be conducted. Finally, there must be evidence of meaningful public engagement and education efforts that are already underway. It is imperative that the provisional application comprises unambiguous documentation of the community's commitment to attaining full IDSC status. Furthermore, the application must include baseline sky quality data, the adopted lighting ordinance, evidence of outreach activities that have been completed to date, an explanation of the specific barriers that are currently preventing full compliance, and a detailed timeline that shows how the community will address the remaining requirements during the provisional period.

2.4. Nature Park Weißbach and Municipality Weißbach bei Lofer

In light of the escalating issue of light pollution in Austria, which has even affected nature parks (cf. Wallner et al. (2023)), the Nature Park Weißbach and the municipality of Weißbach bei Lofer have initiated measures to combat this phenomenon. These measures include the pursuit of certification as an International Dark Sky Park and International Dark Sky Community. The nature park and the municipality itself are therefore briefly presented here.

2.4.1. Nature Park Weißbach

The Nature Park Weißbach is one of Austria's 47 designated nature parks (Wallner et al. (2023)) and is located in the province of Salzburg. Situated within the Salzburg Limestone

2.4. Nature Park Weißbach and Municipality Weißbach bei Lofer

Alps, it is adjacent to the National Park Berchtesgaden, with which it constitutes a single natural area (Tourismusverband Lofer (2025)). The area of the Nature Park Weißbach is approximately 28 km² (Verband der Naturparke Österreichs (2025)) (see Figure 2.6), with an altitude range off 666 - 2,634 m above sea level (Tourismusverband Lofer (2025)).

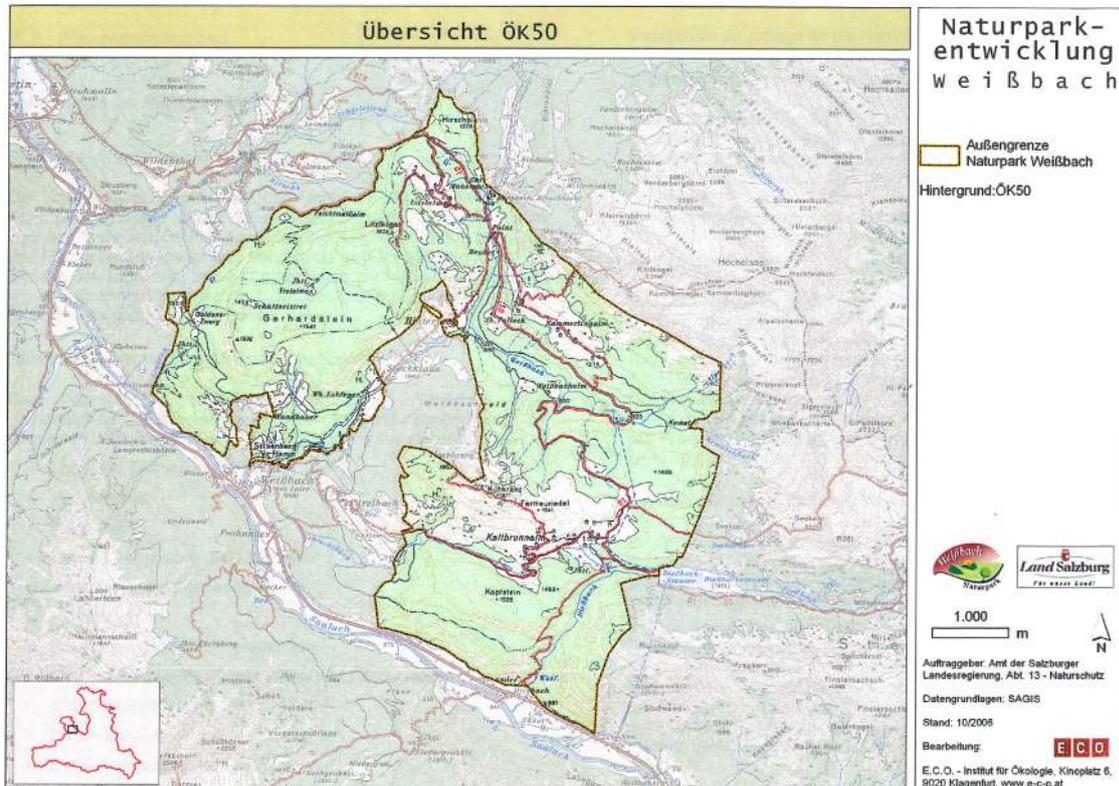


Figure 2.6.: A graphic by Naturpark Weißbach (2025a) showing the area of the Nature Park Weißbach with its outermost boundaries. Reprint with permission.

Forest constitutes the most prevalent habitat type, accounting for approximately 75% of the total area. Around 16.5% of the area is used in various ways as grassland. The third most common habitat type is formed by alpine high-altitude communities and sites bound to rock and scree, accounting for approximately 6.5% of the total (Blühendes Österreich (2025)). The largest area of the region, comprising the three communal alpine pastures of Kallbrunnalm, Litzlalm and Kammerlingalm, is designated as a landscape conservation area. The designation 'nature park' is awarded by the nature conservation department of the Salzburg provincial government to landscape areas that are protected under nature conservation law (protected landscape areas, landscape conservation areas or nature reserves) (see Figure 2.7). Moreover, the Mitterkaser natural forest reserve, a specially protected forest area, is also of significance (Naturpark Weißbach (2025a)).

The nature park also provides a habitat for endangered species, including the Apollo butterfly (*Parnassius apollo*), which is strictly protected in Europe, and various plant

2. Light Pollution and Dark Sky Places

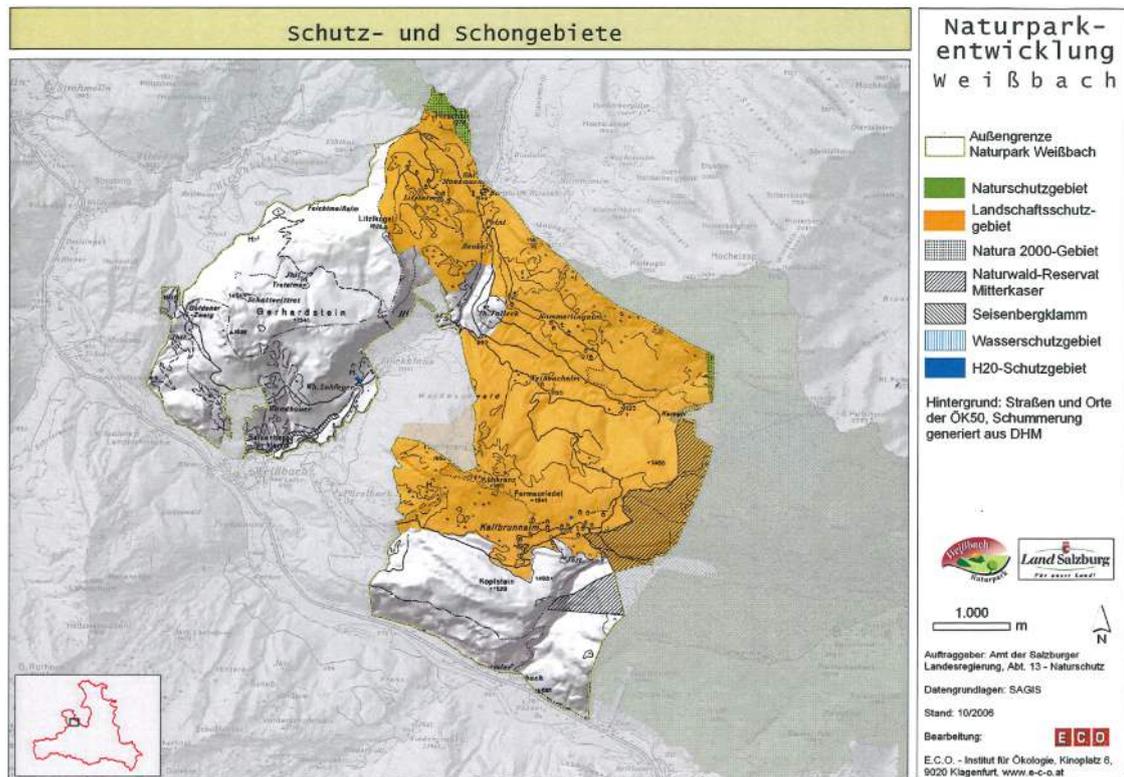


Figure 2.7.: A graphic by Naturpark Weißbach (2025a) depicting the various protected and conservation areas that constitute the Nature Park Weißbach.

Green: Nature reserve; Orange: Landscape conservation area; Checkered: Natura 2000-area; Stripped from top right to bottom left: Mitterkaser natural forest reserve; Stripped from top left to bottom right: Seisenbergklamm; Blue stripes: Water protection area; Blue: H2O protected area
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species, such as lady's slipper, Turk's cap lily and arnica (Verband der Naturparke Österreichs (2025)). In 2013, the Nature Park Weißbach was awarded the title of Austrian Nature Park of the Year (Blühendes Österreich (2025)).

The Weißbach Nature Park was established in 2007 and formally inaugurated on 22. July of that year with an awards ceremony (Blühendes Österreich (2025)). The nature park is overseen by a non-profit association that was established in January 2008 (Naturpark Weißbach (2025b)).

2.4.2. Municipality Weißbach bei Lofer

The municipality Weißbach bei Lofer is located in the province of Salzburg in a widening of the Saalach Valley between Saalfelden and Lofer at 666 m above sea level and covers an area of 69 km². The region is characterised by a mountainous topography, with prominent features such as the foothills of the Steinernes Meer, the Leoganger and Loferer Steinberge mountains, the Reiter Alpe, and the Hochkaltergruppe. The highest point is the Birnhorn, which is located at an elevation of 2,634 m above sea level. The Hirschbichl Pass, which is

2.4. Nature Park Weißbach and Municipality Weißbach bei Lofer

located at an elevation of 1,148 m, serves as a crucial connection between the Austrian province of Salzburg and the southern German state of Bavaria. This strategic point is of historical significance as it was once a border station, marking the former border between these two regions. The municipality comprises the five villages of Frohnwies, Hintertal, Oberweißbach, Pürzlbach and Unterweißbach (Gemeinde Weißbach bei Lofer (2025)). As of 1 January 2025, the municipality of Weißbach bei Lofer had 416 inhabitants (Statistik Austria (2025c)), thus constituting it as the smallest municipality in Pinzgau (Salzburger Nachrichten (2025)). As demonstrated by its status as an exceptionally committed municipality, Weißbach bei Lofer also fulfils supra-regional functions. Weißbach bei Lofer is not only the seat of the Climate and Energy Model Region (KEM), but also the seat of the LEADER Association for Regional Development. Moreover, the municipality has been recognised as the most energy-efficient in the province of Salzburg (Gemeinde Weißbach bei Lofer (2025)). Weißbach bei Lofer also offers a valuable historical perspective, as evidenced by the existence of the oldest farms, which were documented as early as the 11th century (Salzburger Nachrichten (2025)).

3. Light Pollution Measurement Techniques

This chapter provides a concise synopsis of the diverse measuring instruments available for the assessment of light pollution. The individual measuring instruments used for this Thesis will then be discussed in more detail in the course of this chapter.

A general outline of meteorological parameters is also provided, with the primary focus on clouds, which will be pertinent subsequently.

3.1. Quantifying Light Pollution: Instruments and Metrics

The luminosity of the night sky is attributable to two distinct light sources: firstly, natural light sources, such as starlight, moonlight, airglow and zodiacal light; and secondly, artificial sky glow, which is caused by scattered artificial light. The light present within an environment is defined by two fundamental parameters: irradiance, which is the total amount of electromagnetic radiation that strikes a surface, and luminance, denoting the perceived brightness of a given area. The aforementioned parameters are converted into illuminance (lux) and luminance (cd/m^2) when measuring instruments are calibrated to correspond to human visual performance. The magnitude system ($\text{mag}/\text{arcsec}^2$), in which larger values indicate a darker sky, is traditionally employed by astronomers. The darkest natural locations have been found to reach approximately $22 \text{ mag}/\text{arcsec}^2$, whilst those in the vicinity of bright urban areas have been found to reach only $16\text{--}17 \text{ mag}/\text{arcsec}^2$. The conventional approach to determining the 'limiting magnitude' (the faintest star visible to the naked eye) involves the utilisation of the contrast threshold of human vision. Citizen science projects, including Globe at Night and the smartphone application Loss of the Night, facilitate widespread participation in the monitoring of sky brightness. The Loss of the Night application has been shown to achieve an accuracy of up to 0.05 magnitudes through systematic reports on star visibility (Hänel et al. (2018)).

Figure 3.1 by Kocifaj et al. (2023) demonstrates six distinct subject areas in which the quantification of light pollution is imperative.

In the context of light pollution measurement, a categorisation of measuring devices is imperative. This categorisation involves the distinction between two primary instrument types: one-dimensional and two-dimensional instruments.

One-dimensional instruments include the widely utilised Sky Quality Meter (SQM), smartphone applications such as Dark Sky Meter, luxmeters and specialised devices such as the Digilum luminance meter, solar cell-based light meters (Hänel et al., 2018) and TESS-W (Telescope Encoder and Sky Sensor WiFi)(Robles et al., 2021). These devices are typically cost-effective, portable, and well-suited for long-term monitoring

3. Light Pollution Measurement Techniques

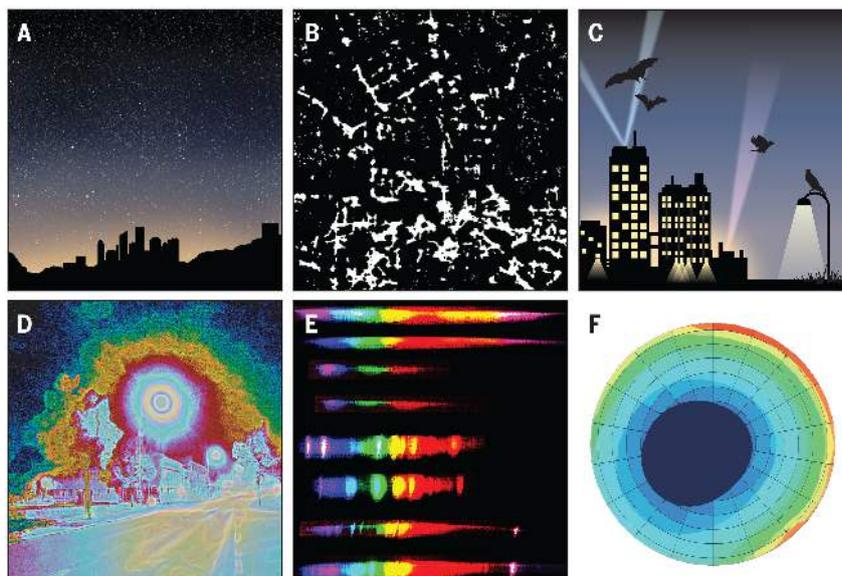


Figure 3.1.: The figure by Kocifaj et al. (2023) delineates six areas in which the quantification of light pollution is imperative. Panel (A) demonstrates the phenomenon of sky glow, otherwise known as increased night sky brightness (NSB), which manifests as luminous domes above urban areas. Panel B illustrates satellite remote sensing of upward radiation from the Earth's surface. Panel (C) offers a visual representation of ecological light pollution, which has been demonstrated to have a detrimental effect on wildlife populations. The illuminance of individual light sources is displayed in Panel (D), with the colour coding denoting the brightness levels of an illuminated building. The Panel (E) displays the emission spectra of individual lighting fixtures. Panel (F) provides a representation of computer-aided modelling approaches. Reprint with permission.

and citizen science applications. However, these instruments are limited in their capacity to measure in multiple directions and their spectral sensitivities are often not perfectly aligned with standardised photometric systems. Consequently, they are unable to discern between natural fluctuations in airglow and moderate levels of artificial light pollution.

Two-dimensional instruments include specialised all-sky monitors, of which examples include ASTMON, employing astronomical charged-coupled device cameras with fisheye lenses, and calibrated DSLR cameras likewise with fisheye lenses. Further instruments are mosaic systems, of which those employed by the US National Park Service are a notable example. These devices provide spatial information about the brightness distribution across the entire sky hemisphere and capture colour information in multiple bands (RGB). The most significant challenges they face pertain to the precise calibration of the equipment (vignetting correction, geometric distortion, and colour sensitivity) and the absence of standardised processing software. It is evident that, with meticulous calibration, DSLR systems have the capacity to attain a measurement accuracy of approximately 10%.

The primary trade-off is that one-dimensional instruments are highly effective for temporal monitoring but are unable to capture spatial gradients, while imaging instruments are capable of acquiring the entire sky but necessitate more sophisticated calibration and processing procedures.

Spectrometers such as the SAND (Spectrometer for Aerosol Night Detection) have been developed for the purpose of analysing the spectral signatures of sky brightness in order to determine the contributions from different sources. This is of particular significance during the transition to LED lighting, as different types of lamps possess differing spectral power distributions. Nevertheless, extended integration times (up to two hours for dark locations) constrain their practical application (Hänel et al. (2018)).

Table 3.1 from Hänel et al. (2018) offers a simplified summary of the diverse measuring instruments and the units in which the measurement results are expressed.

Instrument	Type of measurement	Measurement unit
Visual observations	1D photometric	Limiting magnitude
SQM	1D photometric	$\text{mags}_{\text{SQM}}/\text{arcsec}^2$
Dark Sky Meter	1D photometric	$\sim \text{mag}_V/\text{arcsec}^2$
Luxmeter	1D photometric	lux (illuminance)
Digilum	1D photometric	cd/m^2
Lightmeter	1D photometric	W/m^2 , $\sim \text{lux}$
TESS-W	1D photometric	$\text{mag}_{\text{TESS}}/\text{arcsec}^2$
ASTMON	2D photometric	$\text{mag}_V/\text{arcsec}^2$
DSLR+fisheye	2D photometric	$\sim \text{cd}/\text{m}^2$, $\sim \text{mag}_V/\text{arcsec}^2$
NPS All sky mosaics	2D photometric	cd/m^2 , $\text{mag}_V/\text{arcsec}^2$
SAND	spectroscopic	$\text{W}/(\text{m}^2 \text{ nm sr})$

Table 3.1.: Part of the overview of some measuring instruments and their respective units. The complete table can be found at Hänel et al. (2018). Adjustments have been made with adding the TESS-W.

Additionally, satellite remote sensing, particularly the VIIRS Day-Night Band, provides global coverage, enabling comprehensive analysis of entire cities or countries. However, such measurement is encumbered by various challenges, including inadequate repetition rates, divergent observation angles, and an absence of sensitivity to wavelengths beneath 500 nm (Barentine et al. (2023); Kocifaj et al. (2023)).

In addition, measuring instruments are available for the purpose of conducting ecological studies. Special detectors that mimic animal eyes and drones are utilised to assess the effects of ALAN on wildlife (Kocifaj et al. (2023)).

Figure 3.2 by Kocifaj et al. (2023) presents a comprehensive overview of the five primary approaches adopted by the extant measurement methods for analysing light pollution. This figure offers a clear illustration of the manner in which these diverse methodologies

3. Light Pollution Measurement Techniques

complement each other, encompass different spatial scales, and furnish distinct types of information relevant to the nocturnal light environment.

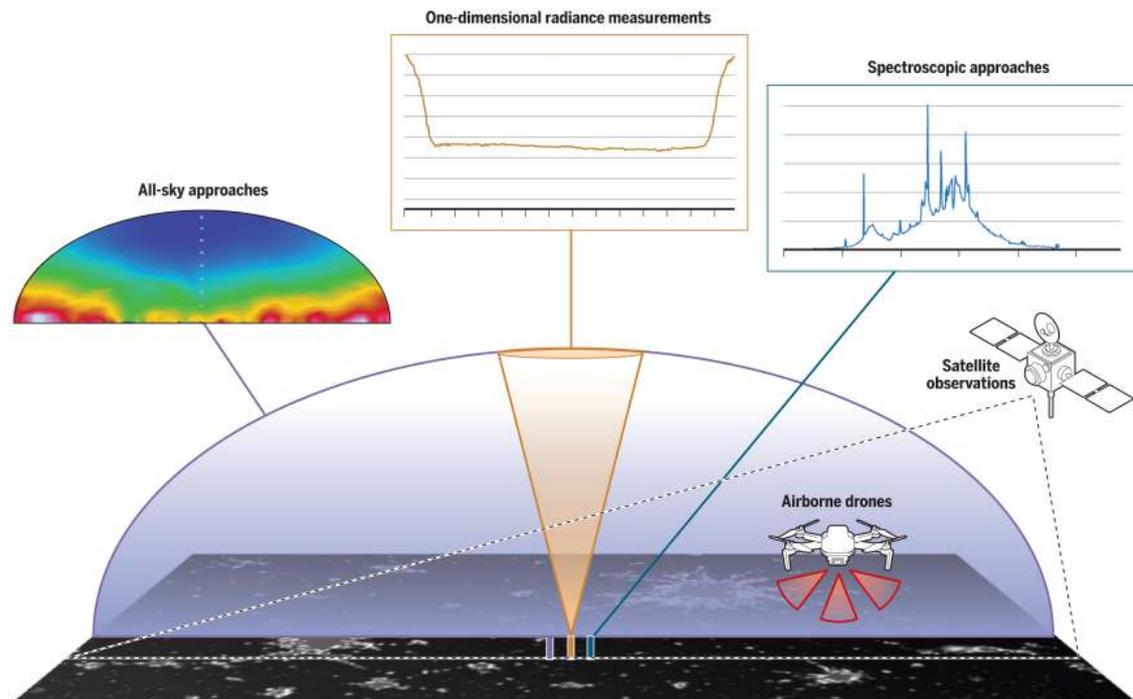


Figure 3.2.: This figure by Kocifaj et al. (2023) delineates five primary methodologies for the analysis of light pollution: The all-sky approaches (denoted by a purple semicircle) are designed to collect information regarding the entire upper hemisphere. Spectroscopic approaches (represented by a blue line) are utilised to ascertain the wavelength of light. One-dimensional radiation measurements (illustrated as an orange cone) generally encompass a limited area in the vicinity of the zenith. Satellite observations (depicted as black dashed lines) are employed to measure the radiation from ground sources that extends into space. Drones (represented by red triangles) are employed to measure spectral radiation and irradiance in numerous directions.

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3.1.1. Sky Quality Meter (SQM): SQM-L, SQM-LU & SQMDroid

The Sky Quality Meter models L and LU (SQM-L and SQM-LU) are instruments designed for the measurement of the brightness of the night sky. Both of these devices utilise a TAOS TSL237S light-to-frequency converter, accompanied by a HOYA CM-500 infrared blocking filter.

The devices have a narrow field of view with HWHM (Half Width at Half Maximum) $\approx 10^\circ$ and FWHM (Full Width at Half Maximum) $\approx 20^\circ$ (Cinzano, 2007). The spectral sensitivity of these devices ranges from 320–720 nm, overlapping the Johnson B and V bands. However, studies have revealed an unexpected near-infrared extension beyond 800 nm due to incomplete filter coverage (Sanchez de Miguel et al., 2017). The range of measurements

3.1. Quantifying Light Pollution: Instruments and Metrics

extends from 16 mag/arcsec² (for bright urban areas) to 22 mag/arcsec² (for darkest skies), with a systematic uncertainty of 10% (0.1 mag/arcsec²). Recent LED-calibrated devices have been shown to measure 0.15–0.2 mag/arcsec² brighter than their older counterparts. The conversion to astronomical V magnitudes necessitates an offset of 0.35 mag (Cinzano, 2007). Spectral sensitivity exerts a substantial influence on the measurements obtained. Specifically, it has been observed that bluer LED lamps provide brighter SQM readings than high-pressure sodium vapour lamps with the same lumen output (Sanchez de Miguel et al., 2017).

The SQM-LU devices provide stable measurements within the temperature range of -15°C to 35°C (Schnitt et al., 2013). The long-term utilisation of this system has been shown to result in a gradual deterioration of approximately 34–53 millimag/arc second² (mmag/arcsec²) per year, a phenomenon that has been demonstrated to be amenable to correction through twilight calibration procedures (Puschnig et al., 2022).

The SQM-L is a handheld, battery-powered device for field measurements (Cinzano, 2007). The SQM-LU model facilitates automated data logging through its USB connectivity, while the SQM-LU-DL variant offers the capacity to store over a million readings, thereby ensuring uninterrupted operation even in the absence of direct supervision (Schnitt et al., 2013). It is imperative to note that both devices necessitate a weatherproof enclosure for utilisation in outdoor environments. Applications of this technology include the certification of dark skies, long-term monitoring (Schnitt et al. (2013); Puschnig et al. (2022)), and the mapping of light pollution (Sanchez de Miguel et al., 2017).

The SQM-L and SQM-LU are illustrated in Figure 3.3.



(a) SQM-L

(b) SQM-LU

Figure 3.3.: Images of the two different SQM models SQM-L & SQM-LU.
Images taken by Raphael Selber.

3. Light Pollution Measurement Techniques

SQMDroid is an Android application that was developed by Hänel and Hänel (2016). The application combines a Unihedron SQM-LU with an Android smartphone to create a versatile, all-in-one device for measuring sky brightness.

The SQM-LU is connected to the smartphone via a USB On-The-Go (OTG) adapter cable, with both devices mounted in parallel. SQMDroid then utilises the smartphone's built-in sensors – GPS, accelerometer, gyroscope and compass – to simultaneously record time, geographical position, device orientation and sky brightness. The integration of these models into a single portable device represents a significant advancement in the field.

The application employs the Android terminal application provided by FTDI to configure the UART interface in the SQM-LU and to transfer measurement data. SQMDroid is a versatile instrument that supports four distinct operating modes. The first mode is manual, in which the user can perform individual zenith brightness measurements and automatically log the date, time and position of the measurement. The second mode is continuous, in which measurements can be taken at fixed locations at user-defined time intervals. The third mode is Roadrunner, which facilitates mobile surveys by car, bicycle or on foot. The fourth and final mode is vector, which enables measurements across different azimuth and elevation directions to characterise the entire sky hemisphere.

All data is recorded in CSV format, including date, time, brightness in magnitudes per square arc second, azimuth, elevation, latitude and longitude. The GPS positioning accuracy is less than five metres, the altitude sensor accuracy is one to two degrees, and the azimuth accuracy is up to ten degrees. It is therefore essential to calibrate the compass before taking measurements in vector mode.

3.1.2. Telescope Encoder and Sky Sensor WiFi (TESS-W)

The TESS-W (Telescope Encoder and Sky Sensor WiFi) photometer (cf. Figure 3.4) is a low-cost device for measuring NSB and monitoring light pollution, developed as part of the European STARS4ALL project (Zamorano et al. (2017); Alarcon et al. (2021)). The deployment of over 200 TESS-W photometers on a global scale has formed the foundation for the establishment of NSB monitoring networks for academic institutions and meteorological agencies (Bara et al. (2019); Fernandez-Ruiz et al. (2023)).

The TESS-W utilises a TSL237 light-to-frequency converter, which is analogous to the SQM sensor. The spectral sensitivity of the converter ranges from approximately 300 to 1100 nm, with a maximum sensitivity of approximately 700 nm (Alarcon et al., 2021). A dichroic filter is a device that limits the effective bandpass to 400–740 nm and provides extended red sensitivity compared to the SQM (400–650 nm). This renders the TESS-W more appropriate for the detection of emission lines from high-pressure sodium vapour lamps and the tracking of changes resulting from LED retrofits (Robles et al. (2021); Fernandez-Ruiz et al. (2023)). The photometer has a field of view with a FWHM of 17° (Bara et al., 2019). The weatherproof housing (87 × 75 × 45 mm) contains the photometer, in addition to an infrared sensor for cloud detection, a WiFi module for data transmission, an internal heater to prevent condensation, and acceleration sensors to check the alignment direction (Zamorano et al., 2017). The calibration of each device is conducted at the Complutense University of Madrid, with the resultant measurement uncertainty being 0.04 mag/arcsec² (Alarcon et al., 2021).

The TESS-W is equipped with an MLX90614ESF-BA infrared thermometer, which utilises

3.1. Quantifying Light Pollution: Instruments and Metrics

the principle of thermal infrared emission to measure the sky temperature and thereby estimate cloud cover (Zamorano et al., 2017). This method is predicated on the principle that clear skies are transparent to infrared radiation and therefore appear cold to the sensor, while clouds are opaque to infrared radiation and re-emit thermal radiation at temperatures close to their cloud base temperature. The presence of clouds can be deduced from the temperature difference, $\Delta T = T_{amb} - T_{sky}$, where T_{amb} is the ambient temperature and T_{sky} is the measured sky temperature (Massetti et al., 2023). Another method that has been employed is NSB variability analysis, which has been shown to achieve higher performance in comparison to the temperature difference method (Alarcon et al., 2021). TESS-W photometers undertake measurements at one-minute intervals and transmit the resulting data in real time via Wi-Fi to STARS4ALL repositories. This data is then made freely accessible via the IoT-EELab portal (Alarcon et al. (2021); Robles et al. (2021)). The spectral sensitivity of the photometer is largely equivalent to that of the VIIRS satellite Day-Night Band, rendering it valuable for ground-satellite calibration studies (Fernandez-Ruiz et al., 2023). Scientific applications encompass the monitoring of trends in light pollution, the detection of natural NSB fluctuations due to air glow events, and the tracking of the effects of changes in lighting technology on night sky brightness (Alarcon et al. (2021); Robles et al. (2021)).



Figure 3.4.: Image of a TESS-W photometer.
Image taken by Paul Pacher.
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3.1.3. Sky Quality Camera (SQC)

The Sky Quality Camera (SQC) is a commercial software program developed by Andrej Mohar of Euromix d.o.o. in Ljubljana, Slovenia (Wallner, 2019). The SQC system integrates specialized software with a DSLR camera equipped with a fisheye lens, enabling the capture of a 180° hemispherical view of the sky, ground, and horizon. This wide-angle capability is imperative for exhaustive analysis of light pollution, particularly at the horizon, where artificial light sources interact most potently with the atmosphere (Vandersteen et al., 2020).

A photometric calibration of the camera systems is required by the manufacturer using classical astronomical photometry techniques under clear, stable atmospheric conditions. The calibration of the instrument is based on standard star brightness measurements and atmospheric extinction corrections, with vignetting correction performed under laboratory conditions. The green channel of the camera chip is primarily utilised for calibration purposes, given its proximity to photopic vision (Wallner (2019); Vandersteen et al. (2020)). The SQC software provides comprehensive photometric measurements, including but not limited to:

- Luminance values (mcd/m^2) for each pixel
- Sky brightness ($\text{mag}/\text{arcsec}^2$)
- Correlated colour temperature (CCT in Kelvin)
- Scalar illuminance across the entire hemisphere

(Jechow et al. (2019a); Vandersteen et al. (2020))

SQC creates full-sky data matrices containing information regarding zenith angles, azimuth angles and luminance values. In addition, it includes an automatic cloud cover detection function and allows users to identify specific sources of light pollution based on their azimuth angles (Wallner (2019); Vandersteen et al. (2020)). Supplementary features have been incorporated, encompassing tools for image subtraction with the purpose of temporal analysis, in addition to prediction simulation capabilities for the modelling of alterations in the illumination scenario (Wallner, 2019).

The SQC software has been employed in a variety of contexts, including the monitoring of sky quality in designated dark sky parks and reserves, the undertaking of ecological studies of light pollution, with particular reference to its effects on wildlife, the quantification of urban light pollution, the investigation of the effects of switching to LED lighting, the analysis of the effects of clouds on night sky brightness, and the characterisation of light pollution from cities (Wallner (2019); Jechow et al. (2019a); Jechow et al. (2019b); Vandersteen et al. (2020)).

In comparison with single-channel devices such as SQMs, SQC offers significant advantages by providing spatially resolved data across the entire sky hemisphere, rather than merely zenith measurements. This facilitates the acquisition of chromatic and spectral data via RGB channels, the identification of particular light pollution sources, and the detection of pollution shifts that would be overlooked in pure zenith measurements (Jechow et al. (2019a); Jechow et al. (2019b)). The software's intuitive graphical user interface is accessible without the requirement of programming skills or in-depth knowledge of photometry, rendering it suitable for deployment in various research applications (Jechow et al., 2019a).

3.2. Challenges and Limitations in Light Pollution Measurements

3.2.1. Atmospheric Variability and the Role of Modelling

A significant challenge inherent to any measurement approach stems from the variability of the atmosphere. The diurnal variations in atmospheric and meteorological conditions can result in significant differences from one night to the next. This complicates the comparison of measurements taken on different days. Atmospheric conditions, particularly the optical depth of aerosols (AOD) and relative humidity, have been demonstrated to exert a substantial influence on night sky brightness (NSB) patterns. An increase in humidity has been shown to result in the growth of aerosol particles, which, in turn, leads to an enhancement in forward scattering and a steepening of the NSB gradients towards light sources. Further challenges are presented by temporal and spatial variations in light sources, differing spectral sensitivities of instruments, lower signal-to-noise ratios in dark environments necessitating complex airglow corrections, and instrument ageing due to exposure to solar radiation (Barentine et al. (2023); Kocifaj et al. (2023)). The absence of consensus measurement standards engenders considerable difficulty in the comparison of results from disparate studies (Barentine et al. (2023); Kocifaj et al. (2023); Green et al. (2022)). Acceptable or target thresholds have rarely been established for light pollution metrics. This means, that mitigation efforts focus exclusively on minimising impacts without determining what an acceptable impact might be or whether light pollution has been successfully mitigated (Green et al. (2022)). Consequently, research should be conducted to gather more information about the local optical properties of the atmosphere, including the morphology of aerosols. This is because irregularly shaped particles disperse light differently than spherical ones. Polarisation measurements, a largely unexplored parameter, have the potential to provide information about light modulation during propagation and reveal the shapes of aerosol particles. The simultaneous collection of meteorological data is imperative, incorporating significant parameters such as AOD, asymmetry parameter, single scattering albedo, relative humidity, and visibility.

Given the limitations of installing monitors in all locations, accurate modelling serves as a 'force multiplier' for both ground-based and satellite-based observations, thereby bridging the gaps between measurement capabilities and research needs. As posited by Barentine et al. (2023), there is a correlation between sky glow and air pollution levels. Furthermore, the effects of different lighting technologies are predicted, and the impact is estimated at medium distances from cities. However, the accuracy of these models is constrained by the inherent variability of urban light sources, characterised by distinct lumen outputs, spectral compositions, and directional emissions. The combination of experiments and theoretical studies provides a complementary information source, with theories capable of filling data gaps and experimental data able to test theories. Rural and naturally dark locations pose a particular challenge for modelling due to lower signal-to-noise ratios and the computationally intensive nature of multiple scattering calculations over longer optical path lengths (Barentine et al. (2023); Kocifaj et al. (2023)).

3.2.2. SkyGlow

The subsequent section delineates the SkyGlow Simulator software, drawing upon the foundational theoretical contributions of Kocifaj (2007), the software introduction by Kocifaj and Kunderacik (2016), the most recent advancements in cloud modelling as expounded by Kocifaj et al. (2025), and the official SkyGlow 6.1 user manual Institute of Physics, Slovak Academy of Sciences (2025).

The SkyGlow Simulator is a software tool that is available to the public for the purpose of calculating the angular distribution of artificial sky brightness from ground-based light sources. The theoretical basis of this model is a scalable radiation transfer model that treats light sources as realistic surface sources with defined spectral and angular radiation properties. The model incorporates the mechanisms of light propagation through the atmosphere by means of molecular (Rayleigh) scattering and aerosol scattering, with attenuation following Beer-Bouguer-Lambert's law. Aerosol scattering is described by the Henyey-Greenstein phase function, while molecular scattering is described by the Rayleigh phase function.

The angular emission pattern of cities is characterised by the City Emission Function (CEF). The CEF implements Garstang's two-parameter model, which incorporates surface reflectivity and the proportion of light emitted into the upper hemisphere. The software has been developed to accept a variety of data inputs including city polygons, spectral power distributions for different lamp types and atmospheric parameters. Among the atmospheric parameters that the software is able to process are the optical depth of aerosols and single scattering albedo. The results are presented as all-sky radiation or luminance maps in photometric or radiometric units.

In conditions of cloudy sky, the observed radiation is comprised of two components: light scattered below the cloud cover and light reflected from the cloud base. In the context of urban environments, the presence of clouds has been shown to have a considerable impact on the brightness of the night sky. When the cloud cover is measured at a height of 1 km, the zenith luminance experiences an increase that is approximately ten times greater than that observed in clear skies.

A significant advancement in SkyGlow is the removal of the limitation of earlier models to idealised conditions. The latest version incorporates stochastic generation of cloud fields for any cloud cover ranging from 0 (clear) to 1 (completely overcast), with random cloud positions, shapes and optical properties over modelling areas of up to $1,000 \times 1,000$ km. The cloud module employs a single-scattering approximation to facilitate the calculation of radiation transfer through clouds. This has significant implications for distant light sources: while clouds enhance the brightness of the sky directly above urban areas, they create a shielding effect at distant observation sites that reduces the brightness of the artificial sky compared to clear sky conditions. This phenomenon can be attributed to the principle of simple scattering, whereby light from distant sources is predominantly scattered away from the observer rather than being deflected back to the observation point multiple times. Consequently, distant locations with minimal light pollution may experience greater levels of sky darkening than on clear nights, when accounting for the effect of artificial sky glow from distant cities.

Between the amplification near the city and the shielding in the distance, a transition zone

has been identified, where the behaviour of the radiation is heavily dependent on certain cloud configurations. Photometers in this zone have been found to provide ambiguous data, the interpretation of which requires modelling. Furthermore, the behaviour of partly cloudy skies deviates from the behaviour of simple averages; clear areas behind broken clouds can exhibit a darker tone than that of completely clear skies, as the surrounding clouds impede the upward diffusion of light.

Nevertheless, it is important to note that the software is not without its limitations. The software employs the nadir view cloud fraction (satellite perspective) as opposed to ground observation cloud cover. It should be noted that currently, only Garstang's parametric function for urban emissions is supported. In addition, the results of partial cloud cover are contingent on specific random configurations, which may necessitate multiple simulations. Moreover, the reported amplification factors are site-specific and should not be directly generalised without site-specific modelling.

3.2.3. The Role of Clouds in Skyglow Variability

Clouds, which are composed of water droplets or ice crystals with a diameter of approximately 10 μm , do not scatter light selectively and are therefore characterised as highly reflective objects with albedos ranging from 10% to 90% (Ścieżor (2020)). Clouds are categorised into three distinct types:

- **Low-level clouds:** Cumulus (Cu), Stratus (St), Stratocumulus (Sc) and Cumulonimbus (Cb)
- **Medium-level clouds:** Altostratus (As), Altostratus (As) and Nimbostratus (Ns)
- **High-level clouds:** Cirrus (Ci), Cirrocumulus (Cc) and Cirrostratus (Cs)

A visual representation of these cloud types is provided in Figure 3.5.

Conventional measurement methods are rendered ineffective in cloudy conditions. Satellite monitoring is inherently limited by cloud cover, while single-channel devices such as Sky Quality Meters (SQM) offer only a limited measurement of zenith luminance, thus providing a restricted set of data regarding the uneven brightness distribution of the night sky (Jechow et al. (2017)). A significant knowledge gap arises from the absence of reference values for cloudy conditions. While the horizontal illuminance under clear skies is established at approximately 0.6–0.9 mlux , no equivalent value exists for cloudy nights (Jechow et al. (2019a)). In 2020, Ścieżor (2020) developed a discrete derivation method for identifying cloud types based on brightness measurements. This method utilised characteristic patterns, whereby cloudless skies exhibited fluctuations below 0.5 $\text{mag/arcsec}^2/\text{hour}$, while low clouds exhibited fluctuations exceeding 2.0 $\text{mag/arcsec}^2/\text{hour}$.

The effect of clouds is contingent upon the extent of light pollution in the local area. In areas where atmospheric contamination is prevalent, these formations have been observed to enhance the intensity of artificial light, while in unspoiled environments, they have been shown to diminish the natural brightness of the sky. In the study undertaken by Ścieżor (2020), a direct correlation was identified between cloud cover and sky brightness. The study further categorised the observed regions based on the slope coefficient, resulting in

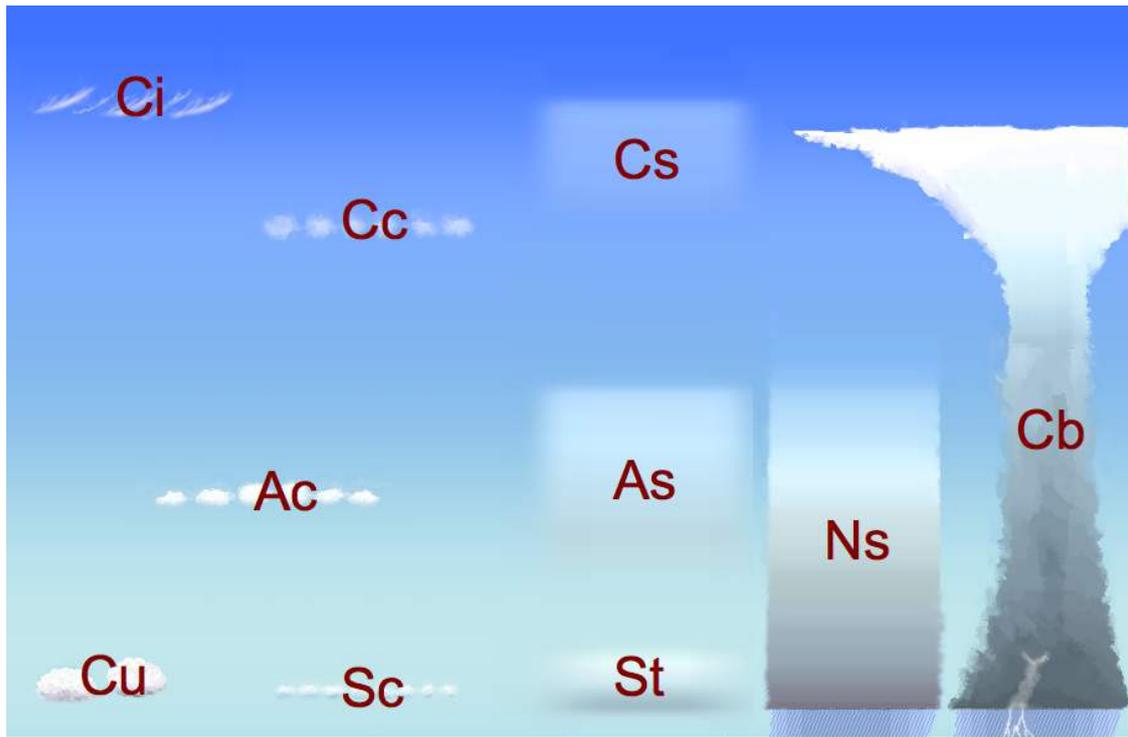


Figure 3.5.: Cloud genera and their typical altitudes. Image taken from Wikimedia Commons contributors (2018).

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the identification of three distinct area categories. Jechow et al. (2019a) documented cloud attenuation in rural locations: At LakeLab (Germany), the attenuation factors outside the zenith were found to be above 5, while in Bonnievale (South Africa) they reached 11.3, with a minimum luminance of 0.05 mcd/m^2 – one of the darkest values ever measured under cloudy skies (cf. Figure 3.6).

Jechow et al. (2017) demonstrated a dramatic increase in sky brightness under cloudy conditions using transects from Balaguer to Montsec Astronomical Park in Spain. At clear nights, there was a decline in the zenith luminance, which decreased from 1.16 mcd/m^2 at an altitude of 1 km to 0.20 mcd/m^2 at an altitude of 27 km. In conditions of moderate cloud cover, the values measured over the same distance range varied from 3.27 mcd/m^2 to 0.49 mcd/m^2 . It is of particular significance that the measurements conducted under conditions of partial cloud cover, at a distance of 22 km, exhibited a higher luminance in comparison to those obtained under clear skies, at a distance of only 2 km from the city (cf. Figure 3.7).

Jechow et al. (2019a) identified a phenomenon of distance shift: when the sky is clear, distant cities dominate the sky glow, while when the sky is cloudy, local sources dominate. At LakeLab, the sky glow observed on clear nights was attributed to the city of Berlin,

which was located 75 kilometres away. Conversely, on cloudy nights, the sky glow was found to be predominantly influenced by a proximate power plant, situated 2.8 kilometres away. This has ramifications for the evaluation of dark sky locations – locales that satisfy the criteria under clear conditions may nevertheless prove unsatisfactory under cloudy conditions owing to previously unobserved local light sources.

In the study conducted by Ścieżor (2020), it was determined that the cloud base exerts a significant influence on the amplification of light pollution. Low-level clouds (Stratus, Nimbostratus) exhibited the highest levels of brightness (approximately 17.9 mag/arcsec²), while high-level clouds contributed the least (approximately 19.2–19.5 mag/arcsec²). At temperatures below the freezing point, aerosol layers that form under nimbostratus or stratus clouds additionally scatter artificial light, thereby further increasing the brightness.

Multispectral digital single-lens reflex (DSLR) analysis revealed consistent spectral shifts under cloudy conditions. Jechow et al. (2019a) observed a reduced correlated colour temperature (CCT) in Germany and South Africa; this finding suggests a shift in wavelength towards red. This capacity is of significant value when assessing the ongoing transition to LED lighting, where spectral alterations complicate the comparison of brightness.

3.2.4. Snow-Induced Skyglow Amplification

In 2019, Jechow and Hölker (2019) investigated the phenomenon of how snow intensifies artificial sky glow. This phenomenon was referred to as 'snow glow'. Snow has a high albedo in the visible spectrum, which means that a significant proportion of the artificial light emitted downwards is reflected upwards and subsequently scattered back to the ground by clouds and the atmosphere. This process establishes a positive feedback loop that significantly amplifies the brightness of the night sky. The effect was quantified by comparing measurements taken under different conditions.

This was achieved by using all-sky DSLR photometry at a location in a suburb of Berlin. In the absence of precipitation and under clear atmospheric conditions, the zenith luminance was measured at 1.3 mcd/m². In conditions of overcast skies devoid of snowfall, this value increased to 7.3 mcd/m² – indicative of a cloud amplification factor of approximately 5.6. However, with a cloudy sky and fresh snow, the zenith luminance rose to 244 mcd/m². This is equivalent to a snow amplification factor of 33 (where a cloudy sky with snow is compared to a cloudy sky without snow) and a combined snow and cloud amplification of 188 in relation to clear conditions devoid of snow.

These disparities are manifestly evident in Figure 3.8, which presents a 3×3 grid of all-sky images from the suburb. The top row of the figure displays full-colour RGB photographs, the middle row shows luminance maps, and the bottom row shows correlated colour temperature (CCT) maps. Each column of the figure represents a different condition, namely clear without snow, cloudy without snow, and cloudy with snow, respectively. The luminance maps serve to emphasise the snow glow effect, with the image captured under clear skies exhibiting cool blue tones with values ranging from 1 to 4 mcd/m². Conversely, the image captured under conditions with snow and clouds displays an intense orange-red colouration with values several hundred mcd/m² higher. This visual representation serves to illustrate the dramatic amplification effect.

3. Light Pollution Measurement Techniques

The illuminance measurements were equally striking. The horizontal illuminance attained 0.79 lx in conditions of snow and cloud, which is more than double the maximum possible illuminance during a full moon (0.32 lx at zenith). In comparison with measurements at a dark reference site in Latvia (0.07 mcd/m² in cloudy conditions), the total amplification factor was found to be approximately 3500 times higher.

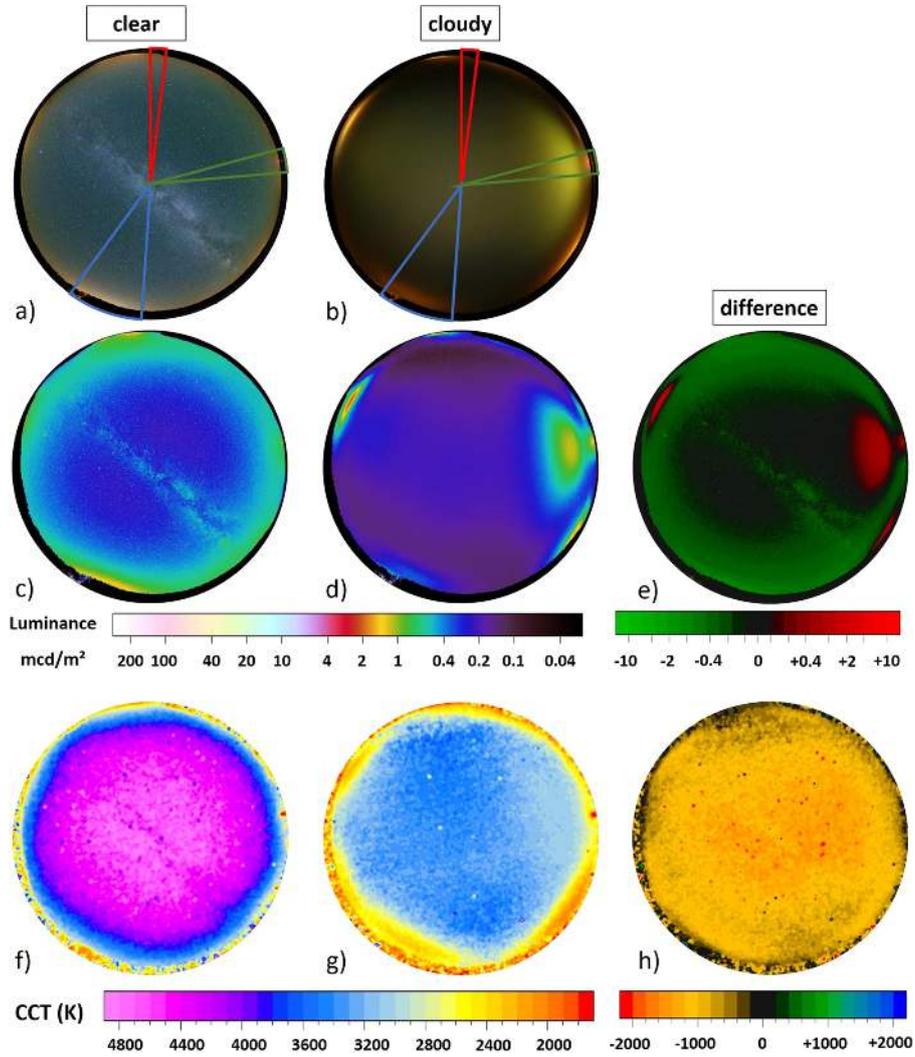


Figure 3.6.: All-sky data from LakeLab, Germany: (a,b) RGB images, (c,d) luminance maps, (f,g) CCT maps for clear and cloudy conditions, with (e,h) difference maps by Jechow et al. (2019a).
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3. Light Pollution Measurement Techniques

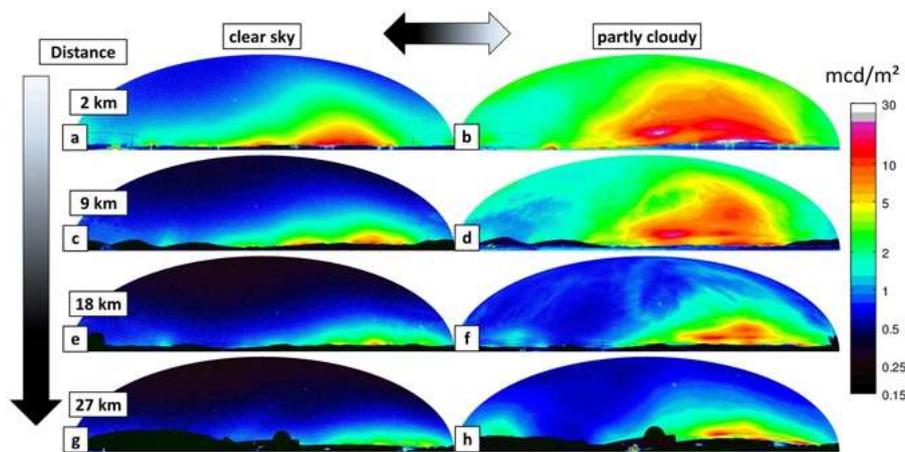


Figure 3.7.: Luminance maps from Balaguer to Montsec. Left: clear sky; right: partly cloudy. Distance increases from 2 km (top) to 27 km (bottom) by Jechow et al. (2017).

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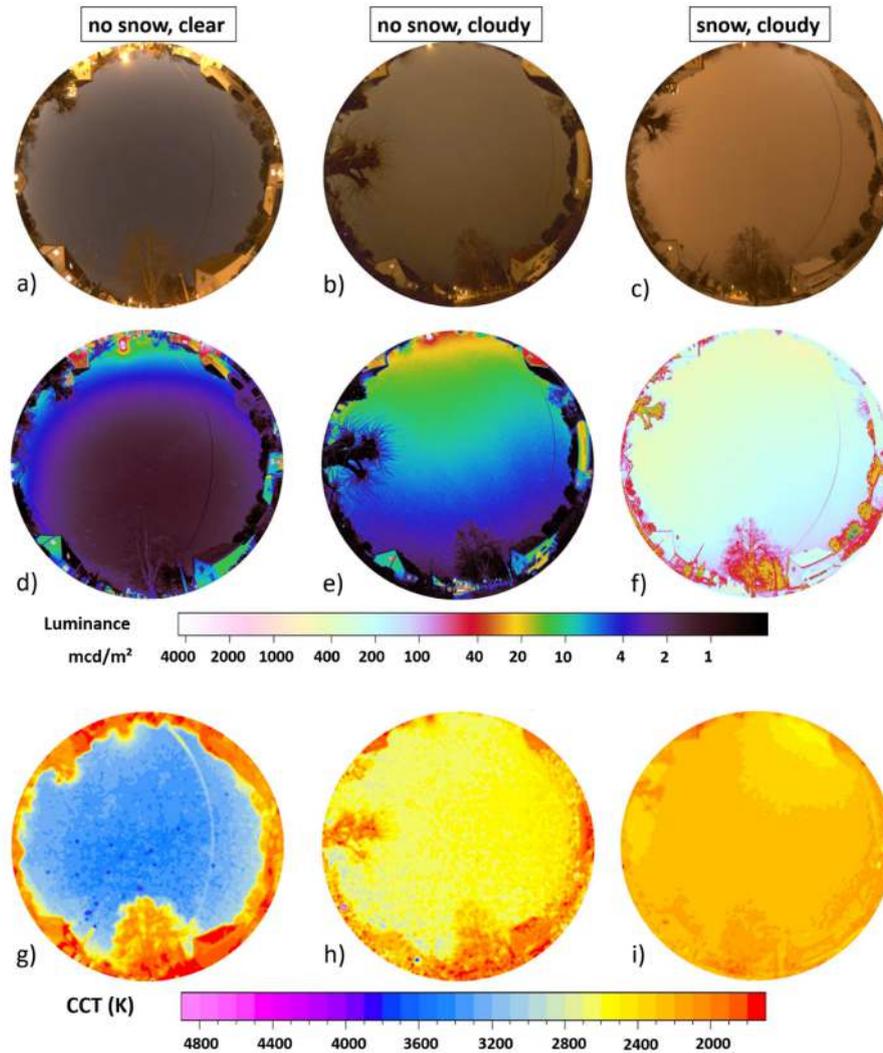


Figure 3.8.: Results of the analysis of collected imaging data, obtained during three nocturnal periods in the suburban area of the German town of Ludwigsfelde, in close proximity to Berlin. As illustrated in panels (a–c), the full-colour RGB is displayed. Panels (d–f) demonstrate the luminance maps, while panels (g–i) illustrate the CCT maps. The left-hand column (a, d, g) displays data collected during a period of clear weather, devoid of snowfall. The central column (b, e, h) presents information gathered during an overcast night, also without snow. The right-hand column (c, f, i) exhibits the results obtained from an overcast night, with freshly fallen snow. Image taken from Jechow and Hölker (2019).

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4. Night Sky Brightness Assessment: Methodology and Study Area

4.1. Roadrunner Measurements

The following measurements were conducted for the Roadrunner measurements:

- measurements with an SQM-LU attached to the car window
- measurements an SQM-L at previously selected locations
- All-Sky Images, made with a DSLR camera with a fisheye lens

Figure 4.1 illustrates the locations that were selected for the measurement process.

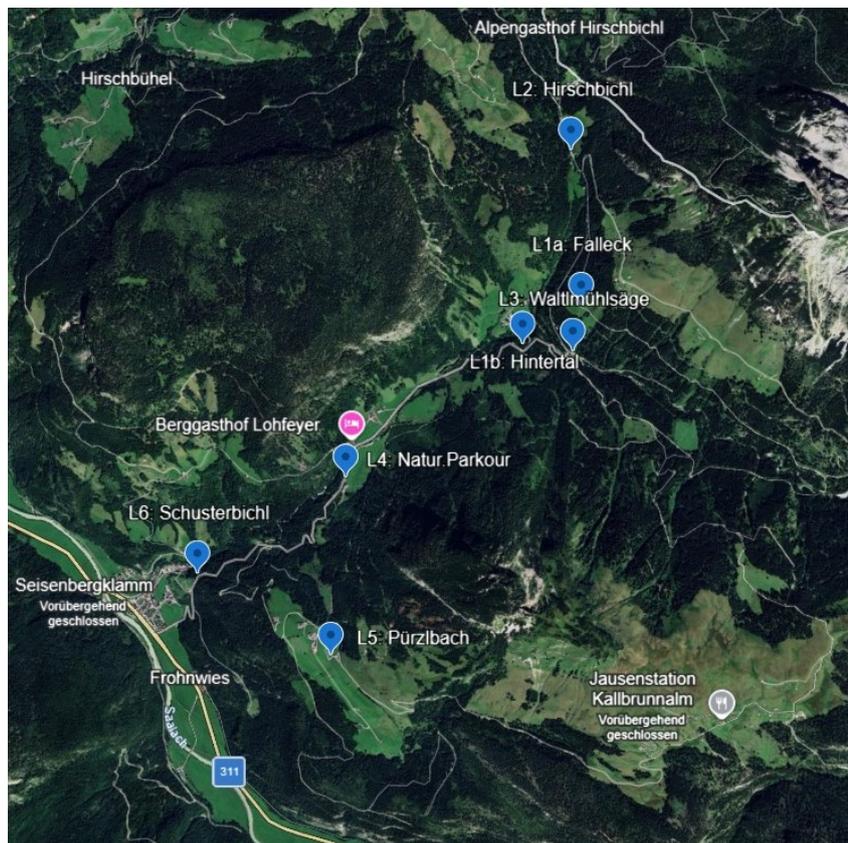


Figure 4.1.: Selected locations in and around the Nature Park Weißbach for the Roadrunner measurements.

4. Night Sky Brightness Assessment: Methodology and Study Area

The locations are:

- **L1a:** Falleck
- **L1b:** Hintertal
- **L2:** Hirschbichl
- **L3:** Waltmühlsäge
- **L4:** Natur.Parkour
- **L5:** Pürzlbach
- **L6:** Schusterbichl

The measurements obtained at the various locations were consistently executed in a uniform manner. Initially, the All-Sky images were captured using a DSLR camera equipped with a fisheye lens. For the All-Sky images, exposure times of 90 and 120 seconds were used. In the analysis of the images, the pictures with an exposure time of 120 seconds were selected, as this is the specified exposure time for SQC. In one instance, the 90 s exposure image was selected due to the presence of clouds and fog, which precluded the possibility of capturing an additional photograph. Subsequently, the SQM-L was used to take measurements. The SQM-L was directed to measure the brightness in all four cardinal directions, thus allowing for the calculation of an average value from multiple measurements.

The Roadrunner measurements were obtained on two separate nights. The initial measurement was conducted on the night of 29. January 2025, with a subsequent measurement taken on the night of 1. May 2025. During the initial night of measurement, locations L1a, L2, L3, L4, L5 and L6 were visited. During the second night of measurement, locations L1b, L4, L5 and L6 were visited. The reason for the discrepancy was that the road to locations L1a, L2 and L3 was closed, and it was not possible to take the alternative route with the car used. Consequently, locations L1a, L2 and L3 were deemed unsuitable and location L1b was selected as a replacement for these three locations. Figure 4.2 and Figure 4.3 demonstrate the routes travelled, based on measurements recorded by the SQM-LU. The SQM-LU was connected to a smartphone, and the values were recorded using SQMDroid. The recording interval was set to 10 seconds.

Figure 4.2 & 4.3 show that the routes are not identical. The initial night of measurement commenced in Weißbach bei Lofer, with the route extending exclusively between this location and the Nature Park Weißbach. Conversely, the subsequent night of measurement was initiated outside Weißbach bei Lofer. The rationale behind this variation was to document values external to and surrounding the nature park, with the objective of ascertaining the extent to which external light penetrates the park. Given the presence of a thoroughfare adjacent to the nature park, it was imperative to ascertain the level of illumination on this road during night.

It is also important to mention that location L6 is the only one where no All-Sky images were taken. The location was positioned on an incline within the confines of the road, a factor that posed challenges in terms of photographic documentation. Furthermore, the presence of power lines from electricity pylons within the camera's field of view necessitated the decision to restrict the measurement process to the SQM-L.



Figure 4.2.: The individual data points of the SQM-LU that were taken during the first Roadrunner measurement.

4.2. TESS

In March 2025, a TESS-W was installed at location L1a to provide a fixed point from which continuous measurements can be taken in the Nature Park Weißbach. Following the initial challenges encountered in the configuration and internet connectivity of the device, it has been consistently providing measurement data since the end of March. The raw data from the TESS-W (designated stars1121) is freely accessible and can be retrieved online².

²https://tess.dashboards.stars4all.eu/d/tess_raw/s4a-photometer-network-raw?orgId=1&from=now-1y&to=now&refresh=1m&var-Tess=stars1121

4. *Night Sky Brightness Assessment: Methodology and Study Area*

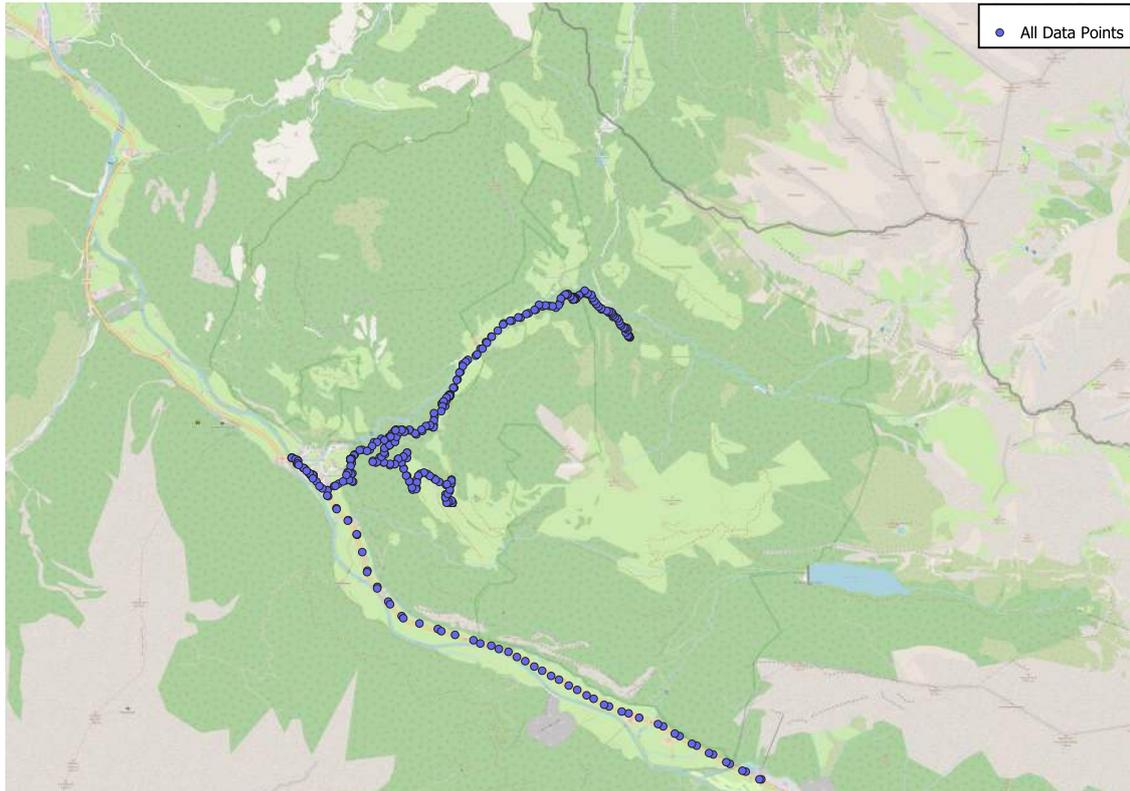


Figure 4.3.: The individual data points of the SQM-LU that were taken during the second Roadrunner measurement.

5. Measurement Results and Analysis

5.1. Ground-Based Night Sky Brightness Measurements and Light Dome Identification

5.1.1. Analysis and Comparison of SQM and TESS-W Data

SQM Data Analysis

As illustrated in Figure 5.1, all measurements recorded with the SQM-LU during the initial night of measurement on 29. January 2025 are presented. The measurements were divided into four categories:

- Magnitudes $< 20.00 \text{ mag/arcsec}^2$
- Magnitudes between 20.00 and $21.19 \text{ mag/arcsec}^2$
- Magnitudes between 21.20 and $22.00 \text{ mag/arcsec}^2$
- Magnitudes $\geq 22.00 \text{ mag/arcsec}^2$

The values for each category are presented in separate maps, as illustrated in Figures A.1, A.2, A.3 & A.4. The categorisation of subjects was undertaken with specific objectives in mind. The most significant category is that of measurements ranging from 21.20 to $22.00 \text{ mag/arcsec}^2$, as values exceeding $21.20 \text{ mag/arcsec}^2$ are mandatory for the attainment of International Dark Sky Park certification. Values in excess of $22.00 \text{ mag/arcsec}^2$ may be attributable to a cloudy sky, the SQM-LU lens being marginally obscured, or measurements being conducted beneath a structure. It is evident that such dark values are not realistic under normal circumstances, as a perfect night sky has a brightness of $22.00 \text{ mag/arcsec}^2$. The range of $20.00 - 21.19 \text{ mag/arcsec}^2$ is intended to demonstrate that the area is well on its way to achieving $21.20 \text{ mag/arcsec}^2$. The range of $20.00 \text{ mag/arcsec}^2$ and below is intended to highlight the necessity for further work in order to meet the minimum requirement for night sky brightness.

Table 5.1 presents a comprehensive overview of all the recorded measurements. All measurements are taken and subsequently divided into values:

- $\geq 18.00 \text{ mag/arcsec}^2$
- $\geq 19.00 \text{ mag/arcsec}^2$
- $\geq 20.00 \text{ mag/arcsec}^2$
- $\geq 21.00 \text{ mag/arcsec}^2$

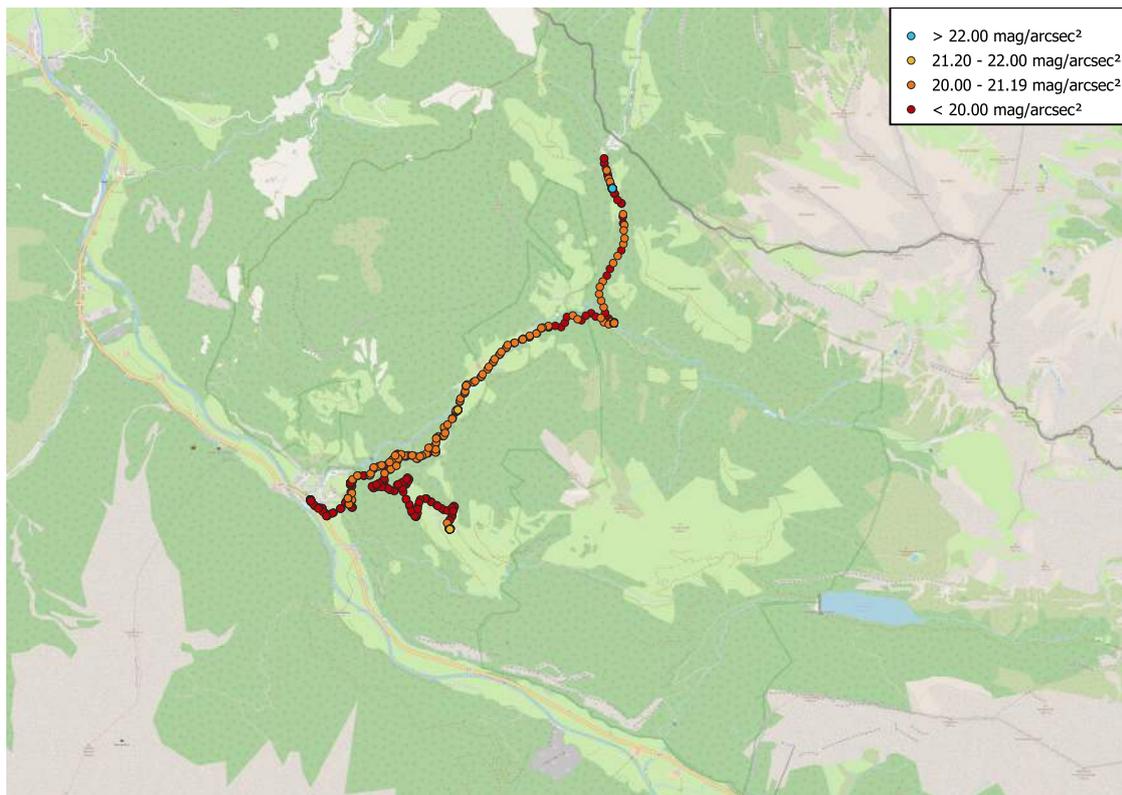


Figure 5.1.: Data points from the first Roadrunner Measurement from 29.01.2025.

Night Sky Brightness [mag/arcsec ²]					
	All	≥ 18.00	≥ 19.00	≥ 20.00	≥ 21.00
n	623	593	560	418	229
Percentage	100%	95.18%	89.89%	67.09%	36.76%

Table 5.1.: Percentage comparison of the total number of measurements recorded with the SQM-LU during the first night of measurement with given threshold values.

Furthermore, the percentage share of these values is also displayed, based on the total measurements.

As displayed in Table 5.2, the individual measurements are presented alongside the SQM-L values at the respective locations, along with the average value that has been derived from the measurements.

Table 5.3 provides a comparative analysis between the mean values of SQM-L and SQM-LU measurements and the measured values that can be obtained through SQC when conducting an area analysis of the night sky. The diameter of 20° at the zenith was selected for this purpose, corresponding approximately to the width of the SQM-L and SQM-LU. The mean value of the SQM-LU measurements was calculated from the data recorded during the observation of the all-sky images and the SQM-L measurements at the same

5.1. Ground-Based Night Sky Brightness Measurements and Light Dome Identification

Night Sky Brightness [mag/arcsec ²]						
Location	L1a	L2	L3	L4	L5	L6
M1	20.99	20.60	20.93	21.09	21.13	19.71
M2	21.07	20.66	20.95	21.09	21.00	19.47
M3	20.97	20.68	20.98	21.00	20.19	19.49
M4	20.90	20.71	20.84	21.02	21.01	20.02
Average	20.98	20.66	20.93	21.05	20.83	19.67

Table 5.2.: Individual data and average values of the SQM-L measurements at the various locations during the first night of measurement.

location. For the final location, L6, no measurement value from SQC is available, as no all-sky image was taken at that location. Consequently, only the values from SQM-L and SQM-LU can be used.

Night Sky Brightness [mag/arcsec ²]						
Location	L1a	L2	L3	L4	L5	L6
SQM-L	20.98	20.66	20.93	21.05	20.83	19.67
SQM-LU	19.97	22.36	20.77	21.12	21.09	19.40
SQC	20.92	20.61	20.93	21.01	21.06	/

Table 5.3.: Comparison of the results of the first Roadrunners measurement using different measuring instruments.

As displayed in Figure 5.2, all measurements recorded with the SQM-LU during the second night of measurement on 1. May 2025 are shown. The measurements were divided into three categories:

- Magnitudes < than 20.00 mag/arcsec²
- Magnitudes between 20.00 and 21.19 mag/arcsec²
- Magnitudes between 21.20 and 22.00 mag/arcsec²

The individual values of the three categories are shown on separate maps in Figures A.5, A.6 & A.7. As no values exceeded 22.00 mag/arcsec², a total of three categories is used for the classification of values.

As shown in Table 5.4, all recorded measured values have been classified according to the criteria outlined in Table 5.1. In this instance as well, the percentage share of values is displayed in relation to the sum of measured values.

The data presented in Table 5.5 showcases the individual measurements obtained using the SQM-L at the designated locations, along with the calculated average value derived from these measurements.

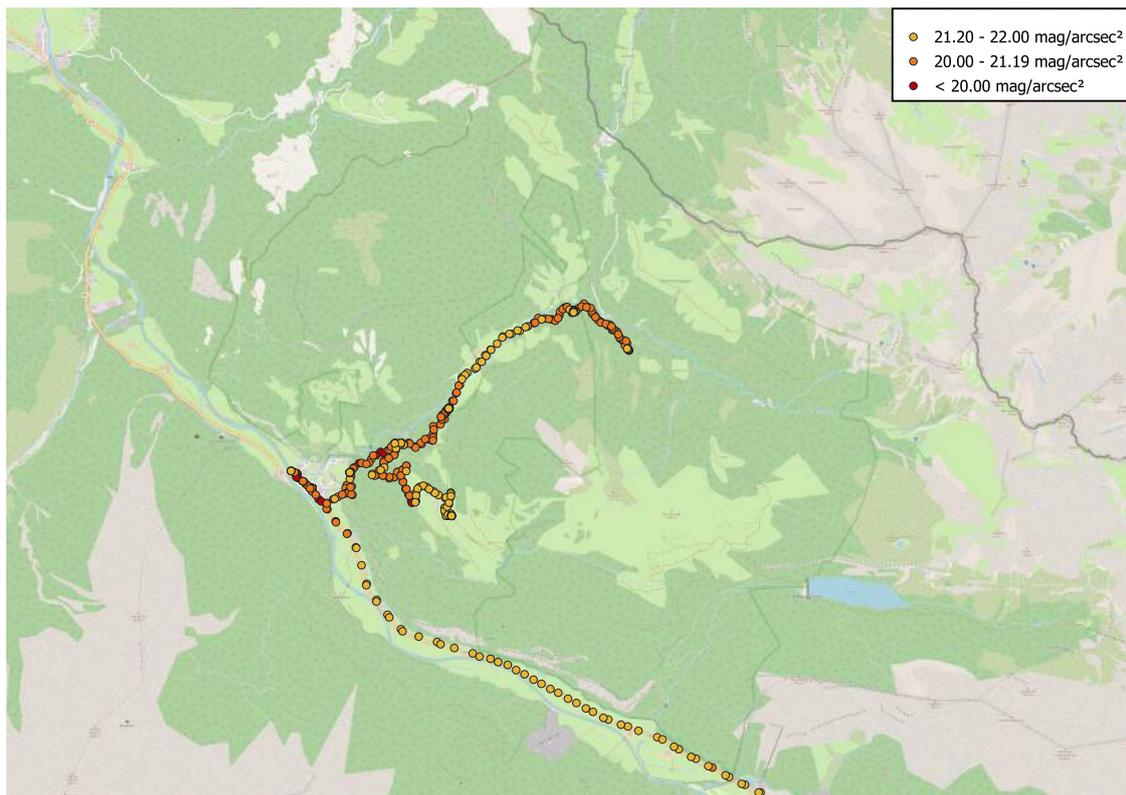


Figure 5.2.: Data points from the second Roadrunner Measurement from 01.05.2025.

Night Sky Brightness [mag/arcsec ²]					
	All	≥18.00	≥19.00	≥20.00	≥21.00
n	614	611	607	577	408
Percentage	100%	99.51%	98.86%	93.97%	66.94%

Table 5.4.: Percentage comparison of the total number of measurements recorded with the SQM-LU during the second night of measurement with given threshold values.

Table 5.6 presents a comparison between the mean values of the SQM-L and SQM-LU measurements and the SQC value, derived from a diameter of 20° at the zenith. Again, there are no SQC measurements available for the last location, L6.

Table 5.1 and Table 5.4 reveal that the number of measured values above 21.00 mag/arcsec² varies considerably. While only 36.76% of all measurements on the night of 29. January 2025 reached a value of 21.00 mag/arcsec² and higher, the number of values on the night of 1. March 2025 was already 66.94%. The reasons for this significant difference can be attributed to two factors. Firstly, the presence of snow at the time of the initial measurement campaign, which resulted in significant reflection of light from the used car and other light sources. Secondly, the presence of cloud and fog during certain periods, which led to the amplification of light from all light sources and consequently contributed to a higher night sky brightness. Despite intermittent cloud cover during the second measurement campaign,

Night Sky Brightness [mag/arcsec ²]				
Location	L1b	L4	L5	L6
M1	21.50	21.49	21.68	21.39
M2	21.40	21.41	21.43	21.36
M3	21.41	21.43	21.41	21.34
M4	21.40	21.40	21.39	21.36
Average	21.43	21.43	21.48	21.36

Table 5.5.: Individual data and average values of the SQM-L measurements at the various locations during the second night of measurement.

Night Sky Brightness [mag/arcsec ²]				
Location	L1b	L4	L5	L6
SQM-L	21.43	21.43	21.48	21.36
SQM-LU	21.39	21.51	21.59	21.46
SQC	21.35	21.49	21.56	/

Table 5.6.: Comparison of the results of the second Roadrunners measurement using different measuring instruments.

the degree of cloud cover was lower than that observed during the first night of measurement.

The measurements obtained with the SQM-L on the initial night demonstrate minor outliers at locations L5 and L6, as illustrated in Table 5.2. This also results in a change to the average value.

A comparison of the average values obtained from the various measuring instruments reveals the presence of discrepancies and outliers, as demonstrated in Table 5.3. A discrepancy of one magnitude is evident between the SQM-LU data and the other values at location L1a. At location L2, the discrepancy is more than 1.5 magnitudes.

The difference observed at location L1a may be attributable to the presence of a house with interior lighting next to the parked car. Consequently, this light could have been measured by the SQM-LU. Conversely, the presence of a lamp equipped with a motion sensor, which was operational for a brief period, could have exerted a substantial influence on the average value.

The discrepancy of more than 1.5 magnitudes at location L2 may be attributable to the proximity of the vehicle to the surrounding trees, which may have obscured the field of view of the SQM-LU. Another possibility is that clouds had gathered at the time, and, as it was otherwise relatively dark where the car was parked, the clouds may have served as additional cover, thereby distorting the measurements.

The Roadrunner measurement values from the second night of measurements demonstrate that the night sky brightness in and around the Weißbach Nature Park can achieve the required 21.20 mag/arcsec² for International Dark Sky Park certification.

TESS-W Data Analysis

The brightness of the night sky was determined with the TESS-W, using measurements from April 2025 to October 2025. The seven-month time window was deemed adequate, with the Roadrunner measurements conducted during the winter and spring seasons, and the TESS-W measurements encompassing spring, summer, and autumn, thereby ensuring the availability of measurements for all seasons.

The raw data from the TESS-W (stars1121) was retrieved from the Grafana website, subsequently organised and examined.

The raw data underwent a three-stage filtration process:

1. **Astronomical night:** Only measurements taken when the sun is below -18° below the horizon are used.
2. **New moon phases:** Only data from the new moon phases of the respective month is used. This includes the entire last night of each phase, i.e. also the morning hours of the following day.
3. **Quality filter:** Measurements with values below 18 mag/arcsec^2 are excluded, as such values indicate disruptive factors (residual twilight, sensor problems, etc.).

This is followed by one of the biggest problems in filtering the data: filtering for a clear and a cloudy sky in the field of view of TESS-W. The determination of a threshold value can be achieved through the calculation of the temperature difference, ΔT , between the ambient temperature, T_{amb} , and the infrared temperature of the sky, T_{sky} . It is evident that, in the absence of a uniform value, there is a discrepancy from one location to another. However, in order to ascertain such a threshold value, the antimode method was employed, as previously described by Massetti et al. (2023).

To this end, the temperature difference, designated as ΔT , is calculated as the difference between the ambient temperature, T_{amb} , and the temperature in the sky, T_{sky} , for each measurement. In clear skies, T_{sky} is observed to be markedly cold (with the IR radiation emanating from the frigid upper atmosphere). Conversely, under cloudy conditions, T_{sky} approaches T_{amb} (due to the radiative effect of the clouds at their respective ambient temperatures). This results in two 'clusters' in the distribution of T, one for cloudy conditions and one for clear conditions. Subsequently, all ΔT values are divided into a histogram comprising 200 bins and displayed as a probability density. The histogram is then smoothed with a Gaussian filter ($\sigma=3$) in order to remove noise and make the two main peaks visible. The objective is to identify all local maxima (peaks) in the smoothed histogram. The two highest peaks are interpreted as the two populations. The minimum of the smoothed curve is then located between these two peaks. This minimum is known as the 'antimode', the point at which the probability density is lowest, i.e. where there are the fewest measurements. This delineation represents the natural boundary between the two populations. Finally, the robustness of the model is assessed by repeating the analysis with different smoothing parameters ($\sigma = 2, 3, 4, 5, 6$). In the event of the antimode maintaining stability, the resultant configuration is robust.

This is followed by a monthly allocation. Each measurement is allocated to the phase of the new moon in which it occurs. Measurements obtained after midnight (e.g. 1. May 01:30 UTC) are attributed to the evening month (April), as they are part of the same night.

5.1. Ground-Based Night Sky Brightness Measurements and Light Dome Identification

Subsequently, for each of the new moon phases, the number of measurements (n), the mean values of the NSB, the standard deviation and the median are calculated for all data and for clear nights. Thereafter, the mean value for all data values and for those of the clear nights across all phases is calculated.

The final step in the process is a review of the number of measurements recorded across a range of NSB thresholds. The following values are presented:

- $\geq 18.00 \text{ mag/arcsec}^2$
- $\geq 19.00 \text{ mag/arcsec}^2$
- $\geq 20.00 \text{ mag/arcsec}^2$
- $\geq 21.00 \text{ mag/arcsec}^2$

The 'Antimode' method determined a threshold value of $\Delta T = 13^\circ\text{C}$. Consequently, all values that exceed or equal this threshold value are designated as measurement data with clear skies, while all other values below this threshold value are designated as measurement data with cloudy skies.

As illustrated in Table 5.7, the number of measurements recorded during each new moon phase is presented, categorised both as a whole and exclusively for those conducted under clear skies. These values are demonstrated graphically in Figure 5.3. It is evident that in less than half of all measurements, the zenith sky was not cloudy.

However, as illustrated in Table 5.8, the analysis reveals that slightly more than 70% of the recorded values exceed 21 mag/arcsec^2 . This finding is further substantiated by Figure 5.3. Figure 5.4 furthermore illustrates the distribution of the number of measured values for cloudy and clear skies, presented in two separate histograms for the purpose of comparison.

TESS-W Data; Night Sky Brightness values in [mag/arcsec²]			
New Moon Phase	Data Range	n (all)	n (clear)
April	20.04.2025 - 30.04.2025	2,783	1,596
May	20.05.2025 - 30.05.2025	1,702	273
June	18.06.2025 - 28.06.2025	1,100	800
July	17.07.2025 - 27.07.2025	2,006	523
August	16.08.2025 - 26.08.2025	3,281	1,318
September	14.09.2025 - 24.09.2025	4,483	1,820
October	14.10.2025 - 24.10.2025	5,719	3,034
Total	April - October	21,074	9,364

Table 5.7.: All TESS-W data (cloudy and clear sky) during new moon phases with average NSB values.

A more detailed examination of the values above $21.00 \text{ mag/arcsec}^2$, particularly those exceeding the required $21.20 \text{ mag/arcsec}^2$, reveals that approximately 39% of all values still meet this minimum standard for Dark Sky certification, as indicated by the aggregate

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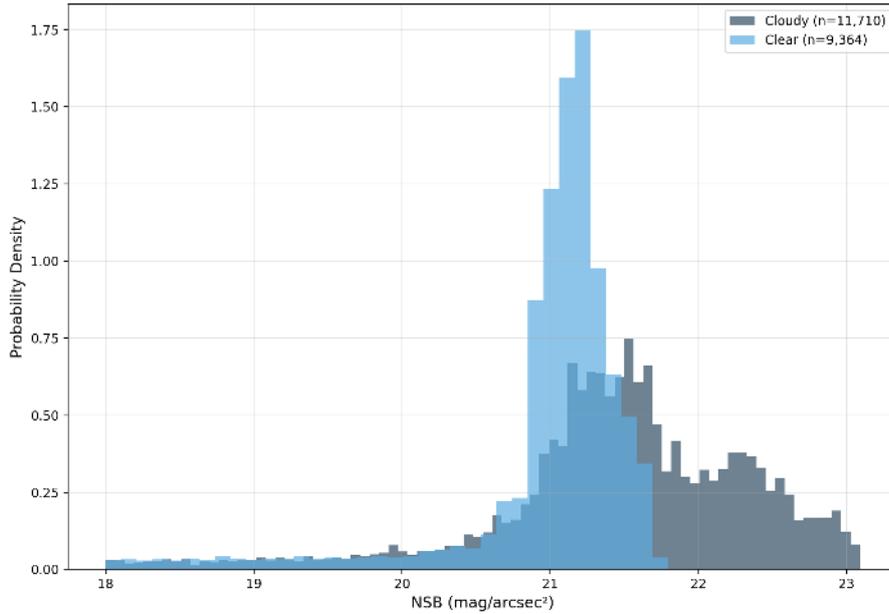


Figure 5.3.: NSB Distribution between cloudy and clear sky data.

TESS-W Data Thresholds				
Threshold	n (all)	Percentage	n (clear)	Percentage
≥ 18.00 mag/arcsec ²	21,074	100.00%	9,364	100.00%
≥ 19.00 mag/arcsec ²	20,456	97.07%	9,060	96.75%
≥ 20.00 mag/arcsec ²	19,631	93.15%	8,708	92.99%
≥ 21.00 mag/arcsec ²	15,959	75.73%	6,592	70.40%

Table 5.8.: Percentage comparison of the total number of measurements recorded with the TESS-W during the new moon phases with given threshold values.

measurements for clear nights (see Table 5.9). A comparison of values ≥ 21.00 mag/arcsec² with those ≥ 21.20 mag/arcsec² reveals that a greater proportion of the latter category exceeds the required limit. Additionally, the values ranging from 21.00 to 21.50 mag/arcsec² and from 21.20 to 22.00 mag/arcsec² can be observed in Table 5.9. The initial range of values is designed to demonstrate the number of values that fall within the required NSB value range, while the subsequent range is intended to illustrate the number of values that are in alignment with the SQM measurements. Figure 5.5 also provides a graphical representation of the number of measurements in the range 21.00 – 21.50 mag/arcsec² as a histogram.

As illustrated in Table 5.10, the exact number and percentage comparison to all measured values on clear nights for values above 21.00 mag/arcsec² in increments of 0.09 mag/arcsec² is also demonstrated. It is important to note that the values only extend up to 21.79 mag/arcsec², as only two values above 22.00 mag/arcsec² were measured during clear nights. These values are further elaborated in Figure 5.6, which provides a graphical

5.1. Ground-Based Night Sky Brightness Measurements and Light Dome Identification

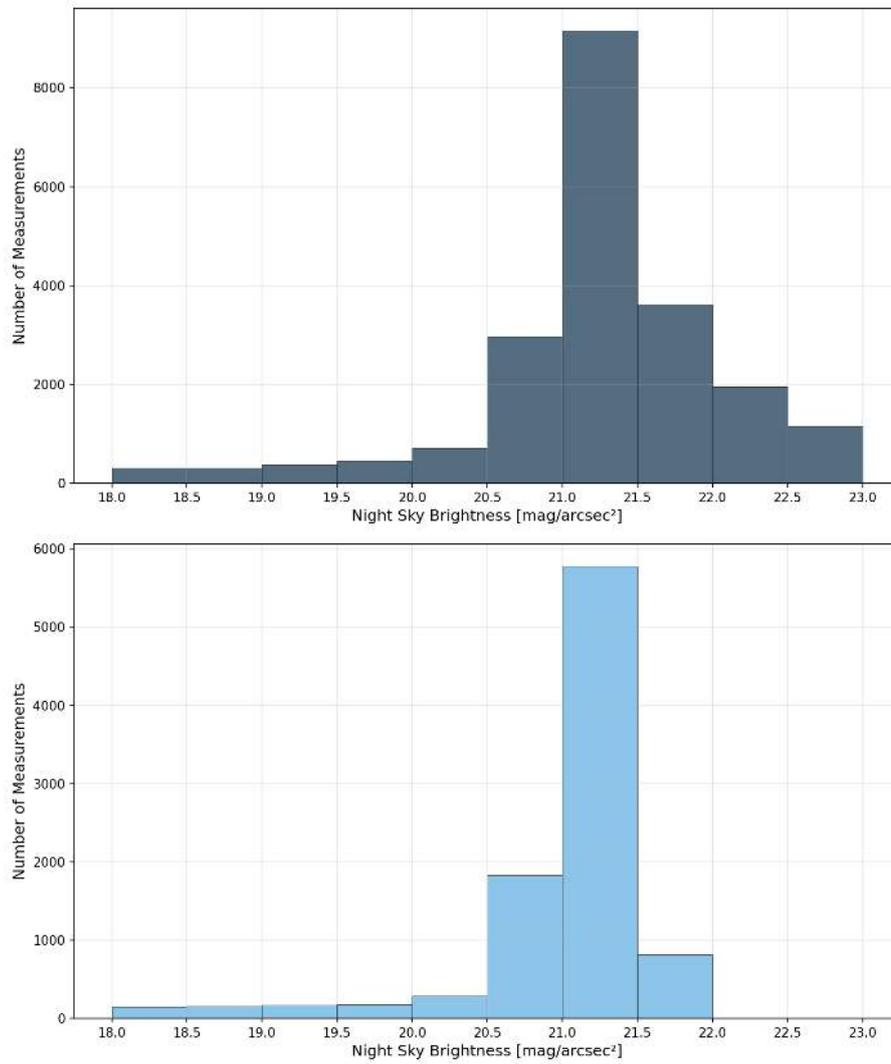


Figure 5.4.: Comparison of NSB distribution between TESS-W data of cloudy nights and clear nights.

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TESS-W Data Thresholds and Ranges ≥ 21.00 mag/arcsec ²		
Threshold / Range	n (clear)	Percentage
≥ 21.00 mag/arcsec ²	6,592	70.40%
≥ 21.20 mag/arcsec ²	3,659	39.08%
21.00 - 21.50 mag/arcsec ²	5,809	62.04%
21.20 - 22.00 mag/arcsec ²	3,657	39.05%

Table 5.9.: Percentage comparison of measurements for clear sky ≥ 21.00 mag/arcsec² and ≥ 21.20 mag/arcsec² with two different ranges, recorded with the TESS-W.

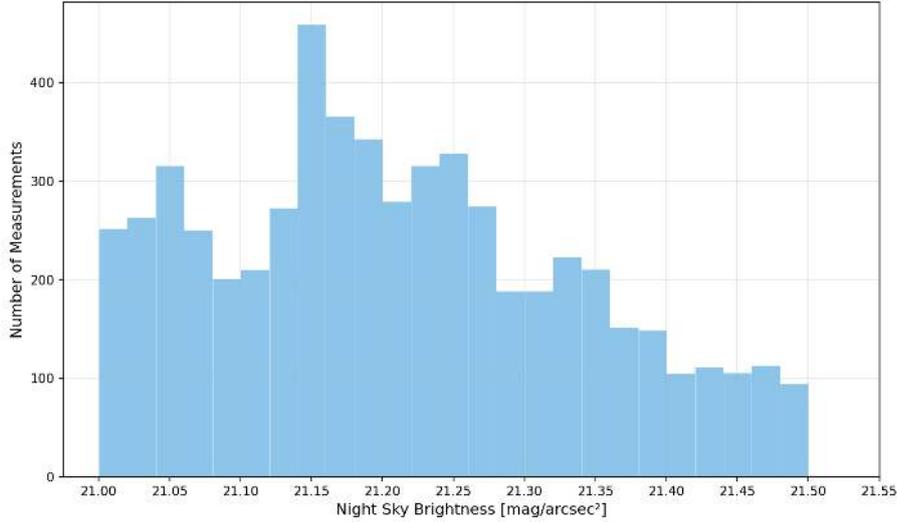


Figure 5.5.: NSB Distribution of clear sky data between 21.00 and 21.50 mag/arcsec².

representation in the form of a histogram.

At this stage, it is crucial to acknowledge that the TESS-W displays magnitude values between 0.1 and 0.3 magnitudes brighter than an SQM, as demonstrated in Costa Ferrer (2022). Consequently, if the TESS-W measurements were to be obtained using an SQM, the values would be darker and a greater proportion of the recorded values would reach, or even exceed, the limit value of 21.20 mag/arcsec² for Dark Sky certification.

In summary, the data obtained from TESS-W, in which 70% of the values exceed 21.00 mag/arcsec² and 39.08% reach the limit value of 21.20 mag/arcsec², supports the statement that the Nature Park Weißbach can be certified for International Dark Sky Park certification. This is also in view of the fact that more measured values are above the limit value, but are displayed by TESS-W as 0.1 – 0.3 mag/arcsec² brighter than they actually are.

TESS-W Data for Values ≥ 21.00 mag/arcsec ² with different Ranges		
Range	n (clear)	Percentage
21.00 - 21.09 mag/arcsec ²	1,282	13.69%
21.10 - 21.19 mag/arcsec ²	1,651	17.63%
21.20 - 21.29 mag/arcsec ²	1,388	14.82%
21.30 - 21.39 mag/arcsec ²	924	9.87%
21.40 - 21.49 mag/arcsec ²	530	5.66%
21.50 - 21.59 mag/arcsec ²	478	5.10%
21.60 - 21.69 mag/arcsec ²	299	3.19%
21.70 - 21.79 mag/arcsec ²	38	0.41%

Table 5.10.: Percentage comparison of measurements for clear sky over ≥ 21.00 mag/arcsec² in different ranges, recorded with the TESS-W.

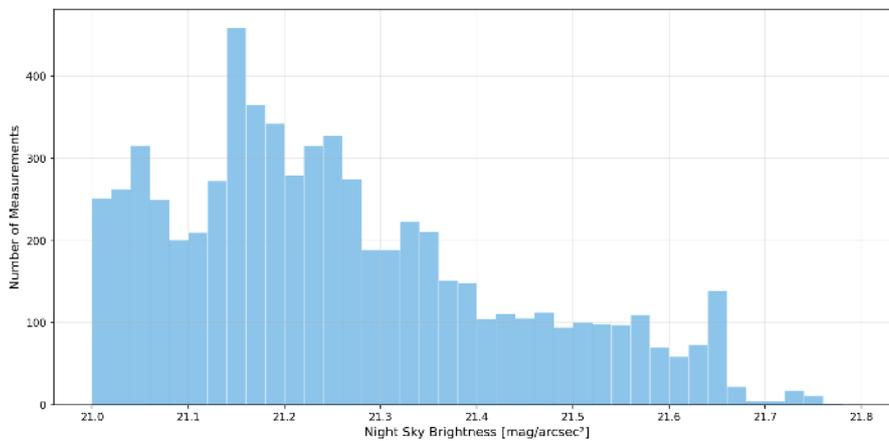


Figure 5.6.: NSB Distribution of clear sky data between 21.00 and 21.79 mag/arcsec².

5.1.2. Light Dome Identification with SQC

The All-sky images captured from the multiple locations were analysed through the usage of SQC software. The analysed All-sky images can be seen in the following Figures: 5.7, 5.8, 5.10, 5.12, 5.14, 5.15, 5.16 & 5.17

Given the presence of clouds during both measurements and their visibility in some of the images, it was necessary to enter the software with the sky condition as either clear or cloudy. In the event of a cloudy sky, the clouds must be marked accordingly.

The SQC evaluation and the Light Pollution Map were then used to identify any light domes from cities in the images.

After analysing the images from the first night of measurements(cf. Figures 5.7, 5.8, 5.10, 5.12& 5.14), the following light domes were identified at the following locations:

- **L2 – Hirschbichl:** Salzburg, Saalfelden, Zell am See & Saalbach (cf. Figures 5.8 & 5.9)
- **L3 – Waltlmühlsäge:** Bischofhofen, Sankt Johann im Pongau, Schwarzach im Pongau & Dorfgastein (cf. Figures 5.10 & 5.11)

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- **L4 – Natur.Parkour:** Hallein, Kuchl & Golling an der Salzach (cf. Figures 5.12 & 5.13)

Upon analysis of the images from the second night of measurements (cf. Figures 5.15, 5.16 & 5.17), light domes were identified in a single location:

- **L5 – Pürzlbach:** Lofer & Sankt Martin bei Lofer (cf. 5.17 & 5.18)

When comparing the SQC images with the Light Pollution Map, it is important to note that the cardinal directions 'West' and 'East' are reversed in the SQC images. Therefore, at first glance, it appears as if the light domes in the SQC images are coming from a different direction than in the Light Pollution Map.

The motivation for the collection and analysis of all-sky images with the SQC was rooted in two fundamental reasons. Firstly, the area analysis in SQC was utilised to measure the brightness of the night sky at the zenith, employing the same field of view as the SQM-L and SQM-LU, with the objective of comparing the measuring instruments. Secondly, SQC was used to identify possible light domes.

The latter proved to be more challenging due to the presence of clouds, as well as the fact that several locations were in close proximity to each other, making it difficult to ascertain which light dome from each location was the dominant one in the sky. Consequently, several cities or towns were identified as potential light sources in the images, despite the uncertainty regarding the origin of the light on the horizon.

A visual analysis of the location L4 – Nature.Parkour in Figure 5.12 and the corresponding radiance map of the light pollution map in Figure 5.13 reveals the presence of additional light domes in front of the light dome in Hallein (the light source at the top right). These were deliberately excluded from consideration, as will be explained in more detail below in the analysis of the SkyGlow simulations.

In this instance, the images and analysis demonstrate a congruent narrative with the SQM data. During the initial night of observation, characterised by a prevalence of clouds, fog and snow, the night sky brightness values exhibited higher levels of luminosity in comparison to those recorded during the subsequent night, which was characterised by an absence of snow and fog. This demonstrates the extent to which the measurements of night sky brightness are influenced by seasonal and meteorological factors, and the significant fluctuations in measured values that can result.

However, the data indicates that the Weißbach Nature Park is capable of attaining the requisite limit of 21.20 mag/arcsec² to be designated as an International Dark Sky Park.

5.1. Ground-Based Night Sky Brightness Measurements and Light Dome Identification

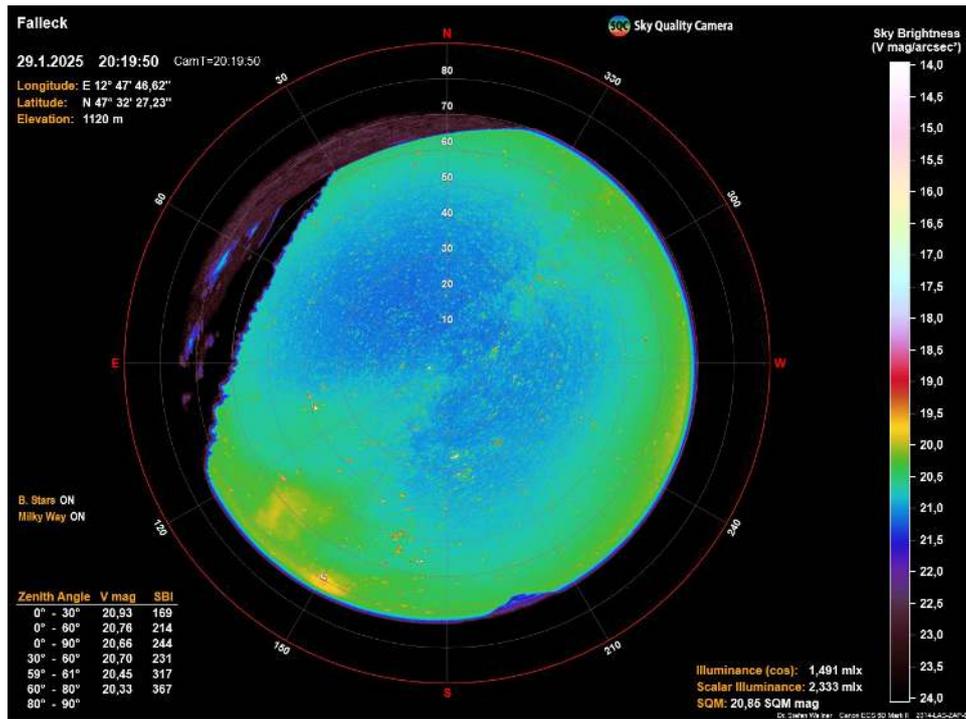


Figure 5.7.: All-Sky Image of the Location L1a: Falleck analysed with SQC. The Image was taken during the first Roadrunner Measurement in the night of 29. January 2025.

5. Measurement Results and Analysis

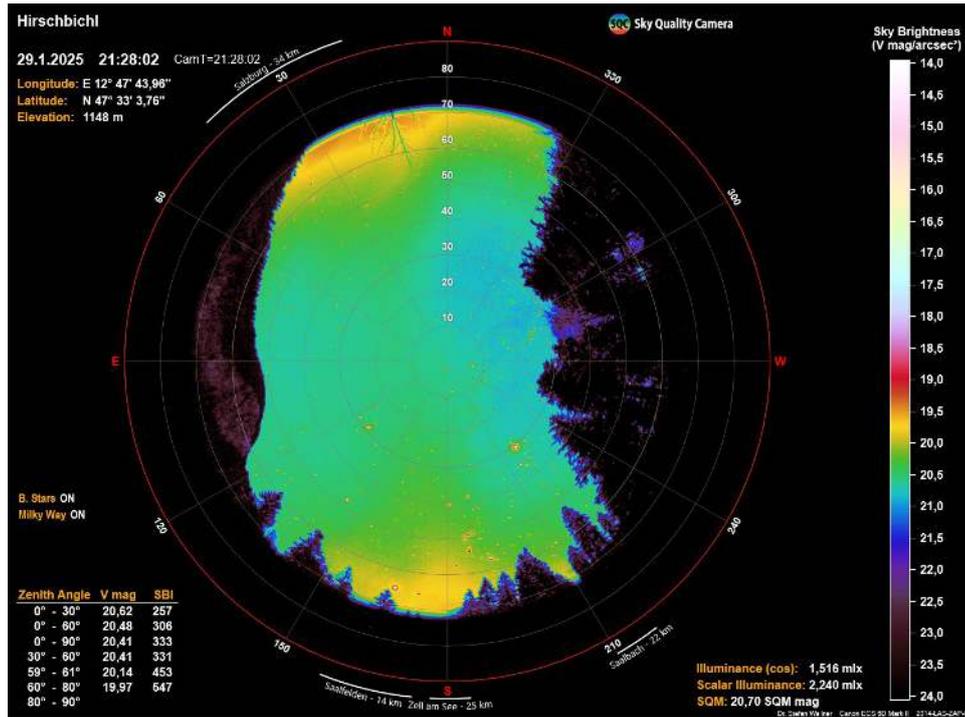


Figure 5.8.: All-Sky Image of the Location L2: Hirschbichl analysed with SQC. Lightdomes from possible light sources are shown: Salzburg, Saalfelden, Zell am See & Saalbach. The Image was taken during the first Roadrunner Measurement in the night of 29. January 2025.

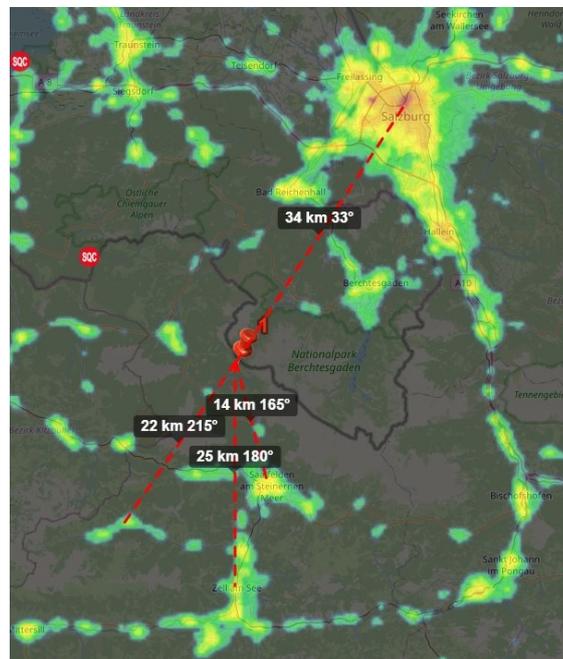


Figure 5.9.: Radiance Map showing the directions and distances of the possible lightdome sources from Figure 5.8.

5.1. Ground-Based Night Sky Brightness Measurements and Light Dome Identification

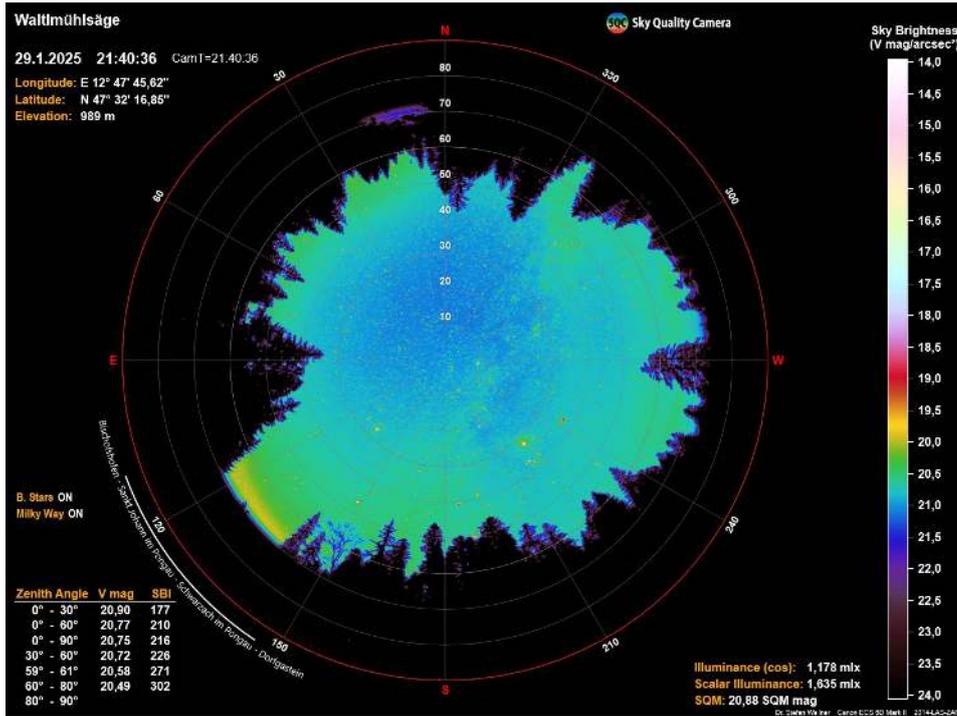


Figure 5.10.: All-Sky Image of the Location L3: Wlatlmühlsäge analysed with SQC. Lightdome from possible light sources are shown: Bischofshofen, Sankt Johann im Pongau, Schwarzach im Pongau & Dorfgastein. The Image was taken during the first Roadrunner Measurement in the night of 29. January 2025.

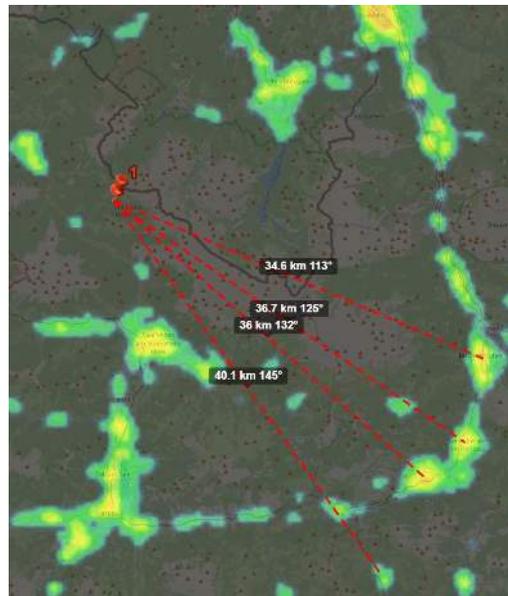


Figure 5.11.: Radiance Map showing the directions and distances of the possible lightdome sources from Figure 5.10.

5. Measurement Results and Analysis

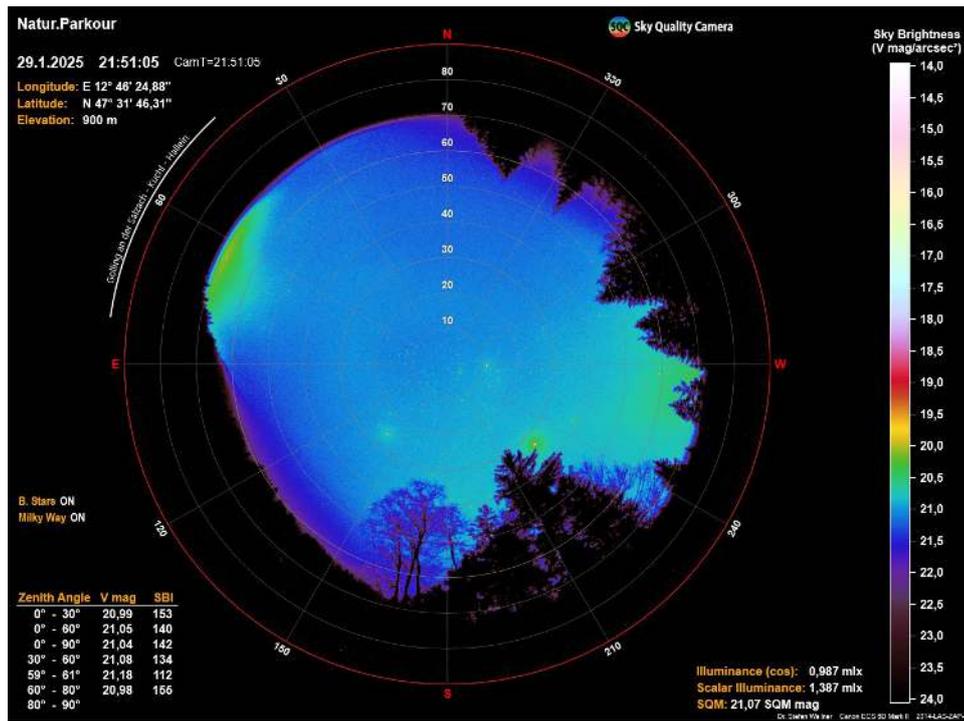


Figure 5.12.: All-Sky Image of the Location L4: Natur.Parkour analysed with SQC. Lightdomes from possible light sources are shown: Hallein, Kuchl & Golling an der Salzach. The Image was taken during the first Roadrunner Measurement in the night of 29. January 2025.

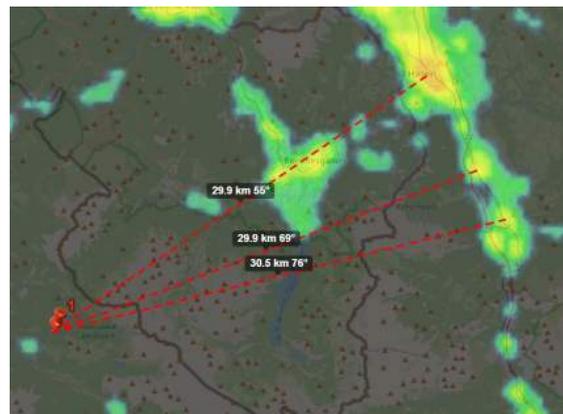


Figure 5.13.: Radiance Map showing the directions and distances of the possible lightdome sources from Figure 5.12.

5.1. Ground-Based Night Sky Brightness Measurements and Light Dome Identification

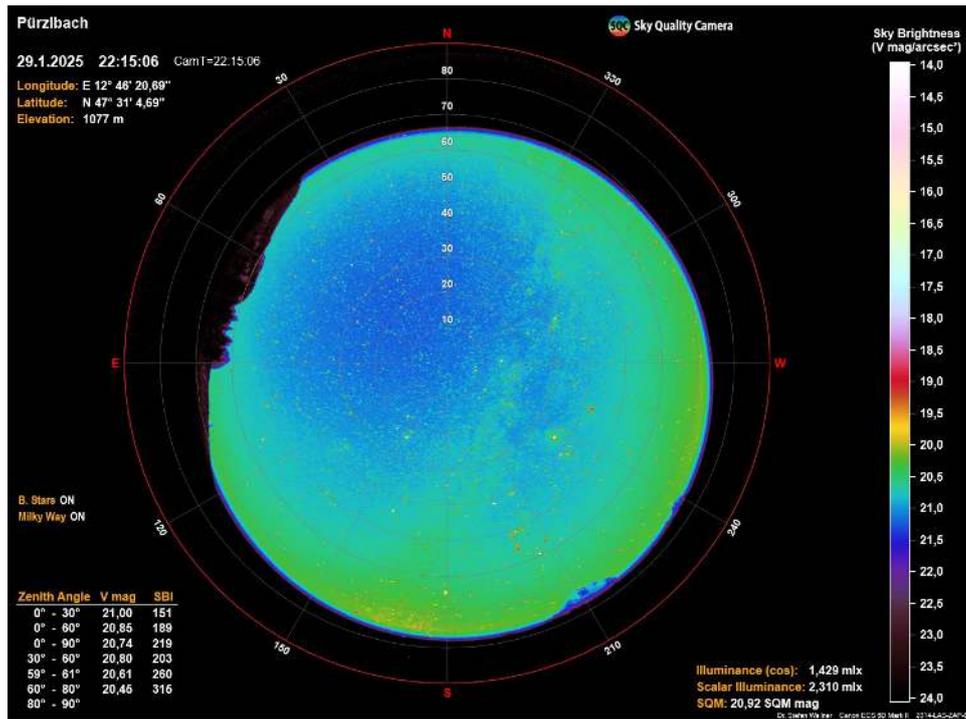


Figure 5.14.: All-Sky Image of the Location L5: Pürzlbach analysed with SQC. The Image was taken during the first Roadrunner Measurement in the night of 29. January 2025.

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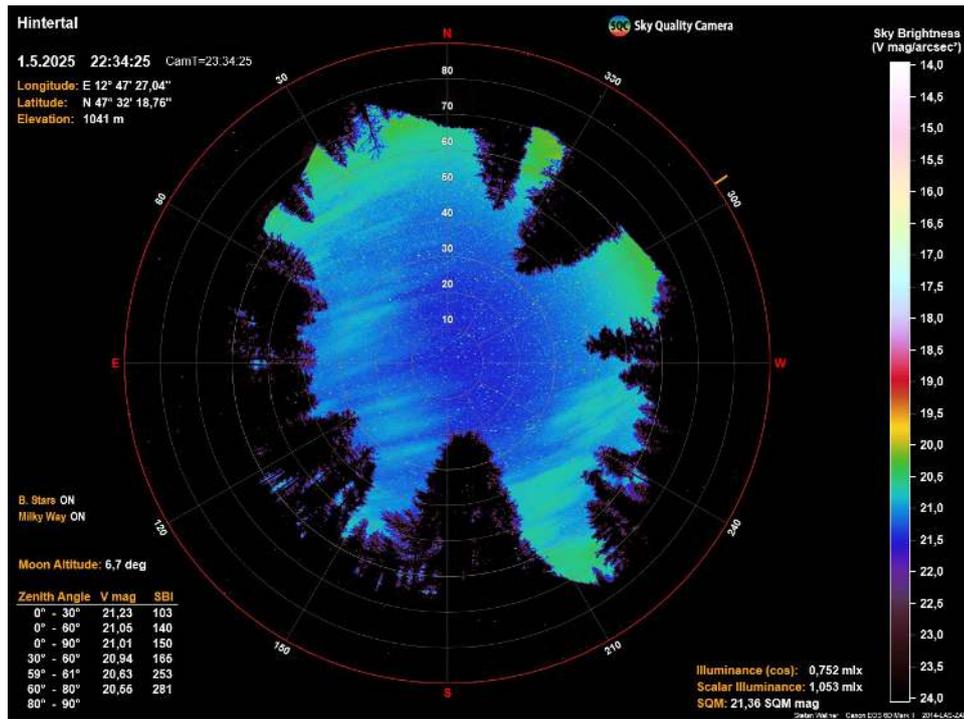


Figure 5.15.: All-Sky Image of the Location L1b: Hintertal analysed with SQC. The Image was taken during the second Roadrunner Measurement in the night of 1. May 2025.

5.1. Ground-Based Night Sky Brightness Measurements and Light Dome Identification

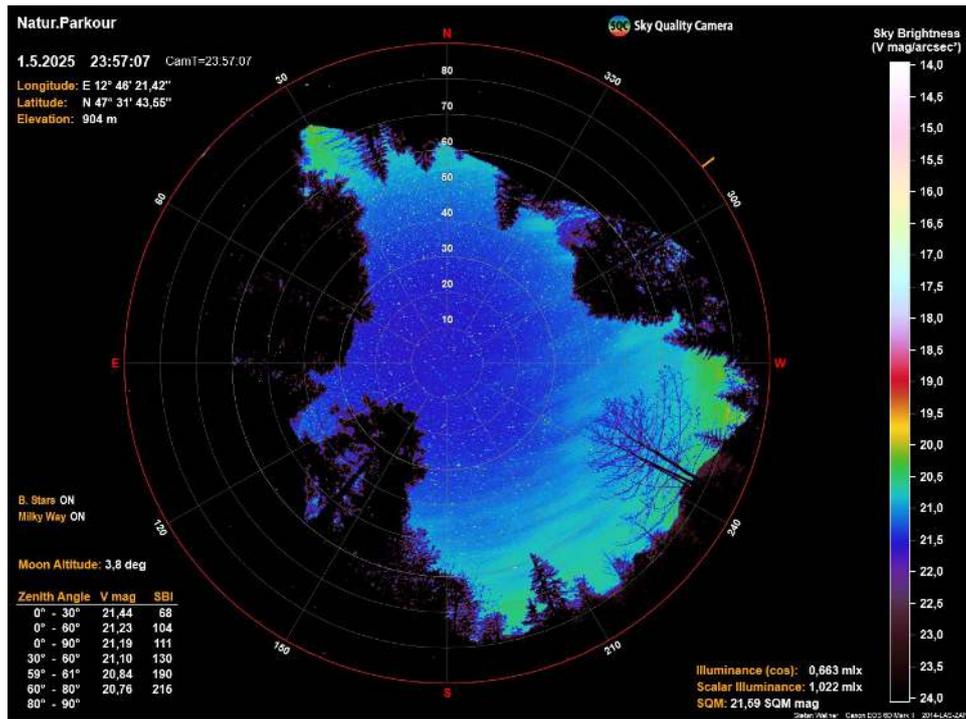


Figure 5.16.: All-Sky Image of the Location L4: Natur.Parkour analysed with SQC. The Image was taken during the second Roadrunner Measurement in the night of 1. May 2025.

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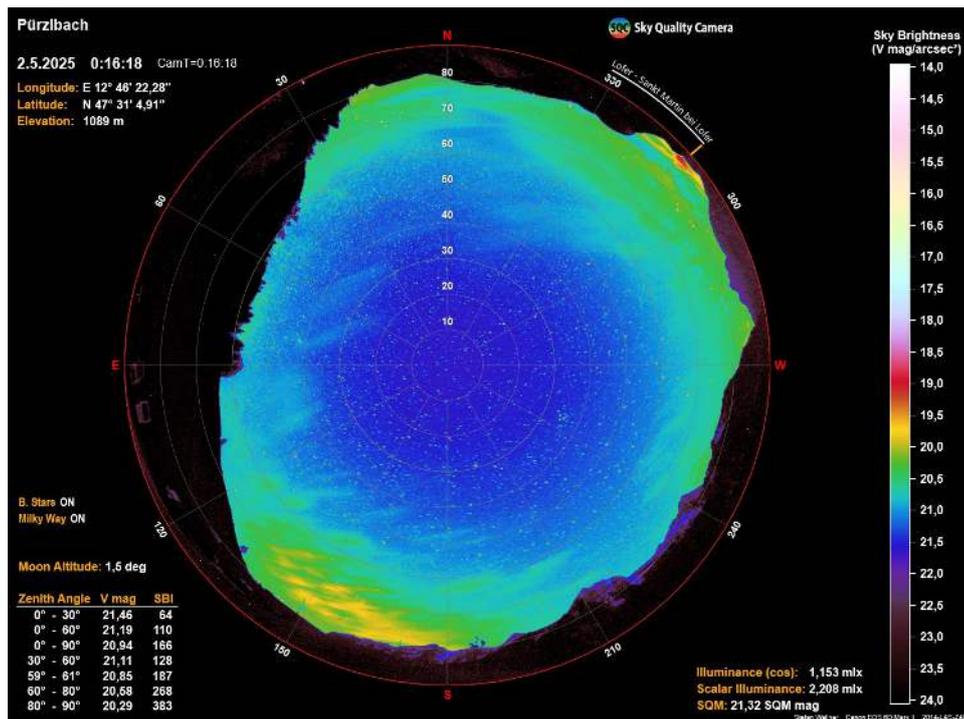


Figure 5.17.: All-Sky Image of the Location L5: Pürzlbach analysed with SQC. Lightdomes from possible light sources are shown: Lofer & Sankt Martin bei Lofer. The Image was taken during the second Roadrunner Measurement in the night of 1. May 2025.

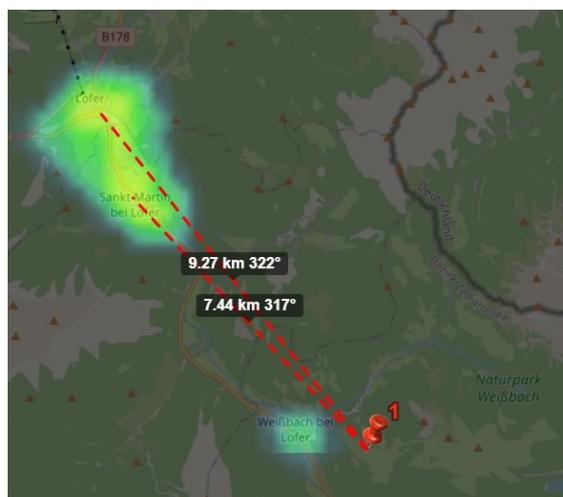


Figure 5.18.: Radiance Map showing the directions and distances of the possible lightdome sources from Figure 5.17.

5.2. Modelling Results Using SkyGlow

The use of SkyGlow is motivated by two objectives. Firstly, it is necessary to determine whether the previously identified light domes are in fact the light domes of the selected locations. Secondly, the objective was to ascertain the impact of varying cloud cover levels on the NSB in the presence of light domes along the horizon. In order to accomplish this objective, it was first necessary to create polygons representing the cities and towns using Google Earth, and thereafter to import these polygons into SkyGlow. Subsequently, simulations were conducted for each location, incorporating various levels of cloud cover. The subsequent findings were then presented in graphical form.

A particular issue encountered pertained to the generation of polygons representing the urban areas from which the light domes were to be simulated within SkyGlow. In the case of larger cities, it is not a problem to find the city boundaries and draw them. In the case of smaller towns within a municipality, the situation is more problematic due to the absence of official town boundaries, with the boundaries of the municipality itself serving as the only established limits. In instances where the light domes of certain towns intersect, or where one dome exhibits a higher degree of dominance over another, it becomes challenging to ascertain the precise boundaries between the two light domes, to determine the preeminent light dome, and to ascertain whether the light originates from a specific locale or the entirety of the town.

For this reason, an attempt was made to take advantage of Google Earth, the Light Pollution Map and the municipal boundaries from Statistik Austria (2025b) to determine the size of the towns and villages as accurately as possible. In instances where precise size determination was not feasible, the delineation of village boundaries was undertaken in accordance with the principles of the light dome. The VIIRS data from the Light Pollution Map from 2023 was the primary source of information for this study.

The data on the population of all towns in Austria was provided by Statistik Austria (2025a), and this data was used to enter the population figures for the various towns and villages. In the event that certain towns were omitted from Google Earth during the creation of the polygons for the cities, their population figures were not taken into account. In order to ascertain the location of the town within its designated area, a thorough examination was conducted in order to determine whether the town's name was situated within the designated light dome area. This procedure was implemented due to the absence of precise geographical boundaries delineating the town.

Once all the cities had been entered into SkyGlow, an attempt was made to carry out simulations at the locations of the all-sky image recordings. In order to achieve this objective, the observer in SkyGlow was situated in the same geographical location as the all-sky images were captured. Subsequently, the settings for local conditions and outputs were configured, followed by those for the city emission function for the individual cities. The fundamental settings remained consistent across all locations. The properties of the aerosols, the horizon and the output (visual, in terms of lumen, lux and cd/m^2) were entered as specified in the user manual. The settings from the user manual were also utilised for the city emission function. The 'Cloudless' option was selected for the simulations that did not include clouds. In the context of the simulations involving clouds, the cloud level was configured to 2 km within the cloud settings. To ensure the generation

5. Measurement Results and Analysis

of fully random clouds in each iteration, the '-1' option was selected during the creation of the cloud fields. Additionally, the spectral albedo of the altocumulus cloud was designated. For the cloud fraction, the values 0.25, 0.5, 0.75 and 1 were selected in order to obtain several degrees of cloud cover. Given the random generation of clouds, three simulations were performed for each of the cloud fractions of 0.25, 0.5 and 0.75. This was done to ensure a statistically more substantial selection and the ability to take an average value from the simulations.

The simulations for locations L2 – L5 for cloudless and overcast (cloud fraction = 1.0) can be viewed in Figures 5.19 – 5.22. The simulations for cloud cover of 0.25, 0.5 and 0.75 for locations L2 – L5 can be viewed in more detail in the Appendix. The appendix also contains randomly generated cloud images for the respective cloud cover levels at the locations specified.

Tables 5.11 - 5.14 illustrate the maximum, minimum and average values at the zenith of 0°–10° for the simulations of the respective locations, in cd/m^2 and as a value on the \log_{10} scale. The values for the cloud fractions of 0.25, 0.5 and 0.75 are the mean values taken from the three simulations. The individual values can be found in the tables in the appendix.

As anticipated, the simulations demonstrate that the distance of the light source from the observer is directly proportional to the observed variation in the colour of the night sky during periods of cloud cover. The issue can be attributed to single scattering in SkyGlow. However, if one were to examine the values for the location L5: Pürzlbach, a different conclusion might be reached. As illustrated in Figure A.15 and evidenced in Table 5.14, the night sky exhibits a heightened level of luminosity in cloudy conditions. It is also noteworthy that the light dome depicted in Figure A.15 does not correspond to the one observed in the all-sky image presented in Figure 5.17. Consequently, it can be hypothesised that Sankt Martin bei Lofer does not constitute a dominant light dome, or does not shine as brightly, and that only the light dome from Lofer is visible.

It would have been advantageous if all locations could have been visited twice and if the all-sky images had shown similar images of the light domes. It is only possible to hypothesise whether the selected cities and towns can be regarded as light domes based on the available images.

It has previously been noted that a problem exists for location L4: Natur.Parkour. This is due to the Radiance Map (cf. Figure 5.13) of the Light Pollution Map also displaying other towns and villages in Germany ahead of the Austrian towns and villages of Hallein, Kuchl and Golling an der Salzach. The following locations are of particular interest: Schönau am Königssee, Berchtesgaden and Bischofswiesen. The rationale behind the exclusion of these cities and towns is the absence of current population figures for 2025. While population figures for individual municipalities were available from various years, data for individual towns themselves was not, as is the case in the data from Statistics Austria. It is assumed that not all residents of the municipality live in the light domes produced by the towns and villages. For this reason, these were simply omitted. However, it should be noted that the light dome of Hallein is more prominent in the sky than the three light domes of the German towns and villages, as illustrated in Figure 5.13.

It should also be mentioned that although more simulations would have been more relevant, especially with regard to the number of different cloud cover levels, this was unfortunately not possible. The proposed plan involved conducting approximately 10 simulations, with cloud fractions of 0.25, 0.5 and 0.75. Furthermore, it would have been beneficial to conduct the aforementioned simulations with the two additional cloud types incorporated into SkyGlow. A compromise was reached, entailing the execution of three simulations per cloud cover level for the altocumulus cloud exclusively. This decision was precipitated by the protracted duration of the simulations, which exceeded the anticipated timeframe. Had the simulations been completed within a shorter timeframe, it would have been possible to perform at least 10 simulations for each cloud fraction, or even all of the planned simulations. However, only a fraction of the planned simulations could be completed.

Summary for Hirschbichl – Luminance Results by Cloud Fraction						
Cloud Fraction	Min [cd/m ²]	Min [log ₁₀]	Max [cd/m ²]	Max [log ₁₀]	Mean 0°–10° [cd/m ²]	Mean [log ₁₀]
0.00	1.402×10^{-5}	-4.85	3.435×10^{-3}	-2.46	1.431×10^{-5}	-4.84
0.25	1.107×10^{-5}	-4.96	3.392×10^{-3}	-2.47	1.187×10^{-5}	-4.93
0.50	9.226×10^{-6}	-5.04	3.450×10^{-3}	-2.46	9.476×10^{-6}	-5.02
0.75	7.926×10^{-6}	-5.10	3.450×10^{-3}	-2.46	8.212×10^{-6}	-5.09
1.00	8.400×10^{-6}	-5.08	3.450×10^{-3}	-2.46	8.722×10^{-6}	-5.06

Table 5.11.: Comparison of luminance values across all cloud fraction scenarios for L2: Hirschbichl.

Summary for Waltlmühlsäge – Luminance Results by Cloud Fraction						
Cloud Fraction	Min [cd/m ²]	Min [log ₁₀]	Max [cd/m ²]	Max [log ₁₀]	Mean 0°–10° [cd/m ²]	Mean [log ₁₀]
0.00	1.198×10^{-6}	-5.92	3.288×10^{-4}	-3.48	1.229×10^{-6}	-5.91
0.25	5.790×10^{-7}	-6.24	2.798×10^{-4}	-3.55	8.394×10^{-7}	-6.08
0.50	5.329×10^{-7}	-6.27	2.718×10^{-4}	-3.57	6.833×10^{-7}	-6.17
0.75	5.030×10^{-7}	-6.30	2.718×10^{-4}	-3.57	5.509×10^{-7}	-6.26
1.00	4.877×10^{-7}	-6.31	2.718×10^{-4}	-3.57	5.035×10^{-7}	-6.30

Table 5.12.: Comparison of luminance values across all cloud fraction scenarios for L3: Waltlmühlsäge.

Summary for Natur.Parkour – Luminance Results by Cloud Fraction						
Cloud Fraction	Min [cd/m ²]	Min log ₁₀	Max [cd/m ²]	Max log ₁₀	Mean 0°–10° [cd/m ²]	Mean 0°–10° log ₁₀
0.00	2.003×10^{-6}	-5.698	5.605×10^{-4}	-3.251	2.059×10^{-6}	-5.686
0.25	1.274×10^{-6}	-5.895	5.050×10^{-4}	-3.297	1.427×10^{-6}	-5.846
0.50	1.038×10^{-6}	-5.984	4.873×10^{-4}	-3.312	1.144×10^{-6}	-5.942
0.75	9.075×10^{-7}	-6.042	4.873×10^{-4}	-3.312	9.372×10^{-7}	-6.028
1.00	8.877×10^{-7}	-6.052	4.873×10^{-4}	-3.312	9.182×10^{-7}	-6.037

Table 5.13.: Comparison of luminance values across all cloud fraction scenarios for L4: Natur.Parkour.

Summary for Pürzlbach – Luminance Results by Cloud Fraction						
Cloud Fraction	Min [cd/m ²]	Min log ₁₀	Max [cd/m ²]	Max log ₁₀	Mean 0°–10° [cd/m ²]	log ₁₀
0.00	2.763×10^{-6}	-5.559	7.076×10^{-4}	-3.150	2.990×10^{-6}	-5.524
0.25	2.760×10^{-6}	-5.559	9.334×10^{-4}	-3.030	4.188×10^{-6}	-5.378
0.50	2.466×10^{-6}	-5.608	1.123×10^{-3}	-2.950	5.387×10^{-6}	-5.269
0.75	1.950×10^{-6}	-5.710	9.636×10^{-4}	-3.016	3.895×10^{-6}	-5.410
1.00	3.692×10^{-6}	-5.433	1.188×10^{-3}	-2.925	7.356×10^{-6}	-5.133

Table 5.14.: Comparison of luminance values across all cloud fraction scenarios for L5: Pürzlbach.

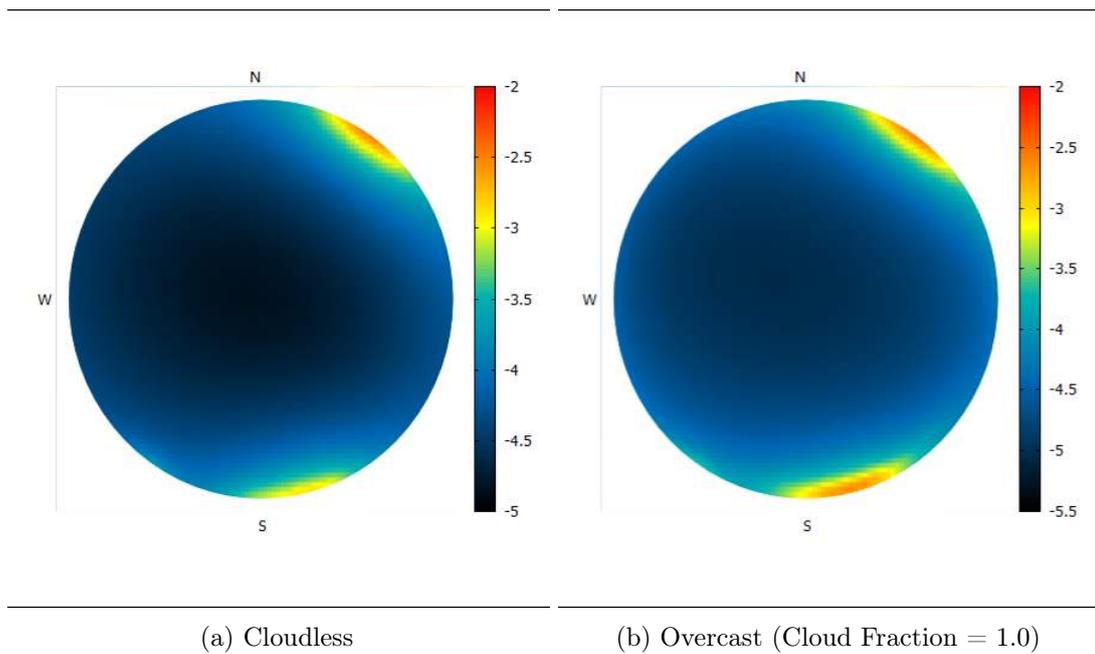
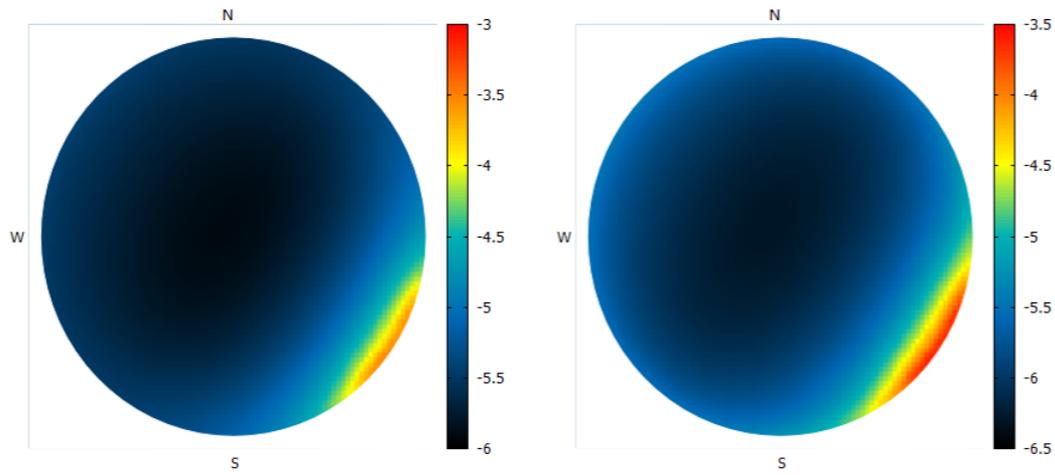


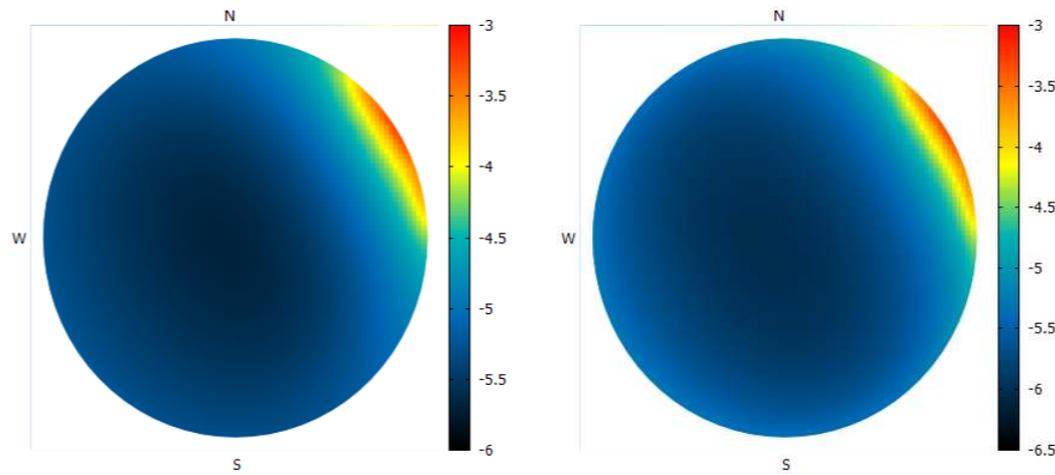
Figure 5.19.: Comparison of SkyGlow simulations for clear and overcast skies for location L2: Hirschbichl.



(a) Cloudless

(b) Overcast (Cloud Fraction = 1.0)

Figure 5.20.: Comparison of SkyGlow simulations for clear and overcast skies for location L3: Waltmühlsäge.



(a) Cloudless

(b) Overcast (Cloud Fraction = 1.0)

Figure 5.21.: Comparison of SkyGlow simulations for clear and overcast skies for location L4: Natur.Parkour.

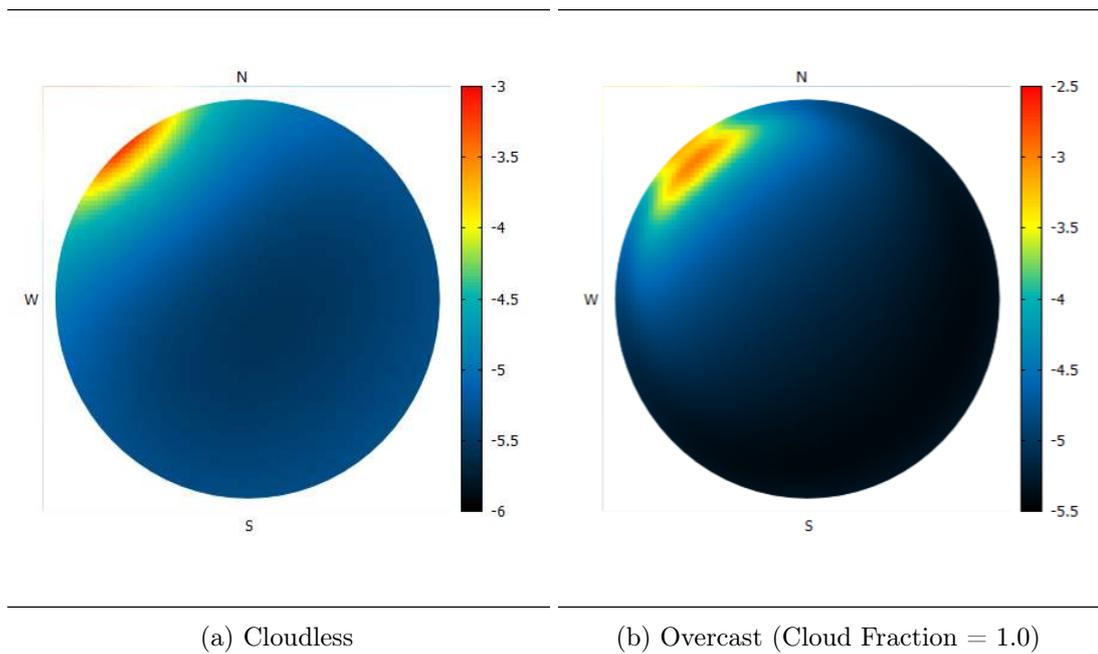


Figure 5.22.: Comparison of SkyGlow simulations for clear and overcast skies for location L5: Pürzlach.

6. Conclusion

As previously stated in the introduction, this work sought to achieve multiple objectives.

To provide an overview of the effects that light pollution can have on animals, the environment, humans and astronomy.

As demonstrated in Section 2.2, light pollution has been shown to impact the metabolism and haematology of adult male Wistar rats. In addition, the stridulation of crickets has been observed to be influenced by light pollution, and butterflies have been found to be attracted to artificial light.

The impact on ecosystems is evident in the alteration of lake characteristics, with an increase in cyanobacteria abundance and organic matter cycling. The effect of light pollution on herbivory and phytochemistry in European beech has been demonstrated, and it has been shown that light pollution can prevent the purpose of artificially created reefs, i.e. to provide protection for marine life, from being fulfilled.

For humans, the phenomenon of light pollution has been demonstrated to increase the risk of developing type 2 diabetes, affect the retina, and generally expose individuals to an increasing amount of artificial light and a decreasing amount of natural light.

In the context of astronomy, light pollution can restrict ground-based observations with telescopes from observatories to locations where the night sky has not yet been affected by ALAN. It can be demonstrated that, as a consequence of the increase in global night sky brightness, there will be limited locations at some point in which this phenomenon will be possible. The presence of a growing number of satellites orbiting the Earth has also been identified as a contributing factor to the observed increase in the brightness of the night sky. It is imperative to ensure that light pollution is mitigated on Earth and in space around the Earth.

To carry out measurements and simulations for the Weißbach Nature Park to obtain Dark Sky Place certification, using various measurement methods.

A series of measurements were taken with the aid of SQM instruments (SQM-L & SQM-LU), and All-Aky images were recorded and processed with SQC. Furthermore, TESS-W data underwent analysis, and simulations were created with SkyGlow. A variety of different measurement methods and instruments were employed, and these ultimately confirmed one thing: the Nature Park Weißbach has achieved the target limit of 21.20 mag/arcsec² required to obtain certification as an International Dark Sky Park.

It is evident that a multitude of Roadrunner measurements in conjunction with the diverse SQM models would provide further validation of this conclusion. It is crucial to bear in mind that the TESS-W displays values 0.1 – 0.3 mag/arcsec² brighter than an SQM, meaning that the TESS-W data would also contain a greater number of measurements that would confirm a night sky brightness of over 21.20 mag/arcsec².

No measurements were taken for the municipality of Weißbach bei Lofer per se, a step

6. Conclusion

which is not actually required by the guidelines. The municipality is endeavouring to install a measuring station equipped with a TESS-W to obtain measurements in this area. Further steps towards the certification of the municipality of Weißbach bei Lofer are not pertinent to the present work.

To identify problems and limitations associated with measuring devices and methods.

A variety of issues and constraints must be taken into account when measuring, determining and modelling light pollution.

A key challenge is the absence of a universally applicable measuring device or method for measuring and modelling light pollution in a consistent manner across all locations. A multitude of measuring instruments exists, each with its own metrics, which may prove superior in certain domains. However, the utilisation of a diverse array of instruments is imperative to ensure comprehensive and precise results.

The TESS-W is an autonomous instrument that is capable of measuring specific parameters without the need for external intervention. It functions by means of an internet connection and a power supply. The utilisation of an SQM-LU facilitates the acquisition of measurements over an extended period. However, it is imperative to note that the initiation of the recording programme and the storage of the data necessitate the use of a computer. The issue arises from the inability to ascertain whether measurements have been recorded immediately; rather, one must first save and retrieve the data to determine if measurements have been taken. The TESS-W facilitates immediate online verification of functionality.

The location of the measurement is of paramount importance in determining the most appropriate method and instrument for the adequate measurement of light pollution.

To highlight meteorological parameters and their associated issues, especially clouds.

It is widely acknowledged that clouds present a significant challenge when it comes to the execution of measurements and the development of models.

During the Roadrunner measurements for this work, the presence of clouds in the sky was consistently observed, as evidenced by all-sky images. On-site measurements are invariably contingent on prevailing meteorological conditions. Conditions must be clear, i.e. free from clouds, fog, rain and other phenomena that might compromise the accuracy of the measurements. A comparison of the images from the first and second nights of measurement alone shows a difference of one magnitude or more. This observation underscores the significant impact of atmospheric conditions, such as snow, fog and clouds, on the accuracy of measurement values when compared to the clarity of a reasonably clear night sky.

The analysis of imagery captured by the TESS-W apparatus presents a challenge in determining the presence or absence of cloud cover in the sky. In the absence of clouds at the zenith, i.e. above the device itself, the presence of clouds on the horizon that scatter light may be detected by the TESS-W. Consequently, the methods for determining whether the night sky is cloudy or not are still somewhat inadequate for the TESS-W, as clouds on the horizon are not taken into account, only those in the recording area of the device itself. A further issue is presented by the SkyGlow simulations. It is evident that the presence of clouds in the night sky, in conjunction with a light source located at a considerable distance, results in the night sky appearing darker. This phenomenon can be attributed

to single scattering. It is only when observing light sources in close proximity to the observer that the effect of the night sky brightness increasing can be perceived. SkyGlow is currently engaged in the redesign of the theory underpinning the software, with the objective of ensuring that the diffusion of light in cloudy atmospheres also reflects the outcomes of measurements.

To identify ways to improve the scientific accuracy of measurements and simulations.

As previously stated, the execution of measurements and simulations is challenging due to the absence of a universal procedure and a universally applicable measuring device.

In the domain of simulations, a multitude of factors must be taken into account to ensure the accurate simulation of light pollution. This necessitates a systematic, step-by-step approach, precluding the possibility of a comprehensive implementation from the outset. Furthermore, it is imperative that a theory is formulated which is capable of accounting for all extant influences, and which can subsequently be processed within the software itself. Consequently, further development is required before simulations can achieve a level of perfection that encompasses all possible functions.

In relation to the measurement instruments themselves, it would be advantageous to possess a device capable of quantifying the brightness of the night sky and concurrently generating all-sky images. This would facilitate the determination of cloudiness from the measured values, not only at the zenith but also on the horizon.

To identify measuring devices and methods that other locations can use to obtain Dark Sky Place certification.

Should certification as an International Dark Sky Park be sought, it is recommended that the measuring instruments and methods employed in this thesis are utilised to carry out the measurements. The TESS-W installation is intended to establish a local measurement network capable of continuous data collection, with the capability of accessing the data at any time. Roadrunner measurements should also be taken to measure the brightness of the night sky itself in a larger area, both in and around the area to be certified. Additionally, the acquisition of all-sky images is imperative to facilitate the identification of surrounding light domes, thereby enabling communication with proximate towns and cities to disseminate information regarding the issue. Subsequent simulations can then be conducted to demonstrate, for example, how the light dome would change if a town or city switched from HPS to LED lighting.

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A. Appendix

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A. Appendix

A.2. International Dark Sky Park Program Guidelines

DARKSKY INTERNATIONAL

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*TO PRESERVE AND PROTECT THE NIGHTTIME
ENVIRONMENT AND OUR HERIT- AGE OF DARK SKIES
THROUGH ENVIRONMENTALLY RESPONSIBLE OUTDOOR
LIGHTING*



DarkSky

International Dark Sky Park Program Guidelines

**2018 Version
Updated September 2023**

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DEFINITION OF AN INTERNATIONAL DARK SKY PARK

An International Dark Sky Park (IDSP) is a land possessing an exceptional or distinguished quality of starry nights and nocturnal environment, and that is specifically protected for its scientific, natural, educational, and/or cultural heritage resources, and/or for public enjoyment. The land may be publicly owned, or privately owned, provided that the landowner(s) consent to the right of permanent, ongoing public access to specific areas included in the IDA designation.

GOALS OF DARK SKY PARK CREATION

- To identify, restore, and protect public lands, such as national, state, provincial, and other parks, and publicly accessible private lands, with exceptional commitment to, and success in implementing, the ideals of dark sky preservation and outstanding night skies.
- To promote eco- and astrotourism
- To promote protection of the natural nighttime environment, public enjoyment of the night sky and its heritage, and/or areas ideal for professional and amateur astronomy
- To encourage conservation professionals to recognize dark skies as a valuable resource in need of proactive protection
- To provide national and international recognition for such parks
- To encourage parks and similar public entities to become environmental leaders on dark sky issues by communicating the importance of dark skies to the general public and surrounding communities, and by providing an example of what is possible with proper stewardship

DESIGNATION BENEFITS

Achieving an IDSP designation brings recognition of the efforts a park has made towards protecting dark skies. It raises the awareness of dark skies among Park leadership, staff, visitors, and the surrounding community. An IDSP designation entitles the Park to display the DarkSky logo in official Park publications and promotions, and enables use of this logo by commercial or other groups within the community when identifying the

park area itself.¹ DarkSky will promote and highlight ongoing Park efforts to protect night skies and maintain pages identifying and describing all IDSPs. The Park managing agency may also identify DarkSky as a partner.

ELIGIBILITY

To be eligible for consideration as an IDSP, a candidate Park must meet *all* of the following criteria:

- 1) All protected public lands, whether managed by national, state, provincial, or local agencies, are eligible.² These may include parks, refuges, forests, wilderness areas, monuments, protected rivers, or other categories of protected lands. Private lands whose owners consent to regular nighttime public access to designated areas of their property in perpetuity are also eligible. Collectively, all public or private lands contemplated in this section are hereafter referred to generically as “parks.”

The Park must provide the opportunity for public nighttime access, with or without supervision. A portion of designated land may meet this requirement, or access must be available for a fraction of the length of the night. In some cases, such as when working with areas that protect endangered wildlife, archeological sites or other sensitive resources, this requirement may be adjusted. Public access to public or private lands may be subject to a nominal entry fee, but must not be contingent on the required paid use of any other product, service, program, or facility available at the site.

- 2) There is no minimum or maximum land area for IDSPs. For larger parks with a minimum total size of 1,000 square kilometers (km²), a smaller portion of the Park less than its full land area may be designated with special permission. A justification explaining why this subset of the larger Park was chosen must be approved in advance by the International Dark Sky Places Program Manager.

¹ For example: an organization can refer to itself as “located in Cherry Springs State Park, an International Dark Sky Park” or other words to the same effect.

² Private inholdings and lands within parks similarly situated are formally exempt from regulation under the terms of this document, but applicants are encouraged to try to obtain voluntary compliance from private landowners.

- 3) The Park must provide an exceptional dark sky resource, relative to the lands and communities that surround it.

MINIMUM REQUIREMENTS FOR ALL PARKS

- 1) The Park must create a quality comprehensive Lighting Management Plan (LMP). Minimum standards are described below in the section “Lighting Management Plan Guidelines.”³
- 2) Typical nighttime conditions characterizing the site must be consistent with or exceed the following criteria:
 - A. The Milky Way is readily visible to the unaided eye;
 - B. There are no nearby artificial light sources yielding significant glare; and
 - C. Any light domes present are dim, restricted in extent, and close to the horizon.

These conditions correspond approximately to a visual-band zenith luminance of 21.2 magnitudes per square arcsecond (0.4 mcd/m²) and a naked-eye limiting magnitude (NELM) of +6.

In order to substantiate the sky quality, measurements of the night sky brightness at the zenith must be made with suitable instruments, or the NELM estimated by a qualified observer. Measurements of night sky brightness must be distributed over a sufficiently long enough period of time in order to average out fluctuations over timescales ranging from hours to seasons in length. Further, panoramic nighttime photography of the horizon must be included in order to substantiate the number and extent of light domes visible from the site.

Applicants should discuss their measurement protocol with the International Dark Sky Places Program Manager and submit all data necessary to substantiate these conditions.

Any designated IDSP that no longer meets these conditions but documents a visual-band zenith luminance from 20.0 to 21.19 magnitudes per square arcsecond or a naked-eye limiting magnitude (NELM) no higher than +5 will be included in a List of Endangered IDSP Sites published on the IDA web- site. IDA reserves the right to suspend or revoke the IDSP designation of a Park with night sky

³ Lighting required by law under the authority of any entity having higher legal jurisdiction over the Park may be formally exempted from the requirements of this section.

quality that falls below a visual-band zenith luminance of 20.0 magnitudes per square arcsecond or a naked-eye limiting magnitude (NELM) of +5.

- 3) The Park's commitment to dark skies and quality outdoor lighting are demonstrated by all of the following:
 - a. The Park recognizes dark skies as an important natural, cultural, and/or scientific resource value as demonstrated by inclusion in approved management documents.⁴
 - b. At least two-thirds of existing outdoor lighting fixtures within Park boundaries conform to the Park's LMP at the time of IDSP application (or an alternative fraction approved by the Dark Sky Places Committee).
 - c. A lighting inventory and a plan to bring 90% of outdoor lighting into compliance with the Park's LMP within five years of receiving an IDSP designation, as well as a written commitment to bring the Park into 100% compliance within 10 years of designation.
 - d. A measurement program must be maintained either by the Park, private landowner(s), or by another public or private organization (university, research center, DarkSky Chapter, astronomy club, etc.) to follow the evolution of light pollution in the IDSP and ensure that the night sky quality does not degrade. Applicants are encouraged, but not required, to submit their measurements to the citizen science projects such as My Sky At Night (myskyatnight.com) and Globe At Night (globeatnight.org).
- 4) A description of current and suspected future threats to dark skies over the park.
- 5) Evidence that the Park has set a leadership example in the restoration of dark skies by implementing at least one of the following:
 - a. Producing at least one "night sky friendly" lighting project that is publicly visible and interpreted.
 - b. Involving at least two external partners in dark sky restoration

⁴ Examples of such documents include General Management Plans, Resource Management Plans, and Facility Development Plans. Consult DarkSky staff as to whether a particular type of management document meets this requirement.

efforts.⁵

- c. Cooperation with at least two nearby municipalities that results in adoption of lighting policies that improve sky conditions in the Park.

A combination of the above or an alternative restoration project may be suggested instead.

- 6) A demonstration of the Park's commitment to public education.
- 7) The importance of dark skies/natural darkness and the benefits of quality lighting must be part of Park interpretation and outreach programs.⁶
 - a. If the Park typically provides interpretive programs, then dark skies must be one of the central themes communicated through on-site interpretation, and at least a portion of the event must include dark sky awareness or preservation specifically including reference to DarkSky and what it means to be an International Dark Sky Park.
 - b. If interpretive programs are not typically offered, then extensive publications, flyers, press releases, media, social media, or other outreach are appropriate substitutes.
- 8) Dedicated programming must occur at least four times per year; however, more events are preferable. These events may highlight the value of natural nighttime darkness in any appropriate way.⁷
- 9) Once established, the Park must erect and maintain appropriate public signage indicating the International Dark Sky Park designation along a roadway entrance, along a footpath entrance if no roadway exists, or at a visitor contact center. If approved by DarkSky International, language as an alternative to "International Dark Sky Park" may appear on the signage and in Park communications regarding the IDSP status. Once the sign is erected, a photograph documenting this sign must be taken and sent to DarkSky International for records, along with a description of its location.

⁵ Examples of potential external partners in restoration efforts include chambers of commerce, electric power utilities, universities, tribal/indigenous nations, environmental and conservation groups, and natural history associations.

⁶ "Dark skies education" refers not only to astronomy education but also to education about wildlife, energy efficiency, safety, and human health. Astronomy education events such as star parties *only* count as "dark skies education" if they prominently feature material about dark skies and outdoor lighting.

⁷ Examples include cultural or historic value, importance to wildlife, and astronomical or stargazing events.

- 10) The Park shall submit an annual report to IDA by 1 October of each year detailing activities and progress towards fulfilling DarkSky IDSP goals during the previous year. The report serves to document that the Park continues to meet minimum program requirements; sustains partnerships, outreach, and interpretive efforts; and makes adequate progress toward LMP compliance thresholds. The report should include dates and brief descriptions of interpretive events, lighting retrofit projects, community outreach, etc. New measurements of the night sky brightness in the Park must be obtained and included in the report. It should also provide information on any new lands acquired since designation and/or the most recent prior report, as well as any potential future sale of land that may result in reassessment of IDSP status (see “Sale or Transfer of Land Ownership,” below). Samples of printed materials and press articles should also be included.

Electronic submission of these documents is required in Microsoft Word or PDF format. If the annual report is not sent in a timely fashion, DarkSky may suspend IDSP status until the annual reporting requirements have been met.

A designated IDSP is exempt from the annual reporting requirement in the calendar year in which the IDSP designation was awarded. If the designation is received after 1 October of a given calendar year, the IDSP’s first annual report to IDA will be due on 1 October of the following calendar year.

DarkSky reserves the right to request stronger or alternative requirements if deemed appropriate and deny IDSP status if these requirements are not met. Any requests by DarkSky will be made through direct contact and communication with the Park.

An IDSP designation is subject to regular review by DarkSky International and possible revocation if minimum requirements are not maintained. More details may be found in the “Reassessment of IDSP Designations” section.

LIGHTING MANAGEMENT PLAN

The Lighting Management Plan (LMP) is a written policy, approved by Park management, that must contain at least the following minimum provisions:

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- 1) The written policy meets or exceeds applicable agency or departmental policies regarding outdoor lighting and conforms to all local, regional, and national laws.
- 2) The use of outdoor light at night is only prescribed when it is strictly needed, where it is needed, and in the appropriate amount for a specific task. The purpose of outdoor light allowed under the policy must be specifically to ensure public safety.
- 3) All outdoor lighting fixtures >500 initial lamp lumens⁸ must be fully shielded⁹ and make appropriate use of timers and motion sensors. Lighting of ≤500 initial lamp lumens may be left unshielded for special purposes, such as historical preservation. The approved special uses must be stated in the LMP. DarkSky will scrutinize these uses to ensure that Park lighting is a suitable example of quality lighting for the public and protects the nighttime environment to the maximum practical extent. DarkSky may request additional descriptions, photographs, or drawings of these lights. These lights are not exempt from the other lighting guidelines, and must still be designed in such a way to minimize impact to the nighttime environment.
- 4) Lighting controlled with motion-activated switches limiting the duration of illumination to less than five minutes after activation is exempt from the other requirements of this section.
- 5) Lighting must be chosen to minimize the amount of short-wavelength light emitted into the nighttime environment. The Park's LMP must restrict lighting in this respect according to one of the following prescriptions:
 - A) The correlated color temperature (CCT) of lamps must not exceed 3000 kelvins; **OR**
 - B) Allowed lighting must not emit more than 25% of its total spectral power at wavelengths < 550 nanometers; **OR**
 - C) The scotopic-to-photopic (S/P) ratio of allowed lighting must not exceed 1.3.

These metrics may be found in manufacturer data sheets for lighting

⁸ "Initial lamp lumens" is defined as the number of lumens of light emitted by a lamp when new and not counting any depreciation of output due to the age of the lamp. This information can be found in manufacturer data sheets.

⁹ "Fully shielded" is defined as a light source screened and its light directed in such a way that none is emitted above the horizontal plane passing through its lowest light-emitting part.

products.

- 6) Visitor activities with respect to the introduction of unnecessary artificial light at night into the park environment must be regulated. This must include reasonable limits on the lighting of camping equipment and recreational vehicles, as well as a general prohibition of inappropriate “light painting,” the use of searchlights, and similar activities. Note that this requirement is in no way intended to compromise visitor safety; lighting required in emergency situations may be exempted from compliance.
- 7) Illuminated signs¹⁰ must meet *all* of the following requirements:
 - A) Sign illumination is permitted only while the associated activity is taking place. For businesses within the Park, sign illumination must be extinguished completely during the hours the business is closed.
 - B) Displays must be single-color on a black background.
 - C) Luminance of the sign as a whole after sunset must not exceed 100 nits (100 candelas per square meter, cd/m²).
 - D) The luminous or illuminated surface area of an individual sign must not exceed 18.6 square meters (200 square feet).
- 8) A policy governing the installation of temporary lighting requiring that any such installation will adhere to the LMP to the greatest possible extent and whose duration will be limited to the shortest possible time.

LIGHTING INVENTORY

A lighting inventory is a formal audit of all artificial outdoor lighting in a park. It is used to determine rates of compliance with the LMP and to identify lighting equipment in need of rehabilitation through retrofitting or replacement. A complete inventory of outdoor lighting in the Park is a requirement for IDSP status, and it must be accompanied by a plan under which Park lighting will be brought into compliance with the LMP under the terms specified in “Minimum Requirements for All Parks” (above).

¹⁰ “Illuminated sign” is defined as any informational or advertising display that is illuminated by either internal or external means. Descriptive terms are adjusted here according to the type of illumination.

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The following must be taken into consideration when collecting and reporting lighting inventory data:

- 1) When there are numerous outdoor light fixtures, it is acceptable to group lights by facility or area. Whether the fixtures are fully shielded, are special purpose fixtures under 500 initial lumens, and what the lighting application is must be noted for each fixture or group of fixtures.
- 2) Daytime photographs or manufacturer diagrams of each fixture type may accompany the inventory.
- 3) Inoperable fixtures, including those physically disconnected from power supplies, must be inventoried. Only those physically disconnected from power supplies may be counted as compliant for the purpose of determining the rate of LMP compliance.

The following is a sample table from portion of a lighting inventory:

Location	Fixture	Fully-Shielded?	Operable?	Special Purpose <500 lumens	Application	Conforms with LMP?
Visitor Center	12 fixtures on 14' pole, 70 W HPS	YES	YES	NO	Parking lot, timer off at 10pm	YES
	2 door lights, 100 W MH	YES	NO	NO	Building egress	YES
	6 bollard (post) lights, 32 W CFL	NO	YES	NO	Walkway	NO – see plan

Restrooms	2 carriage style lights at doorways, 40 W incandescent	NO	YES	YES	Historic Preservation Egress	YES
	6 wall packs, 250 W MH	NO	YES	NO	Occasional night operation	NO – see plan
	8 Glare-busters, 11 W CFL	YES	YES	NO	Egress, Security	YES

PROVISIONAL STATUS

In some cases, a Park interested in becoming an International Dark Sky Park may lack the resources to make a successful application. Provisional status recognizes the Park’s ongoing work to become an IDSP and is intended to be used as leverage to enable the necessary lighting upgrades or retrofits.

Provisional status expires after three years. At any time before the end of its Provisional status, a Park may apply for full status. Material submitted for the removal of Provisional status may be an addendum to the initial application as long as the material includes a current assessment of night sky quality, goals, outreach, and programs listed in the original application.

A Park may apply for Provisional status if *all* of the following conditions are met:

- 1) A Lighting Management Plan has been approved by Park management.
- 2) Minimum sky quality criteria are satisfied.
- 3) An inventory of outdoor lighting in the park (owned by either the park or concessionaires).
- 4) Appropriate outreach efforts have been undertaken.

To be considered for a Provisional status, the minimum quality night sky described under “Eligibility” must be met.

Applicants requesting Provisional status should send a nomination package to IDA that contains at least the following information:

- Documented intent to create and support a DSP
- Initial sky quality measurements
- A Lighting Management Plan
- An action plan describing how the aspiring Park will meet minimum requirements

IDSP APPLICATION PROCESS

NOMINATION

The nomination may be initiated by a DarkSky-qualified nominator.¹¹ Nominators are encouraged to correspond with DarkSky International staff and the Park throughout this process. In addition, the application must include evidence, such as in the form of a letter of support, from the Park leadership, such as a superintendent or administrator, consenting to consideration for IDSP status.

STEPS FOR APPLICANT

- 1) Make initial contact with DarkSky International by phone or email to discuss the process and receive recommendations, followed by continued communications to update DarkSky International staff on progress and receive continued assistance.
- 2) Designate a formal point of contact (POC) person, such as a project manager, and provide their telephone number, and email address to DarkSky International staff. Before and after designation, any changes to this POC, or their information, must be transmitted to DarkSky International immediately in order to ensure continuous communication at all times.
- 3) Obtain a letter of nomination from a qualified DarkSky member nominator, as well as a supporting letter from the Park leadership,

¹¹ A “DarkSky-qualified nominator” is defined as an individual or organization holding a DarkSky membership in good standing at the time that the IDSP application is submitted. The Park managing agency itself may join DarkSky as an organizational member and self-nominate.

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such as a superintendent or administrator. Solicit additional letters of support from community organizations, clubs, groups, universities, etc.

- 4) Upon completion, send the application to DarkSky International staff for review of the document at least one month before the chosen submission deadline date. DarkSky International staff will confirm that the application is complete and ready for submission or return it with suggestions for improvements.
- 5) Submit in plenty of time for DarkSky international staff to review and prepare your application to make the bi-monthly deadline that you prefer, as found on the DarkSky website. Requests to rush applications will *not* be honored; planning ahead is essential if the Park wishes to meet a specific deadline.

TO BE INCLUDED IN IDSP APPLICATION PACKAGE

- 1) Map of the area to be designated, indicating the legal boundaries of the Park.
- 2) Letter of nomination from a qualified DarkSky member nominator.
- 3) Letter of support from appropriate Park administrator.
- 4) Park management documents supporting dark skies and/or the natural nighttime environment as a valued resource.
- 5) If it exists, agency/departmental/municipal policy on outdoor lighting and dark sky protection.
- 6) Documentation of sky quality, light pollution measures, satellite images, maps, photographs, or other evidence that demonstrates the noteworthiness of the Park's dark-sky resource. Measurements of night sky brightness must be obtained using DarkSky-approved night sky brightness measuring equipment. A sufficient number of sites within the Park must be measured to clearly establish the significance of the resource with emphasis on the areas of highest visitation. Data included in the application must contain an updated night sky brightness survey of the Park completed no more than two years before the application's submission along with any other relevant information.
- 7) Lighting Management Plan.

- 8) Documentation signed by the Park administrator showing a Lighting Inventory of the Park and a plan to bring 90% of outdoor lighting into compliance with the LMP within five years and 100% within 10 years of achieving IDSP designation.
- 9) Description of a dark-skies restoration project.
- 10) Description of interpretive programming or products related to dark skies and natural darkness, including examples of successful education efforts (photos, documentation of student projects, etc.)
- 11) A summary of future plans for activities in the Park after receiving IDSP status.
- 12) Proposed alternative wording for IDSP (e.g., “Dark Sky Wilderness,” “Dark Sky Refuge”), if desired, along with a justification for the request.
- 13) If the candidate IDSP is a privately held property, documentary evidence ensuring public access and transit as outlined in the section “Eligibility,” item (3).

Examples of successful past applications are available on the DarkSky website.

DARKSKY REVIEW PROCESS

Six application submission deadlines occur in each calendar year, commencing in January and continuing every other month. Before the Park’s final application is submitted, it is highly recommended that the Park be in regular communication with the International Dark Sky Places Program Manager to perfect the application before the next application deadline.

IDA staff regularly forwards applications to the DSPC for review. Endorsement of applications by the DSPC is by a 2/3 supermajority vote; otherwise, the DSPC will return applications with reasons for denial of an endorsement and specific recommendations for improvement.

If endorsed, the applicants will be notified, and the International Dark Sky Places Program Manager will present the application to the DarkSky Board of Directors (BOD). A waiting period of 10 calendar days then commences during which the BOD has the right to deny IDSP status should it determine that any problems with the application exist.

If the BOD registers no objection within the waiting period, the IDSP designation is considered immediately awarded by DarkSky International.

The Park has the right to choose when the designation is made public, but it must organize the announcement to be made at the same time as the DarkSky International public notice unless otherwise agreed by both parties. Along with the announcement notice, DarkSky will publish the Park's application on its website. By submitting the application, the Park agrees in advance that the application will be made publicly available.

If an application is denied final approval by the BOD, a letter will be sent to the applicant outlining elements of the application that need improvement along with specific recommendations for ways to remedy any problems the BOD identifies. Applications may be resubmitted for future consideration after remediation is complete. Resubmitted applications will be considered without prejudice.

DarkSky realizes that certain circumstances surrounding an IDSP application may cause some potential authors of letters of support (or opposition) to feel uneasy about publicly declaring their opinions about the IDSP designation. In the interest of providing the Dark Sky Places Committee with as full a picture of community sentiment about applications as possible, it is possible for some letters to be suppressed from online publication if it is felt that making the letters publicly available will subject their authors to retaliation or harassment. A prospective IDSP seeking this protection for letter writers must make a formal written request. The International Dark Sky Places Program Manager must approve suppression of publication of any part of an application. Note that suppression of online publication does not prevent either the DSPC or the BOD from reading all submitted letters.

POST-DESIGNATION REVIEW AND MAINTENANCE

The IDSP designation is not awarded in perpetuity. Rather, it is subject to regular review by DarkSky and possible revocation if the minimum program requirements are not maintained. More details may be found in the "Reassessment of IDSP designation" section below.

To ensure that Parks remain exemplary in their protection and restoration of the natural nighttime environment, DarkSky will periodically reevaluate each site in the International Dark Sky Places Program. This is done to confirm that the Park continues to meet the minimum requirements and is making adequate progress toward LMP compliance goals outlined in this document.

Each designated IDSP must submit to DarkSky International a written report of its activities related to the maintenance of its designation on or before 1 October of each calendar year. The report is a short (typically less than ten-page) synopsis of the Park's activities and initiatives during the intervening year.¹² The report should include dates and brief descriptions of any interpretive events, lighting retrofit projects, outreach efforts, etc. Samples of printed materials and press articles should also be included.

Annual reports should not be burdensome to produce, as they are intended as a compilation of information accumulated throughout the year. Annual reports and supporting documentation must be submitted electronically to the International Dark Sky Places Program Manager in either PDF or Microsoft Word format. If the annual report is not received by IDA in a timely fashion, IDA may suspend the site's IDSP status until the annual reporting requirement has been met (see the following section). On or about 1 August and 1 September of each year, the International Dark Sky Places Program Manager will remind local contacts at each IDSP of the pending 1 October annual report submission deadline.

A designated IDSP is exempt from the annual reporting requirement in the calendar year in which the IDA designation was awarded. If the designation is received after 1 October of a given calendar year, the IDSP's first annual report to IDA will be due on 1 October of the following calendar year.

REASSESSMENT OF IDSP DESIGNATIONS

An IDSP designation is intended to represent the beginning of an ongoing relationship between the Park and DarkSky to our mutual benefit. DarkSky will periodically review the nature of that relationship in the required annual reports (see "Minimum Requirements For All Parks", Item G).

From time to time, DarkSky also receives comments from visitors to IDSPs that raise concerns about the veracity and timeliness of information provided to DarkSky by IDSPs. DarkSky may, at its discretion, investigate claims in which it is alleged that IDSPs are not adhering to commitments made to DarkSky and the public in their applications to the Program. This section details the DarkSky procedure for carrying out such investigations, and the rights of IDSPs in such matters.

¹² Examples of acceptable annual reports are available on the individual IDSP pages on the DarkSky website.

INVESTIGATION AND DUE PROCESS

An allegation of impropriety concerning any of the elements of participation in the Program outlined in this document is subject to DarkSky investigation and potential remedial action including temporary suspension and/or permanent revocation of the IDSP designation. DarkSky International staff shall perform due diligence in gathering facts concerning such allegations it deems credible, and will prepare a report of its findings for consideration by the DSPC. The DSPC commits to weighing the evidence fairly and impartially, and to seek to resolve disputes whenever possible through dialog. An IDSP subject to an investigation shall be notified in a timely manner and solicited for evidence contrary to the specifics of the allegation at hand. The IDSP will be given an opportunity to correct any deficiencies with regard to the Program guidelines established by the DarkSky investigation within a reasonable time period to be prescribed by the DSPC.

Failure to achieve consensus through these means risks a DSPC recommendation for suspension or revocation of the IDSP designation. If made, such a recommendation will be forwarded to the BOD for formal ratification before coming into force. The BOD's decision on any disciplinary matters involving an IDSP shall be considered definitive and binding.

Any IDSP so investigated has the right to review the allegations against it and all factual information collected by DarkSky pertinent to the allegations.

REINSTATEMENT FOLLOWING SUSPENSION

If the DSPC recommends a suspension of an IDSP designation, and the BOD ratifies the suspension, the IDSP shall be immediately notified. The status of a suspended IDSP shall be changed to "Provisional" in all DarkSky communications until the designation is reinstated or revoked; however, the process of obtaining reinstatement of a designation is not the same as that outlined in the "Provisional Status" section of these guidelines.

To obtain reinstatement of a suspended designation, the IDSP must provide evidence to the DSPC's satisfaction that the specific issues identified by the DSPC as grounds for the suspension have been corrected and that all Program guidelines are once again met. The DSPC will consider the evidence presented by the DSP and render a judgment to one of the following:

- Accept the reinstatement petition; or

IDA International Dark Sky Park Designation Guidelines

- Reject the petition and recommend revocation; or
- Return the petition with further instructions and a defined deadline for a DSP response.

A suspension left unresolved after one year from the date of the BOD's assent to the suspension automatically becomes a permanent revocation. Revocation entails removal of the IDSP from DarkSky's roll of approved Dark Sky Places, and from mention on the DarkSky website and in member and external communications. DarkSky reserves the right to take legal action against any former IDSP whose designation is duly revoked but continues to use the DarkSky name or logo in advertising, communications, and/or signage.

SALE OR TRANSFER OF LAND OWNERSHIP

DarkSky considers the rights and privileges outlined here in association with IDSP status to be simultaneously permanent and revocable. Furthermore, DarkSky requires that the responsibilities and obligations of the landowner at the time IDSP status is achieved are incumbent upon all future landowner(s) if a participating Park is sold or its title is otherwise transferred to any other public or private owner. A new owner or owners may unilaterally withdraw from participation in the program at any time by indicating these wishes in writing; otherwise, DarkSky will hold a new owner or owners accountable to the provisions of these guidelines in perpetuity.

Any failure of new ownership to abide by the conditions for continued participation in the program laid out in this document, whether indicated by withdrawal or abandonment of responsibilities, will cause DarkSky to take action as described above ("Investigation and Due Process") which may result in the permanent revocation of IDSP status.

A.3. International Dark Sky Community Program Guidelines

DARKSKY INTERNATIONAL

5049 E Broadway Blvd, Suite 105 - Tucson, AZ 85711-3646 USA - +1 520-293-3198 - www.darksky.org

*TO PRESERVE AND PROTECT THE NIGHTTIME ENVIRONMENT AND OUR HERITAGE OF DARK SKIES THROUGH
ENVIRONMENTALLY RESPONSIBLE OUTDOOR LIGHTING*



DarkSky

International Dark Sky Community Program Guidelines

**2018 Version
Updated September 2023**

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DEFINITION OF AN INTERNATIONAL DARK SKY COMMUNITY

An International Dark Sky Community (IDSC) is town, city, municipality, or other similar political entity that has shown exceptional dedication to the preservation of the night sky through the implementation and enforcement of quality lighting policies, dark-sky education, and citizen support of the ideal of dark skies.

GOALS FOR IDSC CREATION

- To identify communities with exceptional commitment to and success in pursuing dark sky preservation and restoration, and their promotion of quality outdoor lighting
- To promote improved outdoor nighttime quality of life for residents and visitors
- To support protection of human health, nocturnal habitats, public enjoyment of the night sky and its heritage, and/or areas ideal for professional and amateur astronomy
- To provide local, national, and international recognition for such communities
- To promote the ideals of DarkSky by encouraging communities to identify dark skies as a valuable community asset and aspiration

DESIGNATION BENEFITS

Achieving this designation brings recognition of the efforts made by the Community government, residents, and public and private organizations to protect the night sky and the nocturnal environment dependent on it. The IDSC designation enhances awareness of dark sky matters on the part of Community residents and visitors.

Designation as an IDSC entitles the Community to display the International Dark Sky Community logo in official publications and promotions and on signs at entrances or within the Community, and to retain the use of this logo by other groups within the Community when identifying the area itself.¹ DarkSky will promote and highlight ongoing Community efforts to protect night skies, and will maintain pages identifying and describing all IDSCs on its website.

¹ For instance, a Community can identify itself as “Flagstaff, the world’s first International Dark Sky Community” or other words to the same effect, or an organization within the Community can state “located in Flagstaff, an International Dark Sky Community.”

ELIGIBILITY

The Community must have some type of legal organization that is officially recognized by outside groups. This can be in the form of a town, city, municipality, or other legally organized community (such as urban neighborhoods and subdivisions), but need not be an incorporated entity. Unincorporated or otherwise informally organized communities are eligible for IDSC status if their governing jurisdictions enact public policy consistent with the requirements of “Minimum Requirements for All Communities” (below) that are legally binding in at least the territory of the Community.

MINIMUM REQUIREMENTS FOR ALL COMMUNITIES

- 1) A quality comprehensive lighting policy like the IDA-IES Model Lighting Ordinance (MLO)² that includes all of the following minimum standards for permanent lighting installations^{3,4}:
 - A) Full shielding⁵ of all lighting fixtures over 1,000 initial lamp lumens⁶
 - B) A limit on the emission of short-wavelength light through one of the following restrictions:
 - i) The correlated color temperature (CCT) of lamps must not exceed 3000 kelvins; *or*
 - ii) Allowed lighting must not emit more than 25% of its total spectral power at wavelengths <550 nanometers; *or*
 - iii) The scotopic-to-photopic (S/P) ratio of allowed lighting must not exceed 1.3.
 - C) A restriction on the total amount of unshielded lighting, such as a limit on lumens per net acre or a total site lumen allowance in unshielded fixtures (or equivalent wattages)
 - D) A policy to address over-lighting. This may be accomplished by limiting the average illuminance for any outdoor application, over the entire task area, to no more than 10% over the light levels recommended by, for example, the Illuminating Engineering Society (North America), the Society of Light and Lighting (United Kingdom), or other similar organization.

² Online: <https://darksky.org/resources/guides-and-how-tos/model-lighting-ordinances/>. (Accessed 2023 Sep 25).

³ More information on developing a lighting policy may be found on the DarkSky website: <https://darksky.org/resources/guides-and-how-tos/outdoor-lighting-for-policy-makers/>. (Accessed 2023 Sep 25).

⁴ Lighting required by law under the authority of any legal jurisdiction higher than that of the Community may be formally exempted from the requirements of this section.

⁵ “Fully shielded” is defined as a light source screened and its light directed in such a way that none is emitted above the horizontal plane passing through its lowest light-emitting part.

⁶ “Initial lamp lumens” is defined as the number of lumens of light emitted by a lamp when new and not counting any depreciation of output due to the age of the lamp. This information can be found in manufacturer data sheets.

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- E) Regulations of new installations of publicly owned outdoor lighting:
- i) A provision that clearly indicates where, when, and under what circumstances new publicly owned outdoor lighting, including street lighting, is warranted, and will be permitted; *and*
 - ii) A provision that requires that adaptive controls⁷ and/or curfews⁸ be employed in all future installations of public outdoor lighting
- F) There must be restrictions on the installation and operation of illuminated signs,⁹ including *all* of the following:
- i) Luminance levels for operation between sunset and sunrise shall not exceed 100 nits (100 candelas per square meter, cd/m²) as measured under conditions of a full white display; and
 - ii) During the first hour after sunset and during the last hour immediately preceding sunrise, sign luminance shall not exceed 100 nits (100 candelas per square meter, cd/m²); and
 - iii) Signs may only be illuminated while the associated activity is taking place; for businesses, sign illumination must be extinguished completely during the hours the business is closed; and
 - iv) The luminous or illuminated surface area of an individual sign must not exceed 18.6 square meters (200 square feet).
- G) Outdoor recreational and/or athletic field lighting may be exempted from the strict shielding and short-wavelength emission requirements above provided that *all* of the following conditions are met:
- i) Illuminating Engineering Society (IES) lighting guidelines (RP-6) are followed according to the appropriate class of play
 - ii) Field lighting is provided exclusively for illumination of the surface of play and viewing stands, and not for any other applications
 - iii) Illuminance levels must be adjustable based on the task (e.g., active play vs. field maintenance)
 - iv) Off-site impacts of the lighting will be limited to the greatest practical extent possible
 - v) A strict curfew requirement (e.g., lights must be extinguished by 10 PM (2200 h) or one hour after the end of play, whichever is later) is observed
 - vi) Timers must be installed to prevent lights being left on accidentally overnight by automatically extinguishing them

⁷ “Adaptive controls” is defined as devices such as timers, motion sensors, and light-sensitive switches used to actively regulate the emission of light from light fixtures.

⁸ “Curfew” is defined as a period of time at night during which lighting must be significantly dimmed in output or extinguished in accordance with an expected decrease in human presence.

⁹ “Illuminated sign” is defined as any informational or advertising sign that is illuminated by either internal or external means. Descriptive terms are adjusted here according to the type of illumination.

International Dark Sky Community Designation Guidelines

- H) Affects an amortization period, applicable to *all* publicly *and* privately owned lighting, to end not more than 10 years from the effective date of the outdoor lighting policy, after which all non-conforming lighting extant at the time of enactment must be brought into compliance with the policy.
- 2) Community commitment to dark skies and quality lighting as shown by:
 - A) City owned lighting conforming with, or committed to conforming with, the lighting policy (if the latter, a detailed plan with a timeline for completion in no more than five years); *and*
 - B) Municipal support of dark skies and quality lighting as demonstrated by city publications, flyers, public service announcements, funding of lighting upgrades, etc.
 - 3) Broad support for dark skies from a wide range of community organizations such as chambers of commerce, local electrical utilities, DarkSky Chapters, lighting retailers, homeowners' associations, and others.
 - 4) Community commitment to dark skies and education as shown by at least one of the following:
 - A) Planning and execution of at least two community dark sky awareness events¹⁰ per year. This may be organized through a local astronomy club, municipality, school, etc.
 - B) Inclusion of dark sky awareness documents (DarkSky brochures or Community-created brochures) with other Community informational documents for residents and visitors.
 - C) Inclusion of dark sky education in Community schools and curriculum.
 - 5) Success in light pollution control as demonstrated by at least one of the following:
 - A) Examples of a number of construction projects appropriate to the Community population and amount of new construction and renovation activity, built under the lighting policy and demonstrating its effective application
 - B) Alternative evidence of success in light pollution control, to be discussed with the International Dark Sky Places Program Manager for compliance.
 - 6) A sky brightness measurement program must be established and maintained either by the Community or by a public or private entity (e.g., university, research center, DarkSky Chapter, astronomy club) to follow the evolution of light pollution in the IDSC. Applicants are encouraged, but not required, to submit their measurements to the citizen science projects such as My Sky At Night (myskyatnight.com) and Globe At Night (globeatnight.org).
 - 7) Once established, the Community must erect and maintain appropriate signage indicating the International Dark Sky Community designation along a roadway entrance, along a footpath entrance if no roadway exists, a public gathering place such as a square or common, or at a municipal government center such as a city or town hall. If

¹⁰ Note that astronomy education events such as star parties do *not* qualify as "community dark sky awareness events" unless the presentation explicitly includes a message relating to dark skies and outdoor lighting.

approved by DarkSky International, language as an alternative to “International Dark Sky Community” may appear on the signage and in Community communications regarding the IDSC status. Once the sign is erected, a photograph documenting it must be taken and sent to DarkSky International along with a description of its location.

PROVISIONAL STATUS

In some cases, a Community interested in the program may lack all of the resources required to achieve a designation outright. If resource unavailability otherwise hinders the progress of a Community’s application, that Community may apply for and be granted Provisional status at the discretion of the DarkSky Board of Directors. Provisional status recognizes the Community’s ongoing work to become an International Dark Sky Community and is intended as a leverage point to successfully enable actions such as lighting upgrades and retrofits.

Provisional status expires after three years. At any time before the end of this period, a Community may reapply for full status. Material submitted for the removal of Provisional status may be an addendum to the initial application as long as the material includes a current assessment of the goals, outreach efforts, and lighting policy listed in the original application and clearly demonstrates that any program requirements left unmet at receipt of the Provisional status have been satisfied.

To be considered for Provisional status, send a nomination package to DarkSky International that includes *all* of the following information:

- 1) Documented intent to create and support an International Dark Sky Community (IDSC)
- 2) An enacted and legally effective outdoor lighting policy, and summary of outreach efforts to date
- 3) A description of the circumstances that currently prevent the Community from meeting the minimum IDSC requirements
- 4) An action plan describing steps the aspiring Community will take to meet all program requirements in the specified Provisional status period

IDSC APPLICATION PROCESS

NOMINATION

The nomination may be initiated by a DarkSky qualified nominator¹¹ who has personally

¹¹ A “DarkSky qualified nominator” is defined here as an individual or organization holding a DarkSky membership in good standing at the time that the IDSC application is submitted. The Community itself may join DarkSky as an

International Dark Sky Community Designation Guidelines

reviewed a Community's outdoor lighting and commitment to night sky preservation. Nominators are encouraged to correspond with DarkSky International staff and the Community throughout this process. In addition, the application must include evidence, such as in the form of a letter of support, from the Community government (e.g., mayor, council) consenting to the nomination for IDSC status.

STEPS FOR APPLICANT

1. Make initial contact with DarkSky International by phone or email to discuss the process and receive recommendations, followed by continued communications to update DarkSky International staff on progress and receive continued assistance.
2. Designate a formal point of contact (POC) person, such as a project manager, and provide their telephone number, address, and email address to DarkSky International staff. Before and after designation, any changes to this POC, or their information, must be communicated to DarkSky International immediately in order to ensure accurate communication at all times.
3. Obtain a letter of nomination from a qualified DarkSky member nominator, as well as a supporting letter from elected representatives of the Community, such as the mayor and/or council of a municipality. Solicit additional letters of support from Community organizations, clubs, groups, universities, etc.
4. Upon completion, send the application to DarkSky International staff for review of the document at least one month before the chosen submission deadline date. DarkSky International staff will confirm that the application is complete and ready for submission or return it with suggestions for improvements.
5. Submit the final application packet electronically in PDF and/or Microsoft Word format to DarkSky International staff for formal review. Submit in plenty of time for staff to review and prepare your application to make the bi-monthly deadline that you prefer, as found on the DarkSky website. Requests to rush applications will *not* be honored; planning ahead is essential if the Community wishes to meet a specific deadline.

TO BE INCLUDED IN IDSC APPLICATION PACKAGE

1. Map of the Community clearly indicating its legal boundaries, and basic factual information about the Community; *and*
2. Letters of nomination support by DarkSky qualified nominator and elected representatives of the Community such as the mayor and/or council; *and*
3. The Community's lighting policy, meeting the minimum requirements as stated in the "Minimum Requirements for All Communities" section; *and*
4. Documentation of examples of Community commitment and construction or renovation projects demonstrating effective application of the lighting policy; *and*

organizational member and self-nominate.

5. Proposed alternative wording for the IDSC (e.g., Dark Sky Village, Starry Sky City), if desired, with a justification for the request.

DARKSKY REVIEW PROCESS

Six application submission deadlines occur in each calendar year, commencing in January and continuing every other month. Before the Community's final application is submitted, it is highly recommended that the Community be in regular communication with the International Dark Sky Places Program Manager to perfect the application by the next application deadline.

The International Dark Sky Places Manager will forward applications to the International Dark Sky Places Committee (DSPC) for review. DSPC review lags the submission dates by one two-month cycle. The total elapsed time between deadline and final IDSC designation approval is approximately 10 weeks.

Endorsement of applications by the DSPC is by a 2/3 supermajority vote; otherwise, the DSPC will return applications with reasons for denial of an endorsement and specific recommendations for improvement. If endorsed, the applicants will be notified, and the International Dark Sky Places Program Manager will present the application to the DarkSky Board of Directors (BOD) for final review and approval. A waiting period of 10 calendar days then commences during which the Board of Directors has the right to deny IDSC status should it determine that any problems with the application exist.

If the BOD registers no objection within the waiting period, the IDSC designation is considered immediately awarded by DarkSky. The Community has the right to choose when the designation is made public, but it must organize the announcement to be made at the same time as the DarkSky public notice unless otherwise agreed by both parties. Along with the announcement notice, DarkSky will publish the Community's application on its website; by submitting the application, the Community acknowledges in advance that the application will be made publicly available. If an application is denied final approval by the DarkSky BOD, a letter will be sent to the applicant outlining elements of the application that need improvement along with specific recommendations for ways to remedy any problems the BOD identifies. Applications may be resubmitted for future consideration after remediation is complete. Resubmitted applications will be considered without prejudice.

DarkSky realizes that certain circumstances surrounding an IDSC application may cause some potential authors of letters of support (or opposition) to feel uneasy about publicly declaring their opinions about the IDSC designation. In the interest of providing the DSPC with as full a picture of Community sentiment about applications as possible, certain letters may be suppressed from online publication if it is felt that making the letters publicly available will subject their authors to retaliation or harassment. A prospective IDSC seeking this protection for letter-writers must make a formal written request. The International Dark Sky Places Program Manager must approve suppression of publication of any part of an application. Note that suppression of online publication does not prevent either the DSPC or the DarkSky BOD from reading all submitted letters.

POST-DESIGNATION REVIEW AND MAINTENANCE

The IDSC designation is not awarded in perpetuity. Rather, it is subject to regular review by DarkSky and possible revocation if the minimum program requirements are not maintained. More details may be found in the “Reassessment of IDSC Designation” section below.

To ensure that Communities remain exemplary in their protection and restoration of natural nighttime darkness, DarkSky will periodically reevaluate each site in the International Dark Sky Places Program. This is done to confirm that the Community continues to meet the minimum requirements and is making adequate progress toward LMP compliance goals outlined in this document.

Each designated IDSC must submit to DarkSky International a written report of its activities related to the maintenance of its designation on or before 1 October of each calendar year. The report is a short (typically less than 10-page) synopsis of the Community’s activities and initiatives during the intervening year.¹² The report should include dates and brief descriptions of any interpretive events, lighting retrofit projects, outreach efforts, etc. Samples of printed materials and press articles should also be included, if available.

Annual reports should not be burdensome to produce, as they are intended as a compilation of information accumulated throughout the year. Annual reports and supporting documentation must be submitted electronically to the International Dark Sky Places Program Manager in either PDF or Microsoft Word format. If the annual report is not received by DarkSky International in a timely fashion, DarkSky may suspend the site’s IDSC status until the annual reporting requirement has been met (see the following section). On or about 1 August and 1 September of each year, the International Dark Sky Places Program Manager will remind local contacts at each IDSC of the pending 1 October annual report submission deadline.

A designated IDSC is exempt from the annual reporting requirement in the calendar year in which the IDSC designation was awarded. If the designation is received after 1 October of a given calendar year, the IDSC’s first annual report to DarkSky International will be due on 1 October of the following calendar year.

REASSESSMENT OF IDSC DESIGNATIONS

From time to time, DarkSky receives comments from visitors to Communities that raise concerns about the veracity and timeliness of information provided to DarkSky by site administrators. DarkSky may, at its discretion, investigate claims in which it is alleged that IDSCs are not adhering to commitments made to DarkSky and to the public in their applications to the Program. This section details the DarkSky procedure for carrying out such investigations, and the rights of IDSCs in such matters.

An allegation of impropriety concerning any of the elements of participation in the Program outlined in this document is subject to DarkSky investigation and potential remedial action

¹² Examples of acceptable annual reports are available on the individual IDSC pages on the DarkSky website.

including temporary suspension and/or permanent revocation of the IDSC designation. DarkSky International staff shall perform due diligence in gathering facts concerning such allegations it deems credible, and will prepare a report of its findings for consideration by the DSPC. The DSPC commits to weighing the evidence fairly and impartially, and to seek to resolve disputes whenever possible through dialog. A Community subject to an investigation shall be notified in a timely manner and solicited for evidence contrary to the specifics of the allegation at hand. The Community will be given an opportunity to correct any deficiencies with regard to the Program guidelines established by the DarkSky investigation within a reasonable time period to be prescribed by the DSPC.

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Any IDSC so investigated has the right to review the allegations against it and all factual information collected by DarkSky pertinent to the allegations.

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To obtain reinstatement of a suspended designation, the IDSC must provide evidence to the DSPC's satisfaction that the specific issues identified by the DSPC as grounds for the suspension have been corrected and that all Program guidelines are once again met. The DSPC will consider the evidence presented by the IDSC and render a judgment to:

- Accept the reinstatement petition; *or*
- Reject the petition and recommend revocation; *or*
- Return the petition with further instructions and a defined deadline for an IDSC response.

REVOCAATION

A suspension left unresolved after one year from the date of the Board's assent to the suspension automatically becomes a permanent revocation. Revocation entails removal of the IDSC from DarkSky's roll of approved International Dark Sky Places, and from mention on the DarkSky website and in member and external communications. DarkSky reserves the right to take legal action against any former IDSC whose designation is duly revoked but continues to use the DarkSky name or logo in advertising, communications, and/or signage.

A.4. Additional Pictures and Tables

A.4.1. Roadrunner Measurements

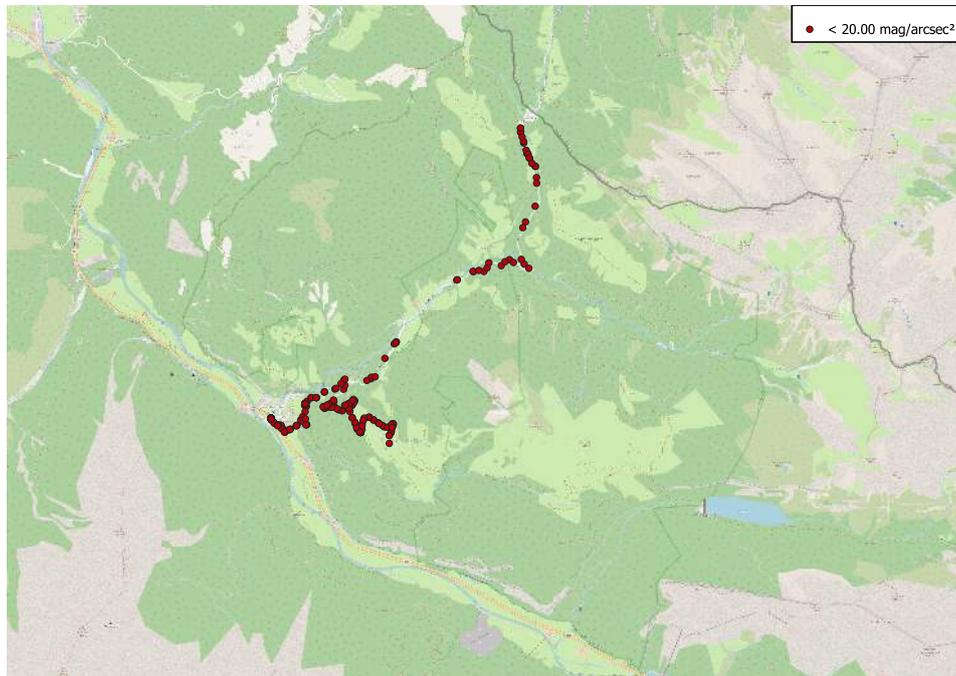


Figure A.1.: Data points below $20.00 \text{ mag/arcsec}^2$ from the first Roadrunner Measurement from 29.01.2025.

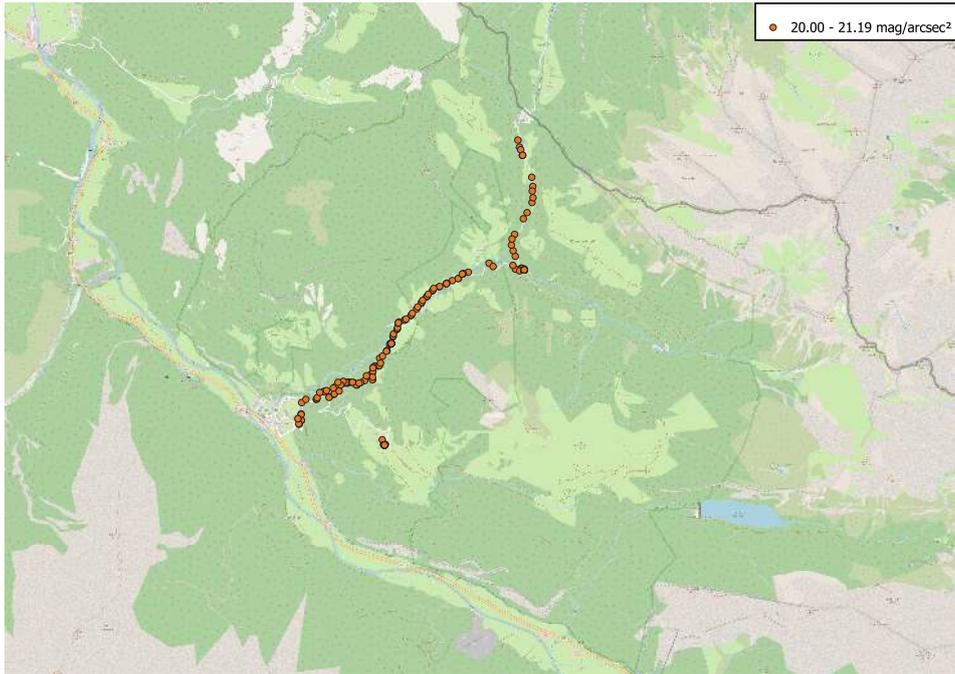


Figure A.2.: Data points between 20.00 - 21.19 mag/arcsec² from the first Roadrunner Measurement from 29.01.2025.

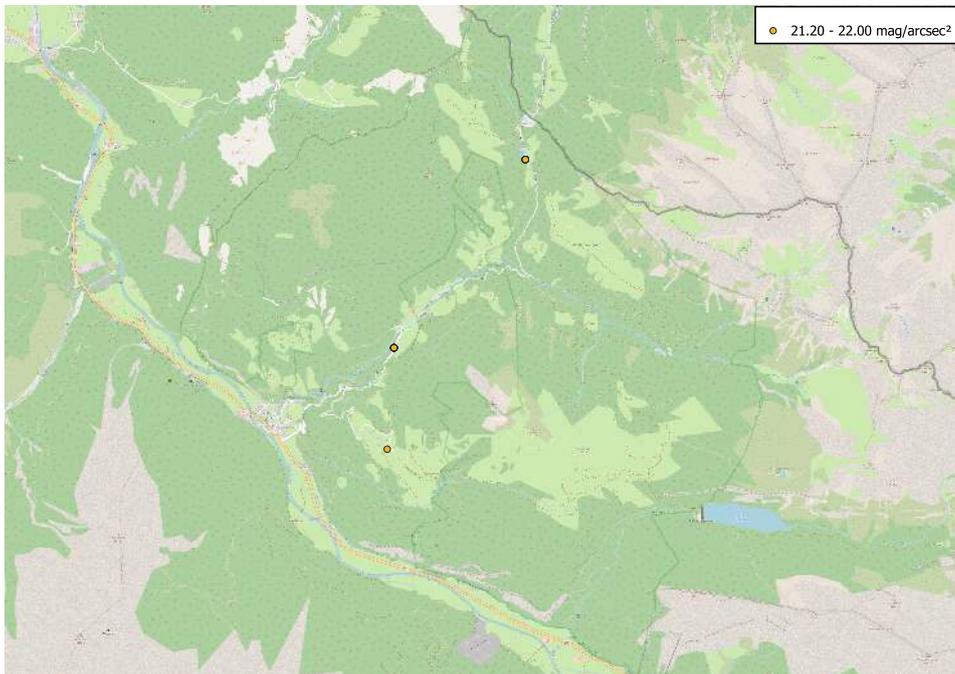


Figure A.3.: Data points between 21.20 - 22.00 mag/arcsec² from the first Roadrunner Measurement from 29.01.2025.

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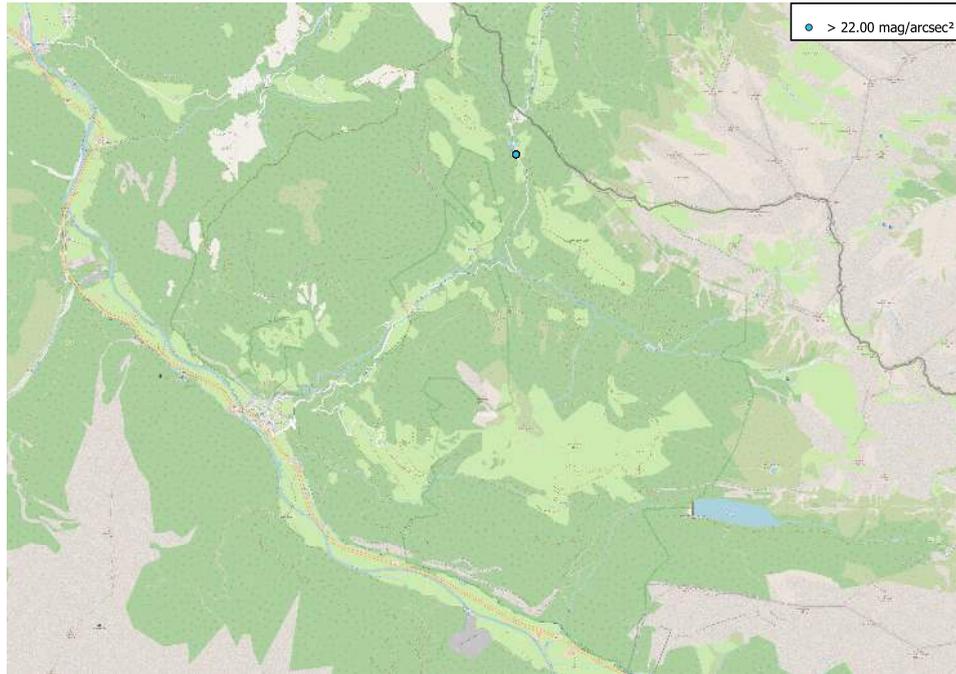


Figure A.4.: Data points above 22.00 mag/arcsec² from the first Roadrunner Measurement from 29.01.2025.

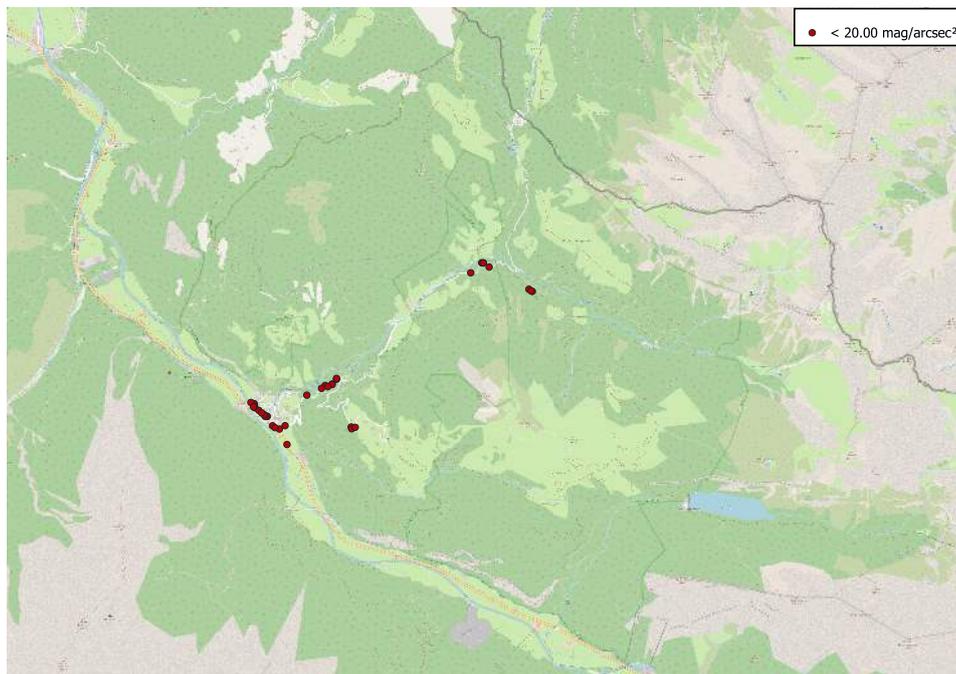


Figure A.5.: Data points below 20.00 mag/arcsec² from the second Roadrunner Measurement from 01.05.2025.

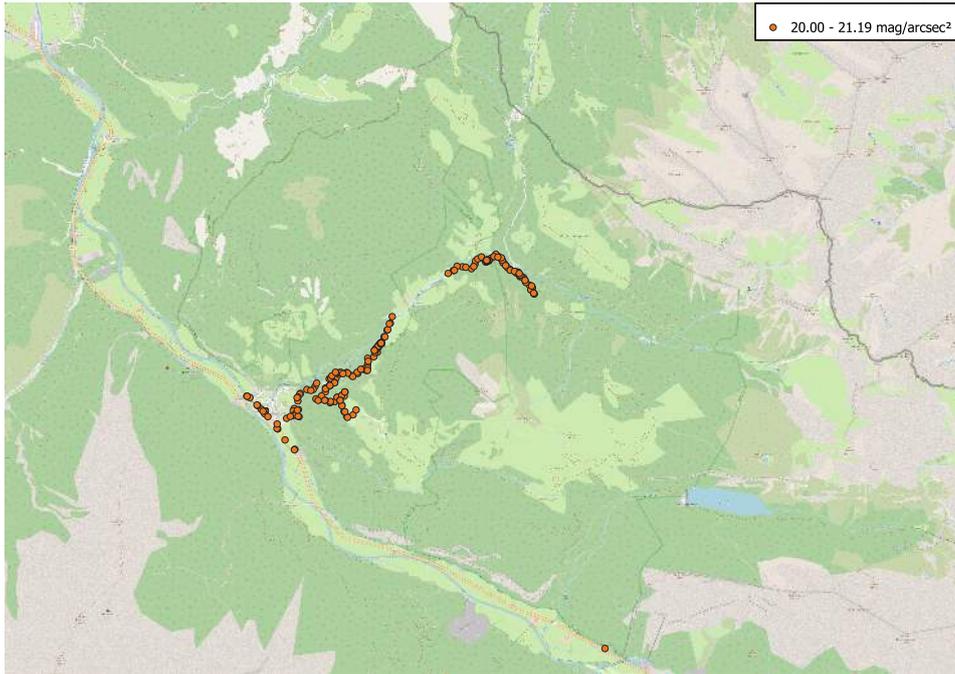


Figure A.6.: Data points between 20.00 - 21.19 mag/arcsec² from the second Roadrunner Measurement from 01.05.2025.

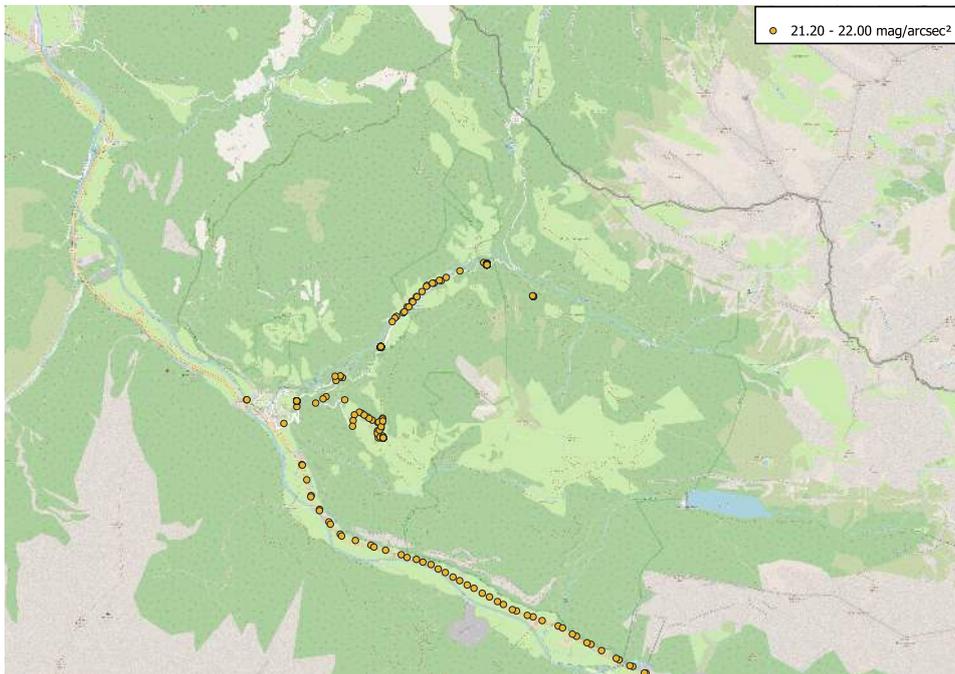
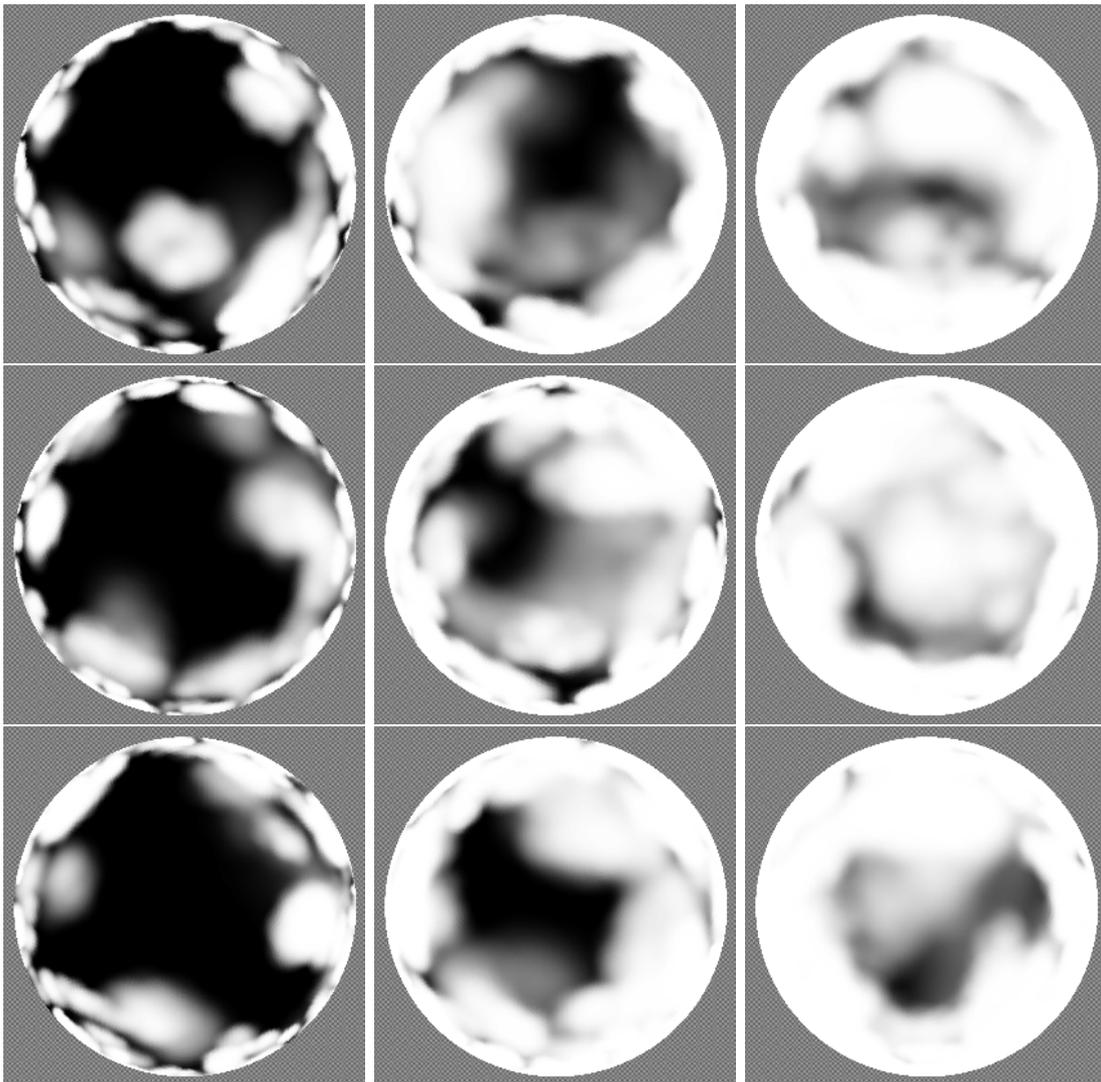


Figure A.7.: Data points between 21.20 - 22.00 mag/arcsec² from the second Roadrunner Measurement from 01.05.2025.

A.4.2. SkyGlow Simulations



(a) Cloud Fields for Cloud Fraction = 0.25 (b) Cloud Fields for Cloud Fraction = 0.5 (c) Cloud Fields for Cloud Fraction = 0.75

Figure A.8.: Comparison of SkyGlow generated cloud fields for cloud fractions 0.25, 0.5 & 0.75 for location L2: Hirschbichl.

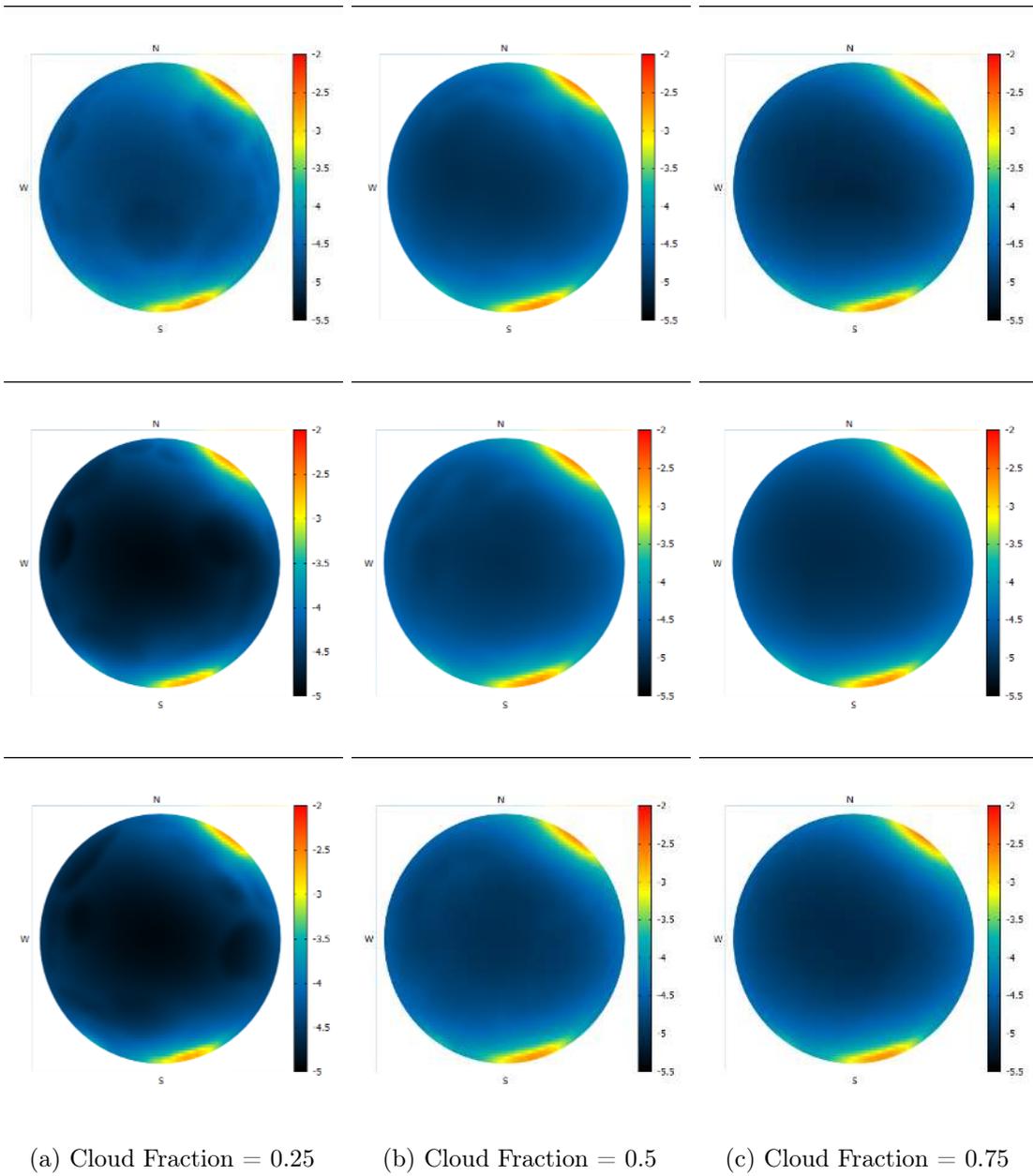
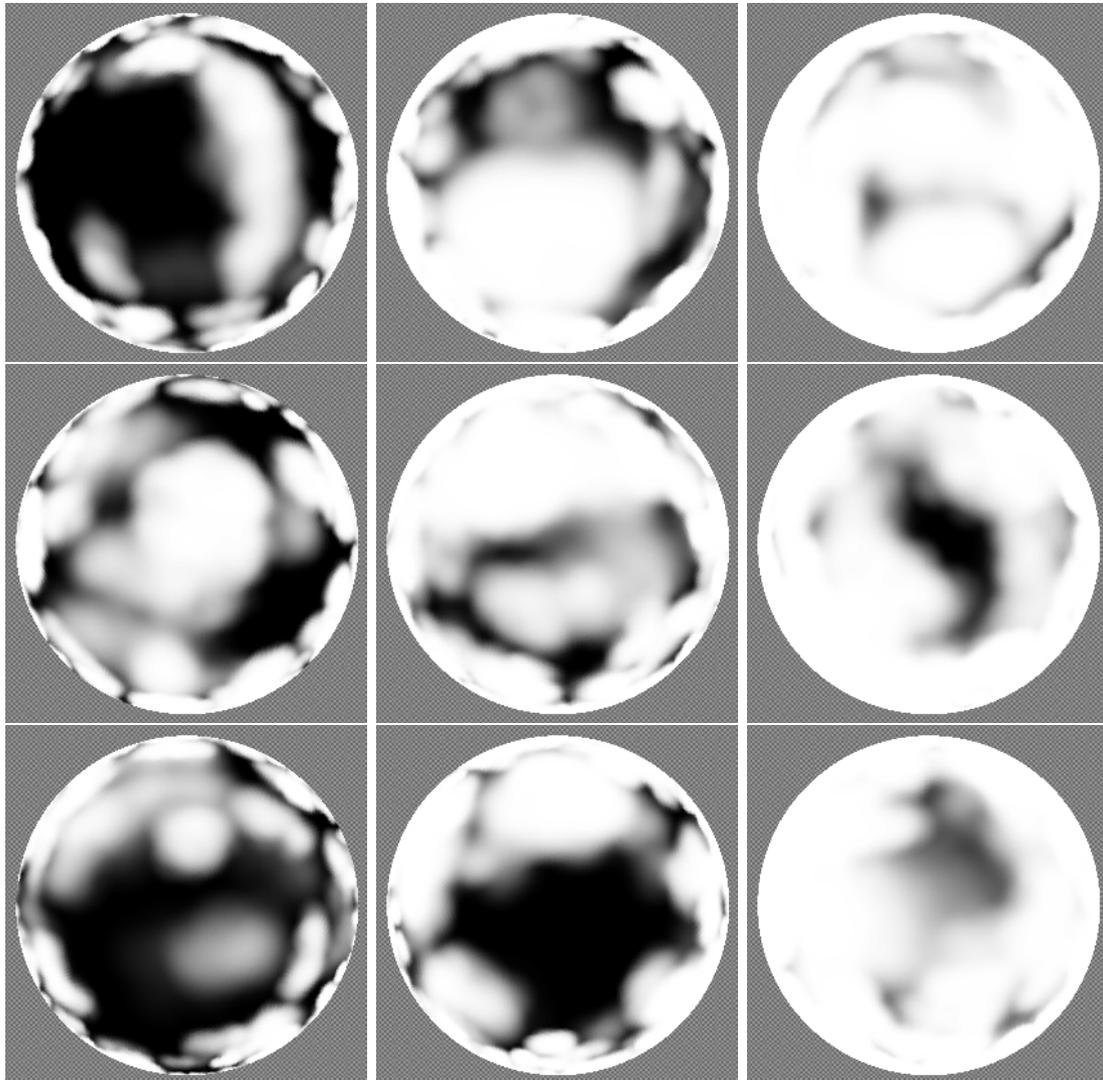
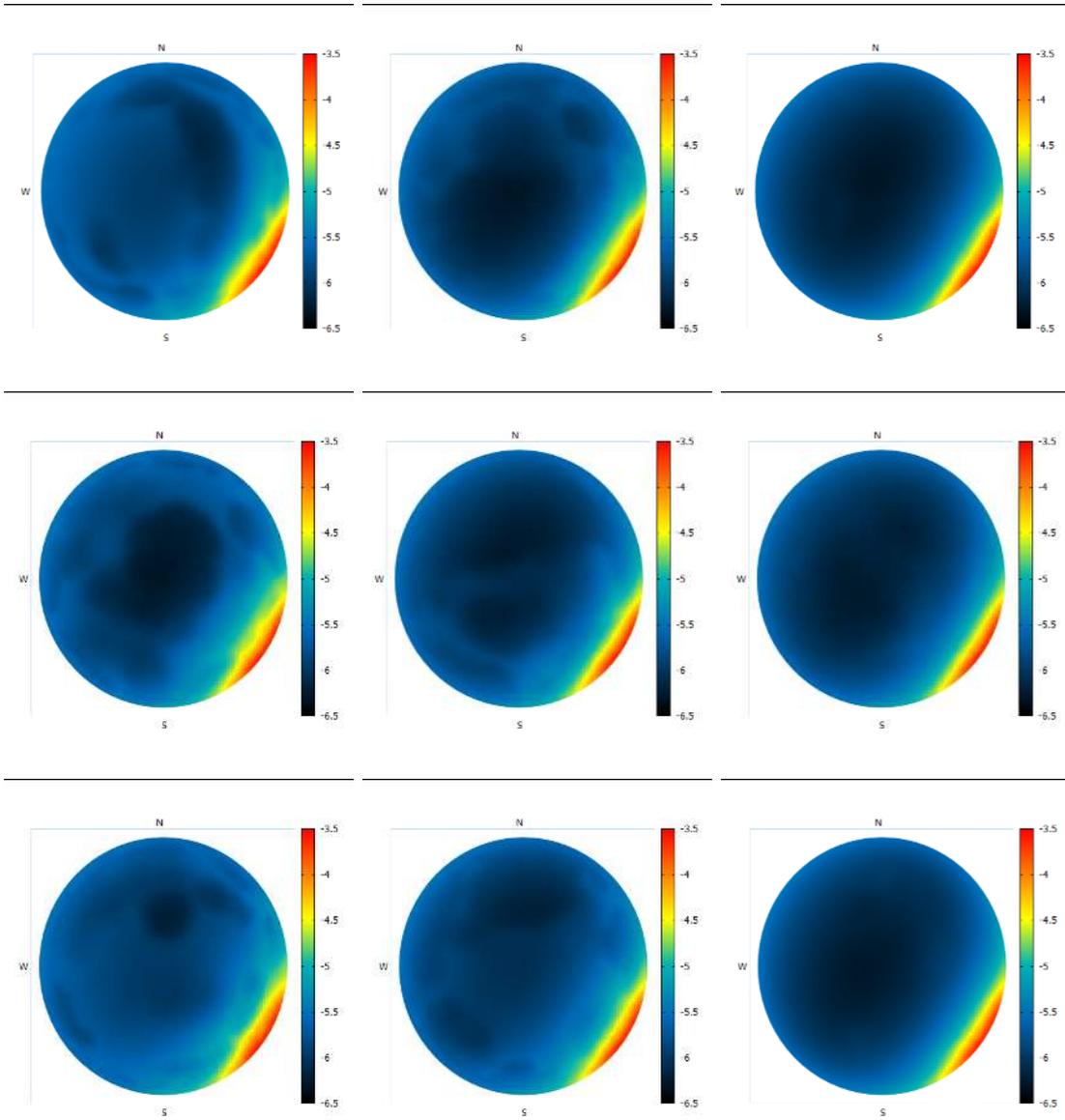


Figure A.9.: Comparison of SkyGlow simulations for cloud fractions 0.25, 0.5 & 0.75 for location L2: Hirschbichl.



(a) Cloud Fields for Cloud Fraction = 0.25 (b) Cloud Fields for Cloud Fraction = 0.5 (c) Cloud Fields for Cloud Fraction = 0.75

Figure A.10.: Comparison of SkyGlow generated cloud fields for cloud fractions 0.25, 0.5 & 0.75 for location L3: Waltmühlsäge.

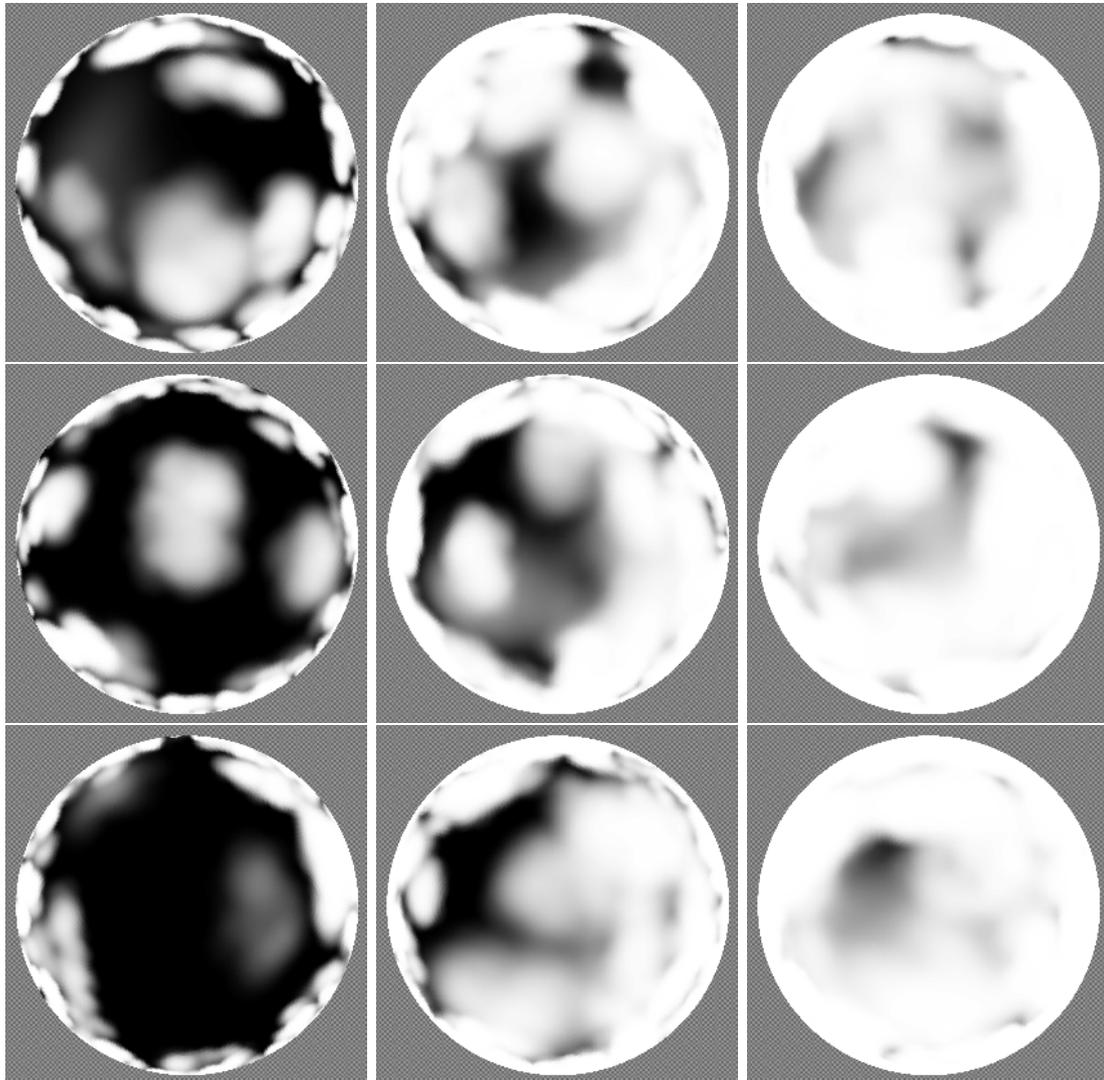


(a) Cloud Fraction = 0.25

(b) Cloud Fraction = 0.5

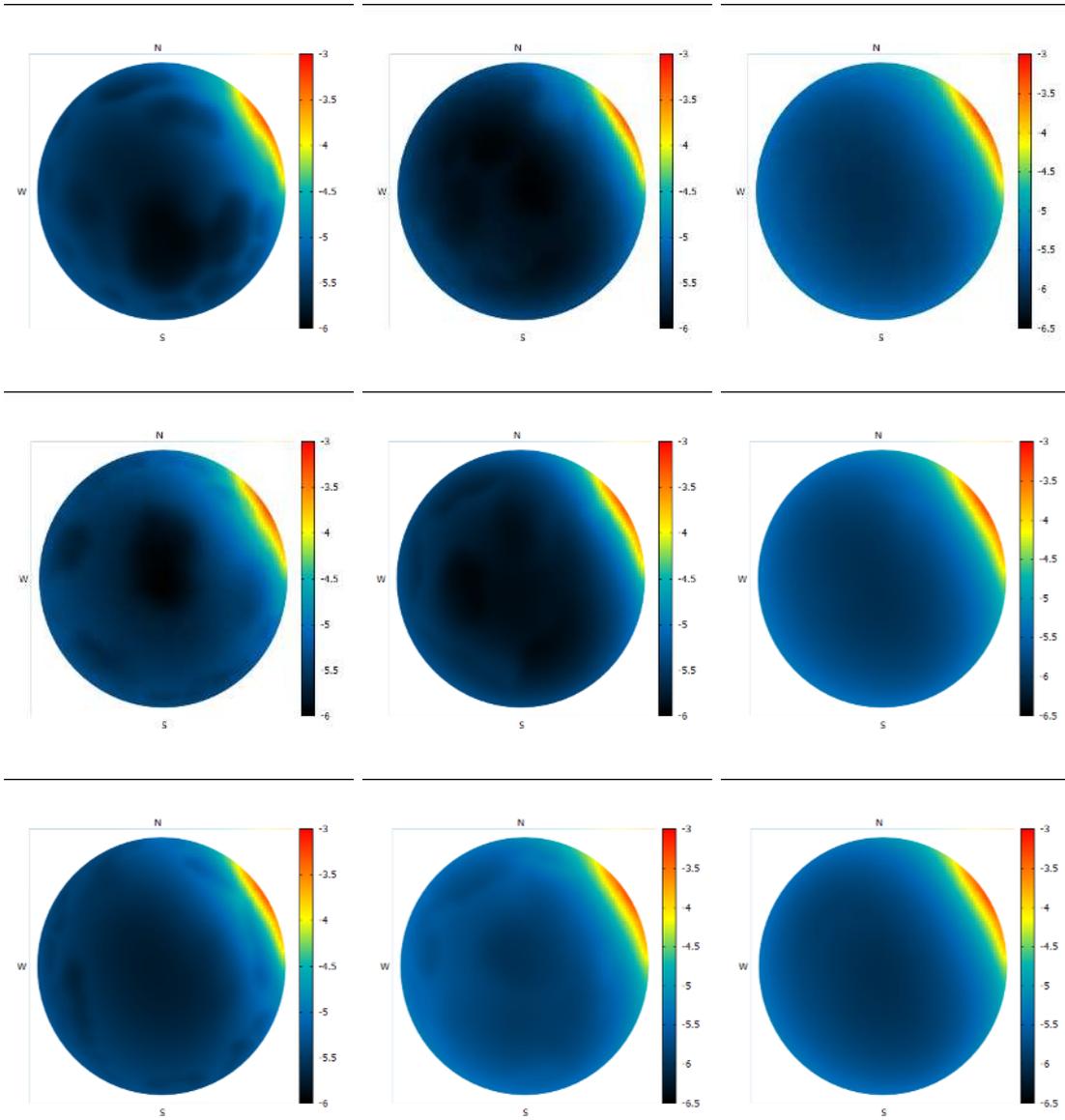
(c) Cloud Fraction = 0.75

Figure A.11.: Comparison of SkyGlow simulations for cloud fractions 0.25, 0.5 & 0.75 for location L3: Waltmühlsäge.



(a) Cloud Fields for Cloud Fraction = 0.25 (b) Cloud Fields for Cloud Fraction = 0.5 (c) Cloud Fields for Cloud Fraction = 0.75

Figure A.12.: Comparison of SkyGlow generated cloud fields for cloud fractions 0.25, 0.5 & 0.75 for location L4: Natur.Parkour.

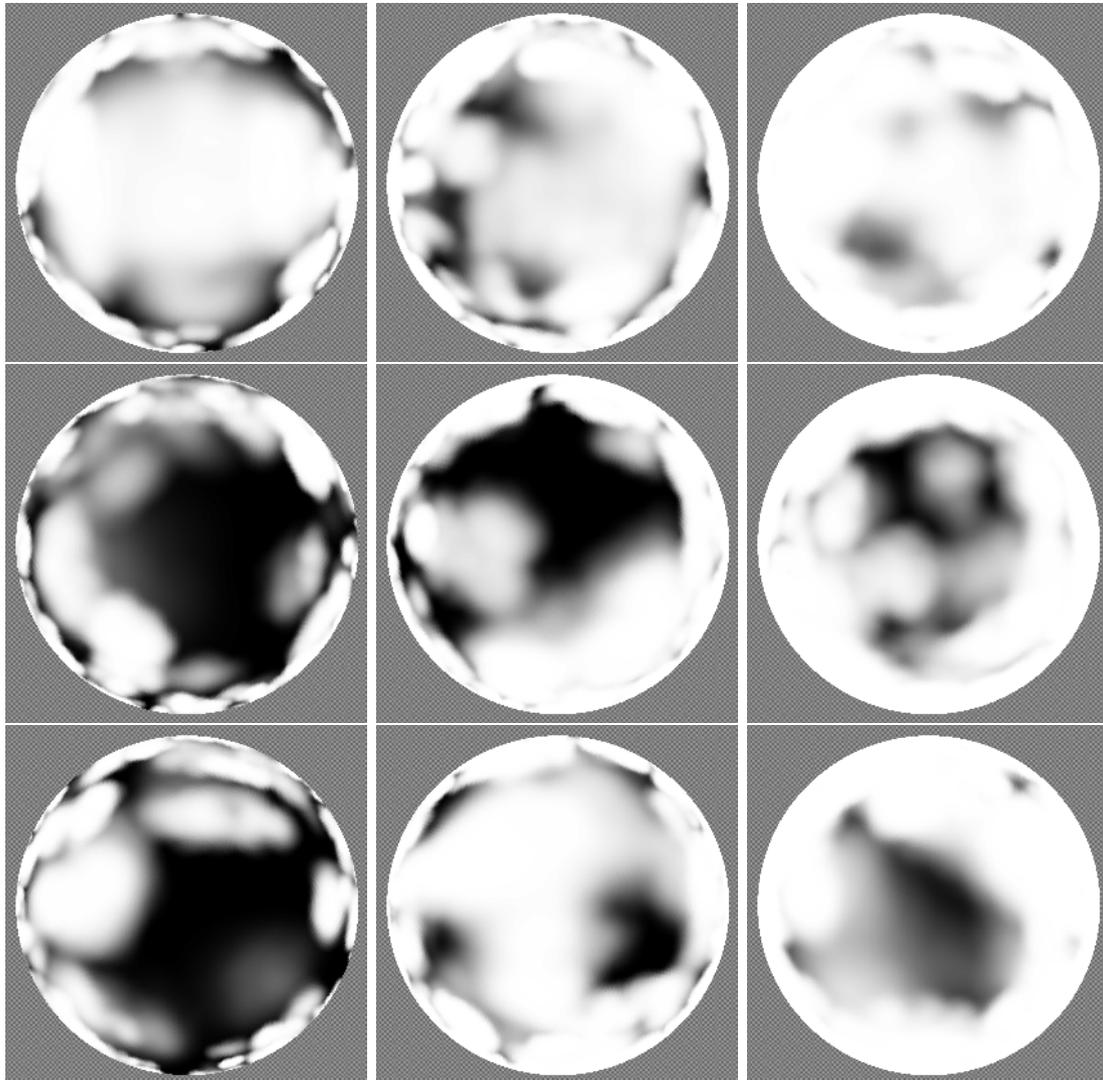


(a) Cloud Fraction = 0.25

(b) Cloud Fraction = 0.5

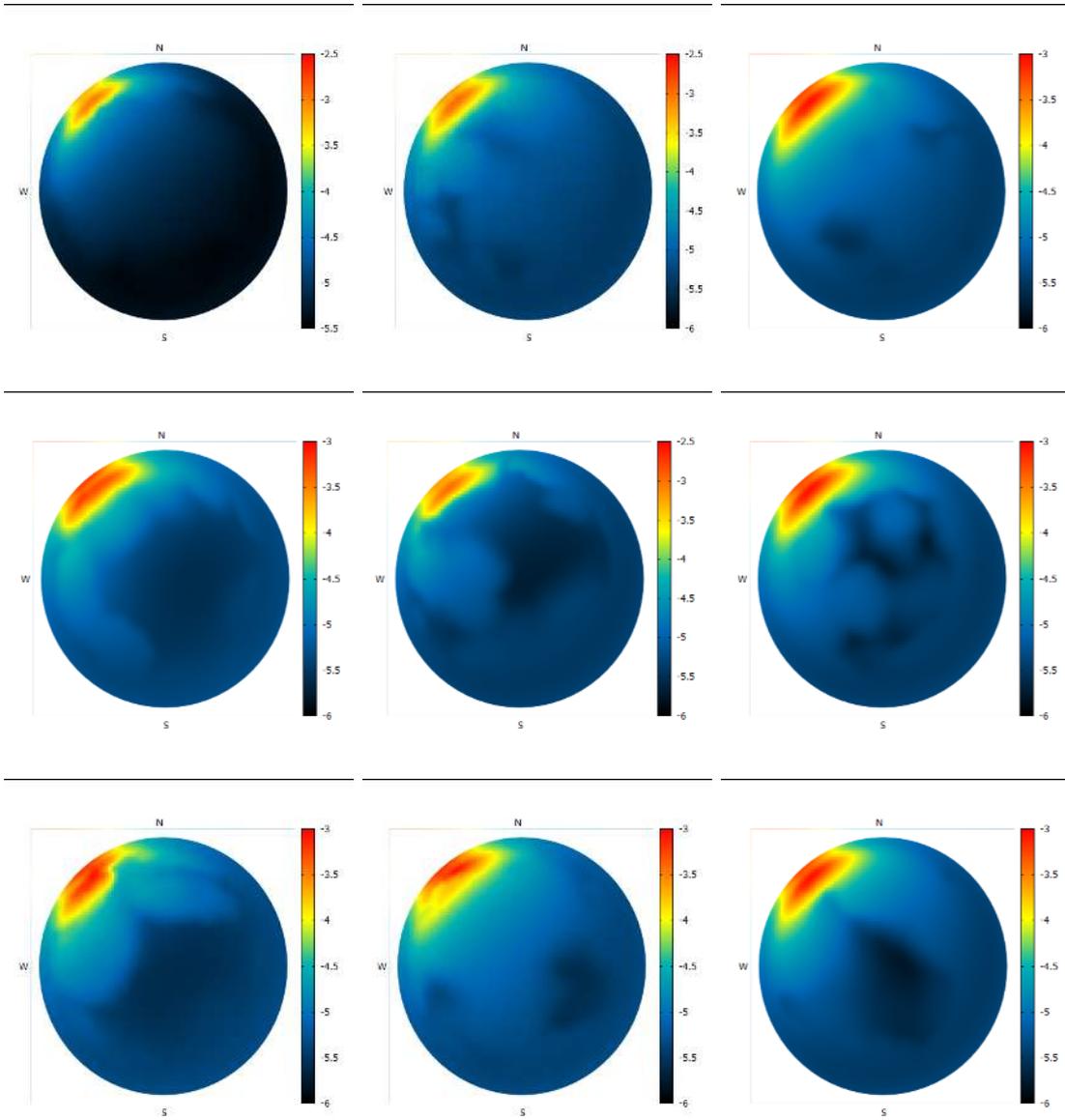
(c) Cloud Fraction = 0.75

Figure A.13.: Comparison of SkyGlow simulations for cloud fractions 0.25, 0.5 & 0.75 for location L4: Natur.Parkour.



(a) Cloud Fields for Cloud Fraction = 0.25 (b) Cloud Fields for Cloud Fraction = 0.5 (c) Cloud Fields for Cloud Fraction = 0.75

Figure A.14.: Comparison of SkyGlow generated cloud fields for cloud fractions 0.25, 0.5 & 0.75 for location L5: Pürzlbach.



(a) Cloud Fraction = 0.25

(b) Cloud Fraction = 0.5

(c) Cloud Fraction = 0.75

Figure A.15.: Comparison of SkyGlow simulations for cloud fractions 0.25, 0.5 & 0.75 for location L5: Pürzlbach.

A. Appendix

Simulation for Hirschbichl – Cloud Fraction 0.25						
Dataset	Min [cd/m ²]	Min log ₁₀	Max [cd/m ²]	Max log ₁₀	Mean 0°–10° [cd/m ²]	log ₁₀
1	9.827×10^{-6}	-5.008	3.364×10^{-3}	-2.473	1.175×10^{-5}	-4.930
2	1.169×10^{-5}	-4.932	3.365×10^{-3}	-2.473	1.193×10^{-5}	-4.923
3	1.169×10^{-5}	-4.932	3.446×10^{-3}	-2.463	1.193×10^{-5}	-4.923
Mean	1.107×10^{-5}	-4.956	3.392×10^{-3}	-2.470	1.187×10^{-5}	-4.926

Table A.1.: Luminance values for cloud fraction = 0.25 for L2: Hirschbichl.

Simulation for Hirschbichl – Cloud Fraction 0.50						
Dataset	Min [cd/m ²]	Min log ₁₀	Max [cd/m ²]	Max log ₁₀	Mean 0°–10° [cd/m ²]	log ₁₀
1	9.108×10^{-6}	-5.041	3.450×10^{-3}	-2.462	9.532×10^{-6}	-5.021
2	9.212×10^{-6}	-5.036	3.450×10^{-3}	-2.462	9.343×10^{-6}	-5.030
3	9.358×10^{-6}	-5.029	3.450×10^{-3}	-2.462	9.552×10^{-6}	-5.020
Mean	9.226×10^{-6}	-5.035	3.450×10^{-3}	-2.462	9.476×10^{-6}	-5.023

Table A.2.: Luminance values for cloud fraction = 0.5 for L2: Hirschbichl.

Simulation for Hirschbichl – Cloud Fraction 0.75						
Dataset	Min [cd/m ²]	Min log ₁₀	Max [cd/m ²]	Max log ₁₀	Mean 0°–10° [cd/m ²]	log ₁₀
1	7.342×10^{-6}	-5.134	3.450×10^{-3}	-2.462	7.670×10^{-6}	-5.115
2	8.302×10^{-6}	-5.081	3.450×10^{-3}	-2.462	8.702×10^{-6}	-5.060
3	8.134×10^{-6}	-5.090	3.450×10^{-3}	-2.462	8.265×10^{-6}	-5.083
Mean	7.926×10^{-6}	-5.101	3.450×10^{-3}	-2.462	8.212×10^{-6}	-5.086

Table A.3.: Luminance values for cloud fraction = 0.75 for L2: Hirschbichl.

Simulation for Waltmühlsäge – Cloud Fraction 0.25						
Dataset	Min [cd/m ²]	Min [log ₁₀]	Max [cd/m ²]	Max [log ₁₀]	Mean 0°–10° [cd/m ²]	Mean [log ₁₀]
1	6.595×10^{-7}	-6.18	2.918×10^{-4}	-3.53	1.012×10^{-6}	-5.99
2	4.901×10^{-7}	-6.31	2.719×10^{-4}	-3.57	5.088×10^{-7}	-6.29
3	5.873×10^{-7}	-6.23	2.756×10^{-4}	-3.56	9.976×10^{-7}	-6.00
Mean	5.790×10^{-7}	-6.24	2.798×10^{-4}	-3.55	8.394×10^{-7}	-6.08

Table A.4.: Luminance values for cloud fraction = 0.25 for L3: Waltmühlsäge.

Simulation for Waltmühlsäge – Cloud Fraction 0.50						
Dataset	Min [cd/m ²]	Min [log ₁₀]	Max [cd/m ²]	Max [log ₁₀]	Mean 0°–10° [cd/m ²]	Mean [log ₁₀]
1	4.928×10^{-7}	-6.31	2.718×10^{-4}	-3.57	5.149×10^{-7}	-6.29
2	5.155×10^{-7}	-6.29	2.718×10^{-4}	-3.57	7.142×10^{-7}	-6.15
3	5.902×10^{-7}	-6.23	2.718×10^{-4}	-3.57	8.209×10^{-7}	-6.09
Mean	5.329×10^{-7}	-6.27	2.718×10^{-4}	-3.57	6.833×10^{-7}	-6.17

Table A.5.: Luminance values for cloud fraction = 0.5 for L3: Waltmühlsäge.

Simulation for Waltmühlsäge – Cloud Fraction 0.75						
Dataset	Min [cd/m ²]	Min [log ₁₀]	Max [cd/m ²]	Max [log ₁₀]	Mean 0°–10° [cd/m ²]	Mean [log ₁₀]
1	4.914×10^{-7}	-6.31	2.718×10^{-4}	-3.57	5.157×10^{-7}	-6.29
2	5.091×10^{-7}	-6.29	2.718×10^{-4}	-3.57	5.952×10^{-7}	-6.23
3	5.086×10^{-7}	-6.29	2.718×10^{-4}	-3.57	5.418×10^{-7}	-6.27
Mean	5.030×10^{-7}	-6.30	2.718×10^{-4}	-3.57	5.509×10^{-7}	-6.26

Table A.6.: Luminance values for cloud fraction = 0.75 for L3: Waltmühlsäge.

Simulation for Natur.Parkour – Cloud Fraction 0.25						
Dataset	Min [cd/m ²]	Min log ₁₀	Max [cd/m ²]	Max log ₁₀	Mean 0°–10° [cd/m ²]	Mean 0°–10° log ₁₀
Dataset 1	1.122×10^{-6}	-5.950	5.045×10^{-4}	-3.297	1.499×10^{-6}	-5.824
Dataset 2	1.035×10^{-6}	-5.985	5.159×10^{-4}	-3.287	1.070×10^{-6}	-5.971
Dataset 3	1.666×10^{-6}	-5.778	4.945×10^{-4}	-3.306	1.713×10^{-6}	-5.766
Mean	1.274×10^{-6}	-5.895	5.050×10^{-4}	-3.297	1.427×10^{-6}	-5.846

Table A.7.: Luminance values for cloud fraction = 0.25 for L4: Natur.Parkour.

Simulation for Natur.Parkour – Cloud Fraction 0.50						
Dataset	Min [cd/m ²]	Min log ₁₀	Max [cd/m ²]	Max log ₁₀	Mean 0°–10° [cd/m ²]	Mean 0°–10° log ₁₀
Dataset 1	1.017×10^{-6}	-5.993	4.873×10^{-4}	-3.312	1.096×10^{-6}	-5.960
Dataset 2	1.112×10^{-6}	-5.954	4.873×10^{-4}	-3.312	1.303×10^{-6}	-5.885
Dataset 3	9.860×10^{-7}	-6.006	4.873×10^{-4}	-3.312	1.032×10^{-6}	-5.986
Mean	1.038×10^{-6}	-5.984	4.873×10^{-4}	-3.312	1.144×10^{-6}	-5.942

Table A.8.: Luminance values for cloud fraction = 0.5 for L4: Natur.Parkour.

Simulation for Natur.Parkour – Cloud Fraction 0.75						
Dataset	Min [cd/m ²]	Min log ₁₀	Max [cd/m ²]	Max log ₁₀	Mean 0°–10° [cd/m ²]	Mean 0°–10° log ₁₀
Dataset 1	8.937×10^{-7}	-6.049	4.873×10^{-4}	-3.312	9.264×10^{-7}	-6.033
Dataset 2	9.189×10^{-7}	-6.037	4.873×10^{-4}	-3.312	9.477×10^{-7}	-6.023
Dataset 3	9.099×10^{-7}	-6.041	4.873×10^{-4}	-3.312	9.374×10^{-7}	-6.028
Mean	9.075×10^{-7}	-6.042	4.873×10^{-4}	-3.312	9.372×10^{-7}	-6.028

Table A.9.: Luminance values for cloud fraction = 0.75 for L4: Natur.Parkour.

Simulation for Pürzlbach – Cloud Fraction 0.25						
Dataset	Min [cd/m ²]	Min log ₁₀	Max [cd/m ²]	Max log ₁₀	Mean 0°–10° [cd/m ²]	log ₁₀
Dataset 1	3.486×10^{-6}	-5.458	1.187×10^{-3}	-2.926	7.261×10^{-6}	-5.139
Dataset 2	2.421×10^{-6}	-5.616	7.084×10^{-4}	-3.150	2.766×10^{-6}	-5.558
Dataset 3	2.374×10^{-6}	-5.625	9.045×10^{-4}	-3.044	2.536×10^{-6}	-5.596
Mean	2.760×10^{-6}	-5.559	9.334×10^{-4}	-3.030	4.188×10^{-6}	-5.378

Table A.10.: Luminance values for cloud fraction = 0.25 for L5: Pürzlbach.

Simulation for Pürzlbach – Cloud Fraction 0.50						
Dataset	Min [cd/m ²]	Min log ₁₀	Max [cd/m ²]	Max log ₁₀	Mean 0°–10° [cd/m ²]	log ₁₀
Dataset 1	3.028×10^{-6}	-5.519	1.188×10^{-3}	-2.925	6.706×10^{-6}	-5.174
Dataset 2	1.984×10^{-6}	-5.703	1.185×10^{-3}	-2.926	2.329×10^{-6}	-5.633
Dataset 3	2.384×10^{-6}	-5.623	9.951×10^{-4}	-3.002	7.125×10^{-6}	-5.147
Mean	2.466×10^{-6}	-5.608	1.123×10^{-3}	-2.950	5.387×10^{-6}	-5.269

Table A.11.: Luminance values for cloud fraction = 0.5 for L5: Pürzlbach.

Simulation for Pürzlbach – Cloud Fraction 0.75						
Dataset	Min [cd/m ²]	Min log ₁₀	Max [cd/m ²]	Max log ₁₀	Mean 0°–10° [cd/m ²]	log ₁₀
Dataset 1	2.587×10^{-6}	-5.587	9.636×10^{-4}	-3.016	6.325×10^{-6}	-5.199
Dataset 2	1.696×10^{-6}	-5.771	9.635×10^{-4}	-3.016	3.295×10^{-6}	-5.482
Dataset 3	1.567×10^{-6}	-5.805	9.636×10^{-4}	-3.016	2.065×10^{-6}	-5.685
Mean	1.950×10^{-6}	-5.710	9.636×10^{-4}	-3.016	3.895×10^{-6}	-5.410

Table A.12.: Luminance values for cloud fraction = 0.75 for L5: Pürzlbach.