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AZIMUTHAL VISUALIZATION OF ARTIFICIAL LIGHT AT NIGHT (ALAN) BASED ON 3D GAUSSIAN SPLATTING

Katarzyna BOBKOWSKA[1*], Pawel TYSIAC[1], Pawel BURDZIAKOWSKI[1], Jakub SZULWIC[1], Camila Palhares TEIXEIRA[2,3], Vinícius Donisete Lima Rodrigues GOULART[3], Alexandre Túlio Amaral NASCIMENTO[2]

[1]*Faculty of Civil and Environmental Engineering, Gdansk University of Technology, Gdansk, Poland*
[2]*Transportation Research and Environmental Modelling Laboratory (TREM), Institute of Geosciences, Universidade Federal de Minas Gerais, 31270-901 Belo Horizonte, Brazil*
[3]*Departamento de Ciências Biológicas, Universidade do Estado de Minas Gerais, 32412-190 Campus Ibirité, Brazil*

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Abstract. Modeling nocturnal light environments is challenging due to the heterogeneous and strongly directional nature of artificial light emission. In this presentation, we propose a method for describing nocturnal lighting conditions based on 3D Gaussian Splatting, which enables individual light sources to be represented as continuous Gaussian primitives with parameters describing intensity, RGB color, spatial extent, and emission anisotropy. The resulting set of Gaussian splats provides a smooth and scalable representation of spatial light distribution without requiring full geometric reconstruction of the scene. In the second stage, the 3D model is projected into an azimuthal brightness profile, visualized as a circular representation corresponding to the observer's horizon. Each viewing angle reflects the cumulative perceived light from a given direction, incorporating both luminance and RGB color distribution, thereby forming a compact and intuitive depiction of the nocturnal light signature. This approach enables identification of dominant emission directions, comparison of different lighting configurations, and delineation of critical azimuthal sectors characterized by elevated light exposure. The present study was tested in a rural area, as this setting captures a wide range of artificial light emission intensities, and the results demonstrated suitability for application across diverse contexts. By using this method, it is possible to delineate areas of influence of light pollution to support decision making from a socio environmental perspective, enabling illumination only where it is necessary and with minimal associated impact. By balancing lighting requirements with the maintenance of natural environmental conditions, the model provides critical information to avoid or mitigate documented ecological impacts, including altered animal behavior and movement, interference with reproduction and foraging, increased predation risk, as well as shifts in species interactions and community structure. The proposed framework bridges modern scene-representation techniques with environmental analysis, offering a practical and transparent tool for assessing nocturnal light environments.

Keywords: Artificial Light at Night (ALAN), 3D Gaussian Splatting, azimuthal visualization, directional light environment, image-based metrics, light pollution.

1. Introduction

Artificial Light at Night (ALAN) has become an integral component of nocturnal landscapes, not only in large urban centers but also in smaller localities, rural areas, and isolated settlements. Although the environmental impacts of ALAN affecting fauna, flora, and human health have been widely documented in scientific literature, ranging from circadian disruption to altered species interactions (Burt et al., 2023; Hassan, 2024; Hearnshaw, 2024; Linares Arroyo et al., 2024; Samanta, 2023), most existing studies rely on spatially aggregated or surface-based representations of light exposure (Górniak-Zimroz et al., 2024; Kocifaj et al., 2023). Such approaches typically overlook a key characteristic of artificial illumination, its directional and spatially heterogeneous nature.

From a biological perspective, light is not perceived as an averaged value distributed across a map, but as a direction-dependent stimulus experienced by organisms moving within or inhabiting three-dimensional environments. Numerous studies have demonstrated that animals, including vertebrates and insects, respond to light intensity, spectral composition, and contrast in a strongly

* Corresponding author. E-mail: *katbobko@pg.edu.pl*

directional manner. In the case of migratory species, artificial light sources may disrupt orientation, movement, and habitat selection depending on their relative position within the landscape, rather than solely on overall illumination levels (Freas et al., 2024; Marangoni et al., 2022; Verheijen, 1960). This underscores the growing need for methods that characterize ALAN not only quantitatively but also in terms of its directional structure.

Small towns and rural environments, particularly relevant due to their proximity to complex biological habitats (Neumann et al., 2025), represent a challenging and underexplored context for ALAN analysis. Unlike large cities, where light pollution often manifests as diffuse skyglow, rural settings are characterized by sparse, heterogeneous, and highly anisotropic distributions of light sources, including individual luminaires, illuminated buildings, and infrastructure elements. Despite their limited spatial extent, such sources may become visually dominant in specific directions. Traditional mapping approaches, including raster-based light intensity products derived from satellite (Bobkowska et al., 2015; Elvidge et al., 2017; Robles et al., 2021), airborne, or UAV imagery (Bobkowska et al., 2024) , are often insufficient for capturing ecologically relevant nocturnal light signatures.

Recent advances in three-dimensional scene representation offer new opportunities to address this limitation. Among these, 3D Gaussian Splatting provides an efficient and flexible technique for representing complex environments using continuous Gaussian primitives without requiring full geometric reconstruction. While this approach has primarily been applied in computer graphics and photogrammetry, its potential for environmental analysis, particularly for modeling spatial light distributions, remains largely unexplored.

In this study, we propose a novel framework for the azimuthal visualization of nocturnal light environments by integrating scene representations derived from 3D Gaussian Splatting with image-based analysis of rendered directional views and graphical representation of the results. By projecting the reconstructed light field onto an azimuthal profile corresponding to the observer's horizon, the method captures how artificial light is perceived from multiple directions, incorporating both luminance and spectral distribution. This representation enables identification of dominant emission directions and critical azimuthal sectors associated with elevated artificial light exposure.

Importantly, the proposed approach provides a directional, scene-based characterization of ALAN that can support biological interpretation and future interdisciplinary research by offering a compact and intuitive visualization of nocturnal light signatures. The framework aims to bridge spatial light modeling, environmental management, and ecological research, supporting informed decision-making in the planning and mitigation of artificial lighting in rural landscapes.

2. Background

2.1. Artificial light at night and environmental impact

Artificial Light at Night (ALAN) is a significant factor modifying the functioning of natural environments (Gaston et al., 2013; Sanders et al., 2020). Its influence can be observed in changes in organism behavior, interspecies relationships, and ecosystem structure.

Literature indicates that artificial illumination can affect organisms at multiple levels of biological organization. Observed responses in animals include alterations in circadian activity patterns, disruption of spatial orientation, modifications of foraging and reproductive behavior, and increased predation pressure in strongly illuminated areas (Burt et al., 2023; Davies et al., 2012). Nocturnal and migratory species are particularly sensitive to these effects, as light cues play a critical role in navigation and environmental perception.

An important aspect of ALAN impact is its capacity to fragment nocturnal environments. Point light sources and illuminated structures may form barriers or "light islands," altering habitat accessibility and spatial continuity used by organisms. This phenomenon is especially relevant in rural and semi-natural landscapes, where individual lighting installations may dominate local night time conditions.

Consequently, ALAN does not merely alter illumination levels but indirectly affects the functioning of entire ecological systems. Understanding these effects requires approaches that account for the spatial and contextual nature of nocturnal light, rather than relying solely on global intensity measures (Kocifaj et al., 2023). Such perspectives represent an essential step toward assessing environmental consequences and designing strategies to mitigate the ecological impact of artificial lighting.

2.2. Spatial representation of light environments

Spatial representation of ALAN plays a crucial role in light pollution research (Levin et al., 2020). Dominant approaches rely on two-dimensional brightness distribution maps that enable analysis of emission intensity and spatial extent across different scales (Falchi et al., 2016). These representations are widely used in regional studies (e.g., UAV-based imaging) and global assessments (e.g., satellite observations), yet inherently simplify the complex structure of nocturnal light environments.

Raster-based products derived from satellite, airborne, or ground-based data represent light as a spatially averaged quantity observed from above (Elvidge et al., 2017). Such approaches neglect the directional nature of emission, limiting the ability to identify local dominant sources and evaluate their relevance from a perceptual perspective. This limitation becomes particularly pronounced in environments characterized by heterogeneous distributions of light sources.

Alternative methods, such as ground-based point measurements or modeling based on luminaire characteristics, provide more detailed descriptions of lighting conditions but are often difficult to scale and rarely account for interactions between light and landscape elements (Hänel et al., 2018; Jechow et al., 2019). Increasingly, the need is recognized for representations incorporating an observer-centric perspective, where not only the location of light sources but also their perception from specific positions and directions is considered.

Despite growing interest in three-dimensional characterization of nocturnal landscapes, robust and scalable methods for systematic directional analysis of light environments remain limited. This gap highlights the need for approaches that integrate spatial and perceptual information into a coherent representation of nocturnal light.

2.3. Image-based metrics in environmental analysis

Image-based metrics are increasingly employed in environmental research to quantitatively describe complex spatial and visual structures. They enable simultaneous characterization of intensity, contrast, structural properties, and chromatic variation, aspects difficult to capture through point measurements or spatial averages alone (Jechow et al., 2019). Across ecological and landscape analysis domains, such approaches support identification of spatial dominance patterns, evaluation of environmental heterogeneity, and assessment of perceptual conditions.

Within nocturnal light environments, image-based descriptors offer particular value by reflecting how light is perceived from specific locations and directions. Analysis of rendered directional views enables assessment not only of brightness levels but also of contrast distribution, presence of localized hotspots, and spectral variability associated with different lighting technologies. Despite this potential, image-based metrics remain rarely applied in directional ALAN analyses or combined with three-dimensional scene representation, indicating a notable research gap.

2.4. 3D scene representation and Gaussian Splatting

Three-dimensional scene representation forms the basis of many contemporary spatial and visual analysis methods. Traditional approaches based on geometric meshes or point clouds enable detailed reconstruction of scene structure but often involve high computational costs and complex processing workflows. In complex environments such as nocturnal landscapes containing multiple light sources, these methods may be difficult to apply efficiently.

3D Gaussian Splatting provides an alternative representation, describing scenes as collections of continuous Gaussian primitives. Each splat encodes local properties such as position, scale, orientation, and radiometric characteristics, enabling smooth and efficient rendering from arbitrary viewpoints (Kerbl et al., 2023). Although primarily developed for computer graphics and photogrammetry, the method's capability to faithfully reproduce complex brightness and color distributions makes it a promising tool for modeling nocturnal light environments (Burdziakowski et al., 2024).

3. Conceptual framework

In this study, the nocturnal artificial light environment is treated as a spatial and directional phenomenon whose influence depends on the relative position of the observer and their orientation with respect to emission sources. Rather than relying on descriptions based on spatially averaged surface maps, the proposed approach focuses on representing light as it is perceived from a specific location in space.

The conceptual framework assumes an observer positioned on a predefined circular trajectory surrounding the analyzed locality, at a fixed height above ground level. For successive azimuthal directions, rendered directional views of the nocturnal scene are generated, corresponding to defined viewing angles toward the center of the analyzed area. Each view represents a two-dimensional projection of a complex three-dimensional light emission structure, capturing both direct sources and effects of scattering and reflection.

The resulting set of azimuthal views enables construction of a directional brightness profile in which each angle is associated with a set of parameters describing light conditions perceived from that direction. This profile may be interpreted as a nocturnal light signature of a locality or any analyzed site (e.g., industrial installations), revealing dominant emission directions, asymmetries in light distribution, and local visual dominance patterns.

Such a representation enables comparison of alternative lighting configurations, identification of sectors characterized by elevated ALAN exposure, and assessment of potential directional influence on surrounding environments. Importantly, the approach shifts the analytical perspective from static, surface-based descriptions toward direction- and perception-oriented characterization, which is particularly relevant in the context of biological responses and lighting management in rural landscapes.

4. Methodology

To operationalize the proposed concept, a processing workflow was developed comprising data acquisition, scene modeling, directional rendering, image-based analysis, and generation of final products (Figure 1). The workflow enables transformation of observations of the nocturnal light environment into a quantitative description expressed through standardized directional descriptors.

The first stage involves data acquisition consisting of either a multi-view image set intended for 3D scene reconstruction or an independent set of azimuthal images captured from controlled observation positions. Although these datasets differ in acquisition strategy, they serve the same analytical purpose – directional assessment of lighting conditions. In the case of representation based on 3D Gaussian Splatting, observer positions can be flexibly defined after reconstruction, allowing directional views to be generated retrospectively. In contrast, when using directly acquired azimuthal imagery, the location and orientation of observation points must be carefully planned prior to data collection.

Within the modeling pathway, multi-view images are used to construct a scene representation using 3D Gaussian Splatting, enabling rendering views from arbitrary observer positions. The details of the reconstruction procedure are beyond the scope of this study and are treated as a preprocessing step providing input data.

Subsequently, observer geometry is defined by placing observation points along a circular trajectory with a specified radius and height, with camera orientation directed toward the center of the analyzed area. Directional images are generated for successive azimuths

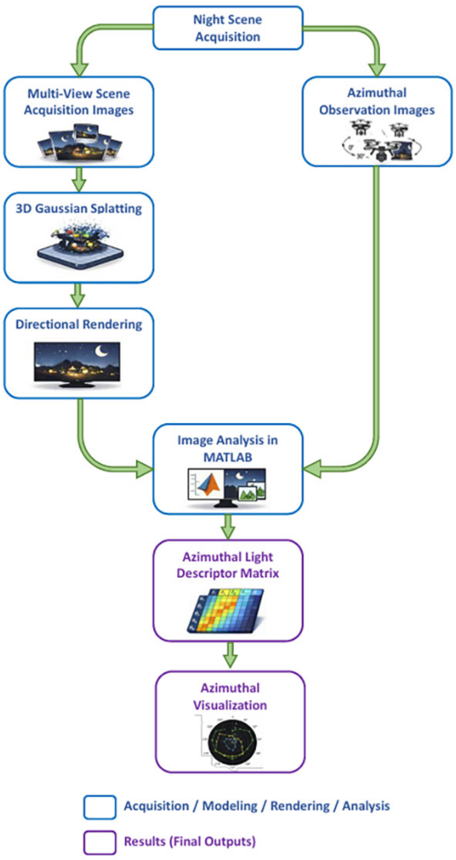

Figure 1.Workflow of the proposed azimuthal ALAN visualization method

either through rendering of the model or by using directly acquired images.

The resulting image set is analyzed in MATLAB, where descriptors characterizing intensity, color properties, and structural features of the scene are computed. The outputs are organized into the Azimuthal Light Descriptor Matrix (ALDM), whose rows correspond to observation directions and columns to image-derived features.

As a result of the implemented workflow, a set of images representing the nocturnal light environment observed from successive azimuthal directions is obtained. To enable quantitative analysis and inter-directional comparison, the images are subjected to feature extraction describing luminance properties, color distribution, and spatial structure of the scene.

A set of image descriptors based on intensity statistics, brightness distribution shape measures, chromatic indices, and textural features were employed. This selection reflects the need to capture both the global level of light emission and its heterogeneity, spectral dominance, and the presence of localized point sources. Descriptors are computed for grayscale imagery as well as for RGB channels, preserving information about the spectral characteristics of lighting. Image descriptors were calculated in MATLAB using standard image-processing functions. Their definitions follow widely established formulations and are therefore not detailed in this study.

The analyzed parameter set is summarized in Table 1. The computed values constitute the basis for constructing the Azimuthal Light Descriptor Matrix (ALDM), which synthesizes the directional light signature of the analyzed area.

The proposed set of image descriptors was selected to provide a multidimensional characterization of Artificial Light at Night (ALAN) from a directional (azimuthal) perspective. In contrast to conventional measures based solely on brightness levels or spatially averaged emission maps, the analyzed features capture both quantitative and qualitative aspects of the nocturnal light environment that are relevant from environmental and biological impact perspectives.

Table 1. Image-based descriptors extracted from rendered nocturnal scenes

Category	Descriptor (output name)	Channel	Description / interpretation	Unit / range
Intensity	Mean	Gray, R, G, B	Mean brightness level (overall exposure)	[0–1]
Intensity	Std	Gray, R, G, B	Intensity variability (global contrast)	[0–1]
Intensity	Median	Gray, R, G, B	Typical brightness level (robust to outliers)	[0–1]

End of Table 1

Category	Descriptor (output name)	Channel	Description / interpretation	Unit / range
Intensity	P5	Gray, R, G, B	Lower tail of intensity distribution (shadows)	[0–1]
Intensity	P95	Gray, R, G, B	Upper tail of intensity distribution (highlights)	[0–1]
Distribution shape	Skew	Gray, R, G, B	Asymmetry of intensity distribution	–
Distribution shape	Kurt	Gray, R, G, B	Peakedness of intensity distribution (hotspots)	–
Complexity	Entropy	Gray, R, G, B	Shannon entropy of intensity histogram	bits
Clipping	PctBlack	Gray, R, G, B	Percentage of near-black pixels (shadow clipping)	%
Clipping	PctWhite	Gray, R, G, B	Percentage of near-saturated pixels (overexposure)	%
Color	Colorfulness	RGB	Perceptual color strength (Hasler–Süsstrunk index)	relative
Color	R/G ratio	RGB	Red dominance over green (spectral proxy)	–
Color	B/G ratio	RGB	Blue dominance over green (proxy for "cool" lighting)	–
Structure	SharpVarLap	Gray	Variance of Laplacian (high-frequency content, sharp light sources)	relative
Texture	GLCM_Contrast	Gray	Local intensity contrast (spatial heterogeneity)	relative
Texture	GLCM_Homogeneity	Gray	Spatial uniformity of light distribution	relative

4.1. Directional feature representation

Let N denote the number of sampled azimuthal viewing directions around the studied locality, and let θ_n, $n \in \{1,\ldots,N\}$, denote the corresponding azimuth angles. Each direction θ_n is associated with a rendered nocturnal image I_n.

For each rendered image I_n, a set of image-based descriptors is extracted using a unified feature extraction function:

$$\varnothing : I_n \rightarrow \mathrm{x_n} \in \mathbb{R}^K, \quad (1)$$

where, $\mathrm{x_n}$ is a K – dimensional feature vector describing the perceived lighting conditions in the given viewing direction. The extracted descriptors include intensity-based, color-related, and structural image features computed from grayscale and RGB channels.

All descriptors are concatenated into a single feature vector for each viewing direction. Stacking these vectors yields the directional feature Azimuthal Light Descriptor Matrix:

$$\mathrm{ALDM} = \begin{bmatrix} \mathrm{x}_1^{\mathrm{T}} \\ \mathrm{x}_2^{\mathrm{T}} \\ \vdots \\ \mathrm{x}_N^{\mathrm{T}} \end{bmatrix} \dot{o}\mathbb{R}^{K \times N}, \quad (2)$$

where, rows correspond to azimuthal viewing directions and columns correspond to individual image-based descriptors.

This representation enables each descriptor to be analyzed as an azimuthal profile, defined by the column vector $\mathrm{ALDM}_{:,K}$ which captures the directional variability of a given lighting characteristic across the full 360° range. The resulting matrix formulation provides a compact and scalable representation of directional ALAN, suitable for statistical analysis, visualization, and identification of dominant emission sectors.

5. Study area: Ocypel, Poland

Ocypel is a small rural settlement located in northern Poland, in the Pomeranian Voivodeship, at the edge of the Tuchola Forest region. The village is surrounded by forested and agricultural landscapes, and several lakes are situated within its boundaries and immediate vicinity. Due to its remote location and limited urban development, the area is characterized by low skyglow levels, making it suitable for localized studies of ALAN.

Figure 2. Sample azimuthal renders of the scene for four viewing directions

Artificial lighting in Ocypel is primarily associated with street luminaires, individual buildings, and tourism-related infrastructure. These sources are spatially dispersed and vary in intensity and spectral composition, resulting in a heterogeneous and strongly directional nocturnal light environment. The proximity of forest ecosystems and water bodies increases the ecological sensitivity of the area. These characteristics make Ocypel an appropriate case study for evaluating azimuthal representations of nighttime light emissions in rural landscapes.

6. Results

To illustrate the operation of the proposed approach, a directional visibility analysis of the central part of the study settlement was conducted using a set of renders generated from the 3D Gaussian Splatting model. Figure 2 presents example nocturnal scenes produced for successive observation azimuths. These views do not correspond to a single, strictly predefined observer geometry – the camera position, orientation, and tilt angle may be defined by the operator during rendering depending on the analytical objective. This flexibility constitutes an important advantage of a scene representation based on a 3D model, enabling the investigation of different perceptual configurations without the need for additional field data acquisition.

In the presented example, however, unified geometric assumptions were adopted in accordance with the proposed methodology: all observations were generated at the same distance from the central reference point, while maintaining a constant camera tilt angle and fixed horizontal and vertical field of view; the only variable parameter was the observation azimuth. This ensured comparability of the resulting renders and isolated effects attributable solely to viewing direction.

The selected observation set captures visually dominant light emission sources as well as reflection effects from terrain and built surfaces. The analysis is demonstrative in nature and serves as an example application of the method for describing the directional characteristics of the nocturnal light environment.

Each generated view was subjected to image-based analysis, and the resulting values were stored in the form of a directional descriptor matrix (Azimuthal Light Descriptor Matrix – ALDM). The feature set includes measures describing luminance level, brightness statistics, chromatic properties, and spatial image structure, enabling a multidimensional characterization of Artificial Light at Night (ALAN) that extends beyond emission intensity alone.

To provide a synthetic representation of relationships between observation direction and descriptor values, heatmap visualizations were applied (Figure 3), representing a transformation of the ALDM. For graphical clarity, only selected features of highest interpretative relevance were presented, while redundant or highly correlated descriptors were omitted. Additionally, the visualization was divided into two panels: the first focusing on luminance and tonal saturation effects, and the second on chromatic properties and image structure. This separation improves interpretability by avoiding overloading a single figure with excessive information.

The analysis reveals an asymmetric structure of the light environment, maxima of luminance and contrast appear in selected azimuthal sectors, whereas other

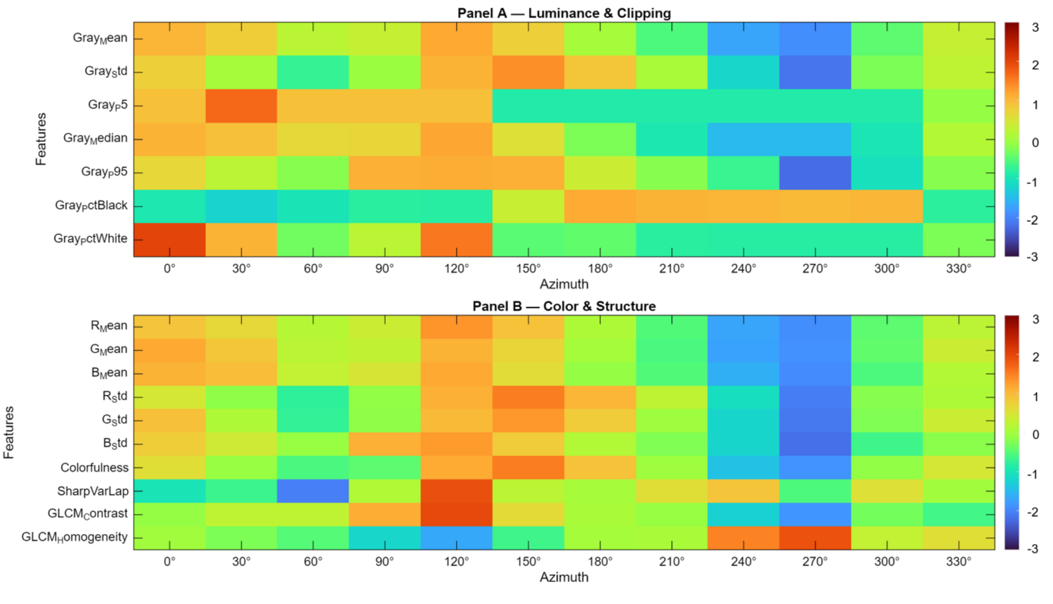

Figure 3. Heatmap visualization of selected Azimuthal Light Descriptor Matrix (ALDM) features as a function of viewing direction. Panel A summarizes luminance distribution and clipping-related descriptors, while Panel B presents color balance and structural scene metrics. Values are standardized across azimuthal directions to emphasize directional variability of nocturnal light conditions

directions exhibit markedly lower signal intensity. This confirms the directional nature of light emission in rural environments, where individual localized sources with limited spatial reach tend to dominate.

For a more intuitive interpretation of the directional structure of illumination, selected descriptors were additionally presented in the form of polar plots (Figure 4). This visualization enables direct reading of azimuthal profiles of luminance and chromatic parameters. The results indicate pronounced variability in brightness and contrast levels between observation sectors, suggesting the presence of dominant light sources associated with local infrastructure. At the same time, the distribution of mean RGB channel values reveals heterogeneity in the spectral characteristics of light, potentially reflecting the diversity of lighting technologies in use.

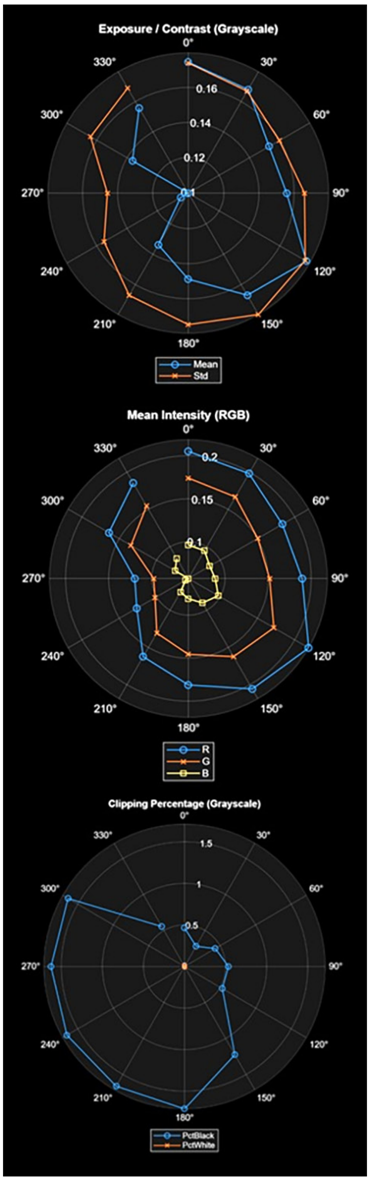

Figure 4. Azimuthal light signature of the study location represented by polar plots of selected ALDM descriptors, illustrating directional variation in luminance, spectral balance, and saturation effects

The resulting azimuthal profiles constitute a directional light signature of the study location, a synthetic description that enables identification of dominant emission directions, assessment of light environment heterogeneity, and detection of sectors potentially relevant in terms of ALAN exposure. Although the presented results concern a single demonstrative case and a local area of the village centre, they confirm the usefulness of the proposed approach for the quantitative and visual characterization of the directional structure of nocturnal light environments.

7. Discussion

The obtained results confirm that a directional representation of the nocturnal artificial light environment enables the asymmetric character of artificial light emission in small settlements to be captured. Visualizations in the form of heatmaps and polar plots reveal substantial variability in luminance, contrast, and chromatic parameters between azimuthal sectors, which can be related to the spatial distribution of local light sources such as street luminaires or illuminated buildings (Falchi et al., 2016; Gaston et al., 2013; Kyba et al., 2017; Levin et al., 2020) .

Azimuthal profiles may be interpreted as a synthetic light signature of the study area, enabling a transition from qualitative scene observation to quantitative description. This perspective is particularly relevant in an ecological context, as organism responses to light depend on direction, intensity, and spectral composition of the stimulus rather than solely on an averaged illumination level (Azevedo et al., 2025; Bobkowska et al., 2016; Davies et al., 2012; Gaston et al., 2013; Sanders et al., 2020).

Directional analyses of light have previously been conducted using hemispherical photography and zenith sky brightness observations represented in polar coordinates. While such methods allow assessment of skyglow and diffuse emissions, they do not capture the perception of the horizontal structure of environmental illumination. The proposed approach extends this paradigm by incorporating the analysis of spatial scenes and direct emission sources (Hänel et al., 2018; Jechow et al., 2019).

From a methodological standpoint, the use of a 3D scene representation enables flexible definition of observer geometry and generation of views without repeated field data acquisition, representing an advantage over approaches relying exclusively on measurement imagery. Furthermore, transforming scenes into standardized quantitative descriptors enables comparisons across locations and integration with environmental analyses (Burdziakowski et al., 2024; Kerbl et al., 2023).

It is important to acknowledge the limitations of the present analysis, the results concern a single demonstrative case and one observation configuration, and interpreting descriptors as indicators of environmental impact requires further field validation. Future work should extend the study to multiple observer heights and configurations, integration of photometric measurements, and linkage of azimuthal profiles with ecological or spatial datasets.

A key direction for further methodological development is also the standardization of the approach with respect to referencing obtained values to physical units describing light conditions. The current implementation enables reliable relative comparisons between observation directions through controlled rendering geometry and a standardized descriptor set; however, full photometric interpretation requires radiometric calibration or integration with in-situ measurements. The structure of the proposed framework provides a solid basis for such unification, opening the possibility of transitioning from relative descriptors toward quantitative indicators of illuminance or luminance in future research.

8. Conclusions

This study proposes an approach enabling a directional description of the nocturnal light environment, addressing the need to move beyond surface-based and spatially averaged representations of exposure to Artificial Light at Night (ALAN). The use of a 3D scene representation based on 3D Gaussian Splatting, combined with image-based analysis of rendered azimuthal views, allowed the heterogeneous and directional structure of light emission to be captured – a characteristic particularly relevant in rural and small-settlement landscapes.

The introduction of the Azimuthal Light Descriptor Matrix (ALDM) enabled the transition from visual observation of scenes to their quantitative characterization, encompassing luminance, contrast, as well as chromatic and structural image properties. The resulting visualizations (i.e., polar profiles and heatmaps) made it possible to identify dominant emission sectors and directional variability in lighting conditions, forming a synthetic light signature of the analyzed area.

Although the presented analysis is demonstrative in nature, the results indicate that azimuthal representation can serve as a useful tool supporting environmental research, biological interpretation, and lighting planning in landscapes. Integrating spatial scene modelling with perceptual analysis opens perspectives for developing ALAN monitoring methods that reflect the actual observational context of organisms. Future work may include methodological standardization, radiometric calibration, and linking results with ecological datasets.

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