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Development of a Skyglow Investigation System for Simulated Urban Environment

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Abstract

The emergence of Artificial Light at Night (ALAN) has generated an urban skyglow that is disturbing astronomy performances as well as the local biomes. Pricey satellite data or fancy photometers are usually used for Skyglow detection, although these systems do not capture the actual effects of city shapes and lighting configurations of the glow on a small scale. The purpose of this project was to bridge that gap by constructing a low cost, small-scale skyglow investigation system capable of simulating and quantifying light pollution in a regulated, urban-like environment. To capture readings of light illuminance, the TSL2591 High Dynamic Range Digital Light Sensor and paired with a smartphone fisheye lens as a visual support was used. The experiment consisted of multiple variables which include testing the linearity of the system with brightness levels ranging between 0 to 10, vertical attenuation between 0 to 25 cm, spatial spread with a grid scan and shielding efficiency by comparing an unshielded and shielded system. The findings indicated that there is a definite linear association between the source brightness and the skyglow and the vertical data demonstrated the existence of an Urban Canyon effect where in the reflections slow the attenuation forecast. An observation of the spatial Light Dome in the unshielded form reaching its maximum zenith light with 1.48 Lux which was reduced by Full Cut-Off shielding to 0.07 Lux at 95.27 % reduction. These results confirm that our prototype is a robust instructional and exploration tool on studying the mechanics of skyglow and as an example of how geometric shielding is an essential engineering resource to address the problem of light pollution in cities.

1. Introduction

The fast proliferation of Artificial Light at Night (ALAN) has completely altered the atmosphere in the night altering a clear sky to this irritating glow known as skyglow. Giving up fire lighting and switching to the use of electricity was a huge step forward to civilization in the past and of course it came with a certain share of unforeseen ecological and astronomical issues. The overwhelming amount of artificial light impairs one's ability to view the night's stars and there are significant environmental effects [1, 2]. Skyglow is simply the lightning of the night sky through the scattering of artificial lights on the air molecules and dust and most people in cities can no longer see the Milky Way. Skyglow often occurs when artificial light is scattered back down to the ground from the atmosphere making the clear night sky look like it is glowing in amidst of the night [3]. It is not only losing pretty sight, but it is also disrupting our circadian rhythms and it is disrupting the ways of the animals navigating and reproducing [4]. Conducting astronomical study was completely impossible as the unregulated light sources were so much brighter than the natural background light that there was no way to escape the impact. The visible count of stars (with the human eye) has drastically reduced, with indications by 2025, of a total extinction of the Milky Way in most of Europe, which will have continued increase in artificial light [5].

Today we primarily observe skyglow using remote equipment such as the VIIRS satellite imagery and ground-based photometers such as the Sky Quality Meter (SQM). However, existing methods possess significant limitations. Satellite imagery often lacks the spatial resolution to analyse street-level interactions, while professional photometers like the SQM are often inaccessible for small-scale research. Furthermore, these tools cannot easily isolate specific variables [6]. In addition, such techniques are less likely to record the Urban Canyon Effect - light bouncing around stuck between buildings and the sky, causing the levels of skyglow in the local area to soar [7]. Due to such loopholes, it is increasingly demanded that there be low cost and simulation-based methods that allow the researcher to manipulate single variables, such as the shielded fixtures and the density of packing of the buildings under controlled conditions [6].

That is why this paper narrows down to the construction of a miniaturized Skyglow Investigation System to recreate the dynamics of city light pollution. We seek to measure the intensity of light sources as the cause of skyglow by measuring the scale model of a city with low-cost TSL2591 HDR digital light sensor. The study closes the gap between theory and practice of urban planning, providing strong data on the importance of geometry tweaking to deliver serious reduction of upward light and revert to a cleaner night sky. The primary objectives of this study are: (i) to develop a cost-effective sensor-based system for skyglow simulation; (ii) to quantify the vertical attenuation profile of reflected light; and (iii) to evaluate the efficacy of geometric shielding in reducing upward light flux.

2. Research Methodology

2.1 Prototype Design and Setup

To replicate a real urban setting, a small and semi-closed model of a city was created. The model was placed in a box that was light tight to ensure that external light does not enter the box. The box ceiling was painted a matte white to create an effect of the scattering layer in the sky, such as clouds or aerosols to reflect light back to the sensor. An LED array was positioned at the bottom to replicate the appearance of city lights.

(a) (b)

Fig. 1 The prototype as shown in (a) and the sensor top-down view as shown in (b)

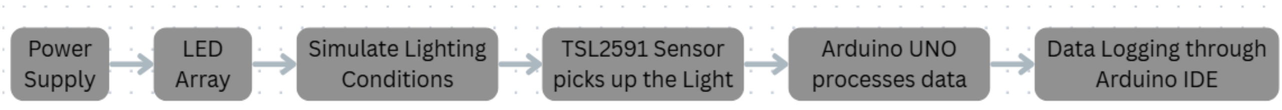


Fig. 2 Functional Block Diagram of the Skyglow Investigation System

2.2 Instrumentation

Measurements were taken with the TSL2591 high-dynamic-range digital light sensor, which measures between 188μ Lux up to 88, 000 Lux which allows for precise low-light detection essential for skyglow monitoring. Unlike standard SQMs which provide a single integrated reading, this sensor setup allows for spatial profiling across the model's cross-section. The sensor was connected to a microcontroller through the I2C. Qualitative checks were also made using a smartphone with a clip-on fisheye lens to take wide-angle hemispheric images of the simulated sky. To minimize measurement uncertainty, the sensor was housed in a matte-black baffle to restrict off-axis stray light. An integration time of 100ms was maintained to balance sensitivity with noise reduction.

2.3 Experimental Procedure

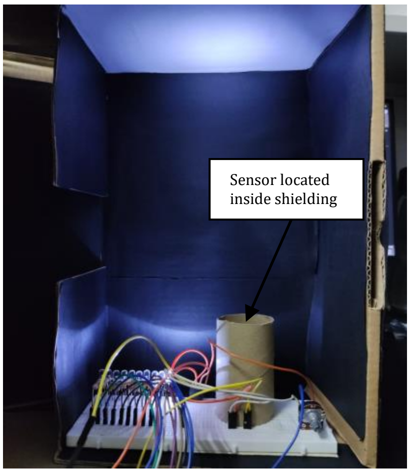
The data collection was divided into distinct factors that influence skyglow which includes the four phases:

- • **Phase 1: System Linearity Checking.** The brightness of LEDs increased on level 0 to 10 and maintained the sensor at the center (z= 0 cm). This ensured that the response of the sensor was linear with the increase in light.
- **Phase 2: Vertical Attenuation Profile.** To simulate an Urban Canyon, the sensor was moved in 5cm steps between 0cm and 25cm above the light source leaving LEDs at full brightness. This quantifies the decay and scattering of light with height.
- **Phase 3: Spatial Grid Scan.** A comprehensive grid scan was performed to visualize the volume of the skyglow. The count of illuminance was measured at a matrix of 35 coordinate points (x= -15 to +15cm, z= 0 to -20cm) at the cross-section of the model.
- **Phase 4: Shielding Efficiency Test.** The illuminance of light was carried in three conditions: Unshielded (omnidirectional light), Partial Shielding (lateral baffles), and Full Shielding (cut-off hoods which only allow light to reach the lowest point).

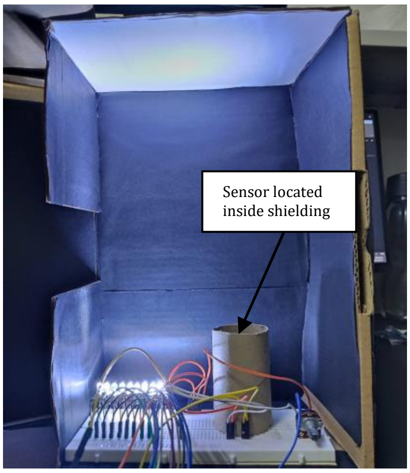
3. Result

The results consist of sensor-based quantitative results from a TSL2591 high-dynamic-range light sensor, as well as visual skyglow patterns captured via a smartphone with the aid of a fisheye lens. The aim of the observations is to show how lighting intensity, measurement distance and shielding change skyglow trends in the simulated environment. The analysis is divided into four types of analysis which includes lux versus LED brightness, lux versus vertical distance, spatial light intensity distribution and lux versus obstruction/shielding. The visual fisheye images complement the quantitative lux measurements and help to serve a qualitative characterization of the skyglow distribution. In combination, these observed results will address the function of the prototype and its efficiency as a simplified study platform for skyglow.

3.1 Illumination Level Test (Illuminance vs LED Brightness Level)



(a)



(b)

Fig. 3 Illuminance at (a) Level 1 and at (b) Level 10

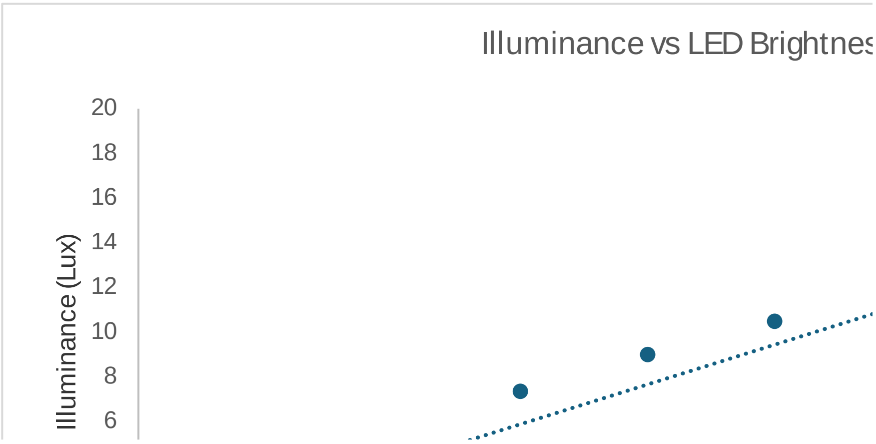


Fig. 4 Linearity verification showing the correlation between LED input levels and measured illuminance

The experimental data shows a definitive strong positive linear relationship between brightness (measured as LED input power) and measured illuminance. In Figure 3 you can see that the maximum illuminance reached with the device was 16.84 Lux at level 10 from 0.00 Lux at baseline. The steady increase in this illuminance reading indicates that TSL2591 was operating within the linear range without being saturated or hitting its limit. As highlighted by Ada (2014), this range is critical for obtaining accurate radiometric measurements [8]. The other feature of this prototype is its ability to read urban light levels with a consistency that indicates stable power supply and ability to distinguish between slight variations in urban brightness.

The results show that the prototype can simulate increasing urban brightness conditions. Higher illumination levels dramatically increase lux values, demonstrating direct proportionality between artificial light intensity and measured skyglow inside the model. This behaviour reflects real-world observations in which brightly illuminated urban areas produce stronger skyglow.

3.2 Vertical Skyglow Profile (Illuminance vs Distance of Sensor from LEDs)

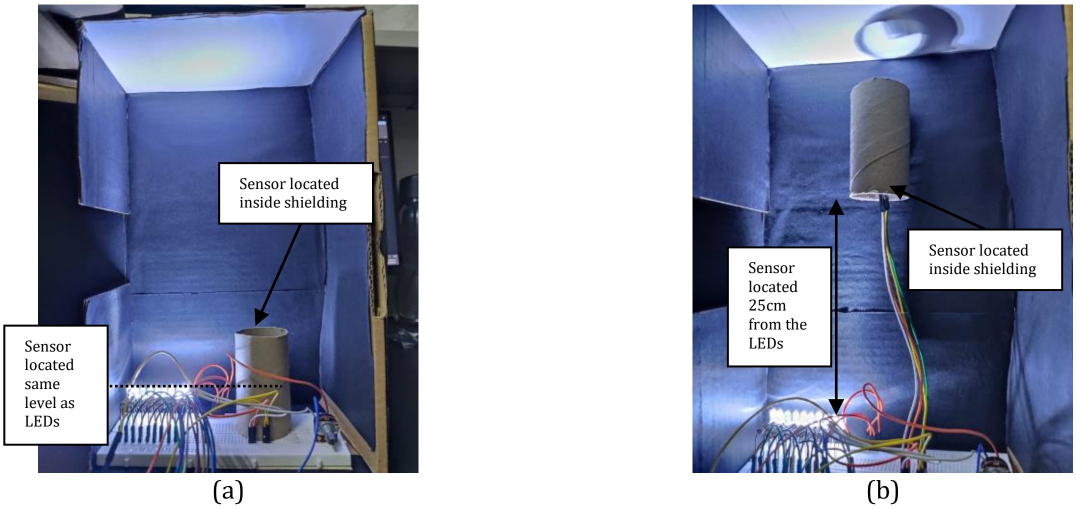


Fig. 5 Sensor at (a) 0cm and (b) 25cm from the LEDs

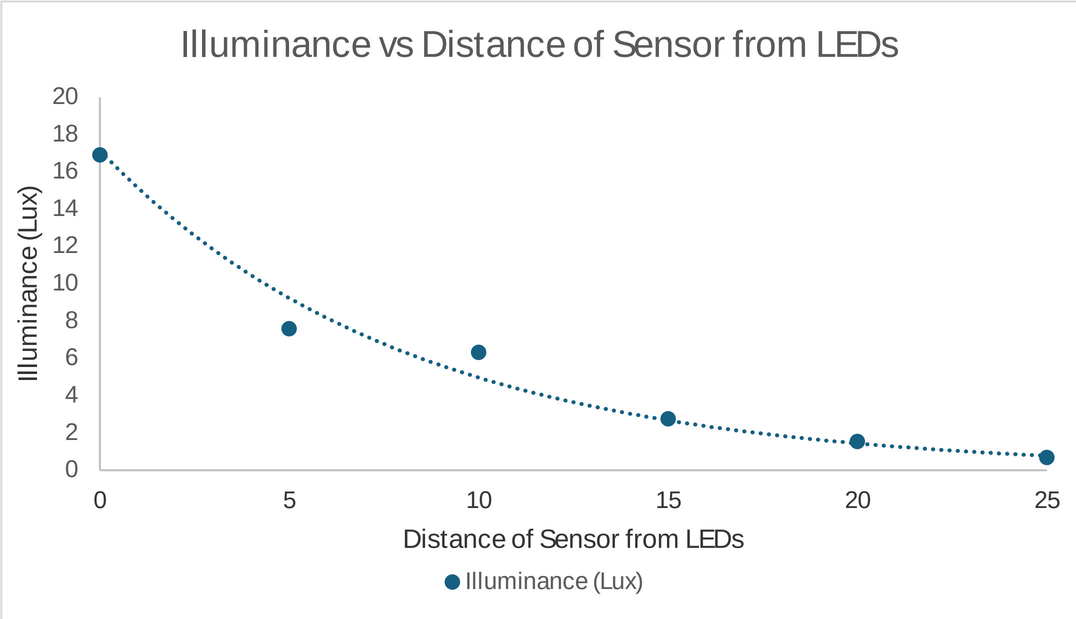


Fig. 6 Vertical attenuation profile demonstrating the decay of light due to the 'Urban Canyon' reflection effect

The data plotted in Fig. 5 for the vertical profile supports a pattern of decreasing illuminance from the increase in distance travelling from the light source. The degree of attenuation doesn't completely follow a theoretical model (the Inverse Square Law: $1/R^2$) that is typically used in theory for light to get to its destination but however, the attenuation still occurred. For example, measurements made at 10 cm from the unshielded light source showed that the intensity was 6.32 Lux, which is greater than what would be expected under the assumption that only direct-beam spread occurred. This finding implies that walls and ceilings surrounding the user were likely reflecting light toward the user, which reflects the Urban Canyon Effect and the atmospheric scattering described by [9]. The effect of what is referred to as "trapped" light also provides an example of how aerogels and cloud cover reflect light from city sources back down toward earth and in doing so, this maintains an elevated level of skyglow at high altitudes.

The results demonstrate that skyglow intensity decreases with distance from the light source, almost consistent with attenuation and scattering phenomena. Although the model is simplified, the pattern mimics real atmospheric scattering trends where skyglow reduces at higher altitudes.

3.3 Spatial Light Intensity Distribution

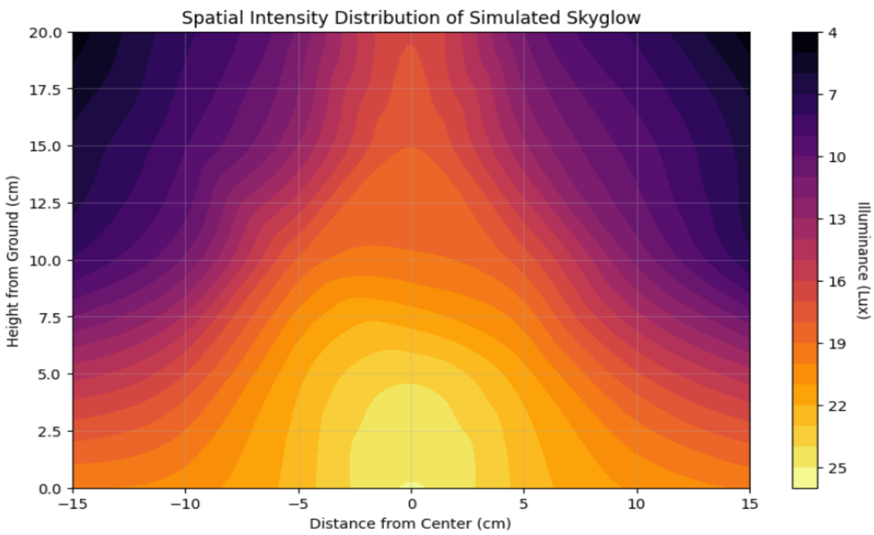


Fig. 7 Spatial heat map visualizing the 'Light Dome' intensity distribution in the unshielded setup

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According to the analysis of spatial distribution (Fig. 6), there exists a significant 'Light Dome' above the simulation of the model. The illumination level was found to be the highest, which is 25.05 Lux, at the center of the dome but it was also observed that the outer edge was illuminated to an extent of approximately 4.44 Lux where 20 cm up high and 15 cm away from the central point of the light source. This shows that the light is spreading horizontally from the light source and reflecting off the simulated sky (or ceiling) and forming a dome of light that is being seen from a distance.

The light dome shown in this study is very similar in shape to anthropogenic light domes found above actual cities such as Las Vegas when using satellite imagery, therefore confirming that the prototype has effectively simulated the scattering geometry of uncontrolled urban lighting.

3.4 Shielding Efficiency (Illumination vs Shielding)

The data is represented as Graphs in Word and Python with the help of Matplotlib and SciPy. The grid scan was processed using cubic interpolation to produce smooth 2-dimensional iso-lux contour maps (heat maps). The shielding effectiveness was quantified using the Reduction Efficiency (η) as per Equation (1):

$$\eta = \left(\frac{E_{unshielded} - E_{shielded}}{E_{unshielded}}\right) \times 100\ \% \tag{1}$$

where E represents the mean illuminance measured at the zenith.

Table 1 Shielding Condition with Illuminance

Shielding Condition	Average Illuminance (Lux)	Shielding Efficiency (%)
None	1.48	0.00
Partial Shielding	0.84	43.23
Full Shielding	0.07	95.27

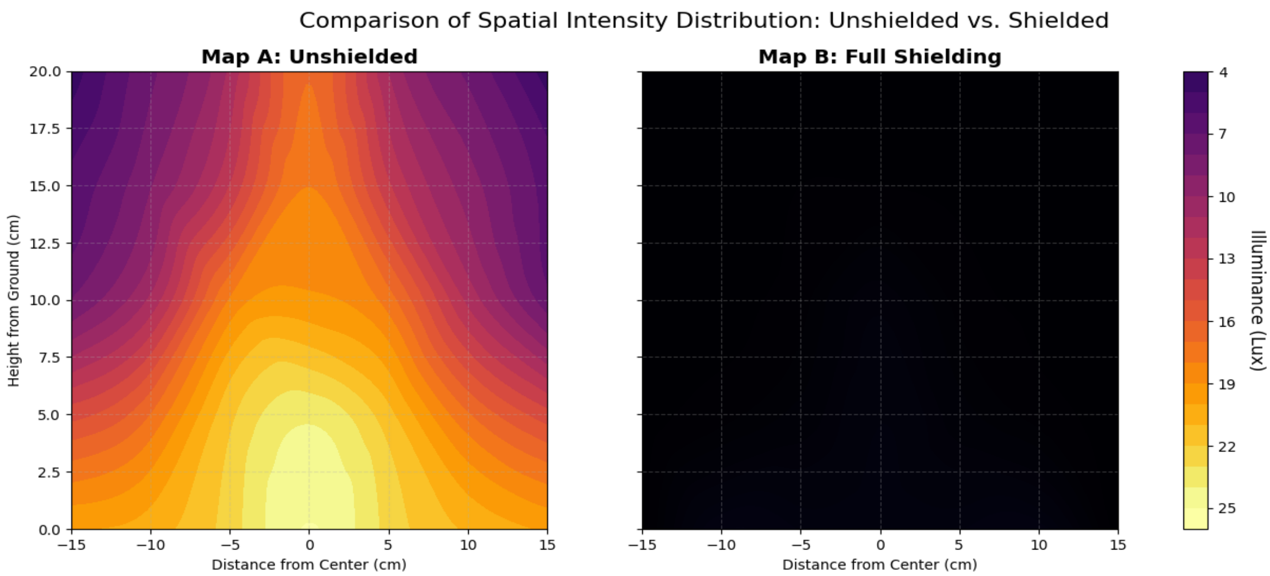


Fig. 8 Comparison Heat Map of Spatial Light Intensity Distribution for Unshielded vs Shielded

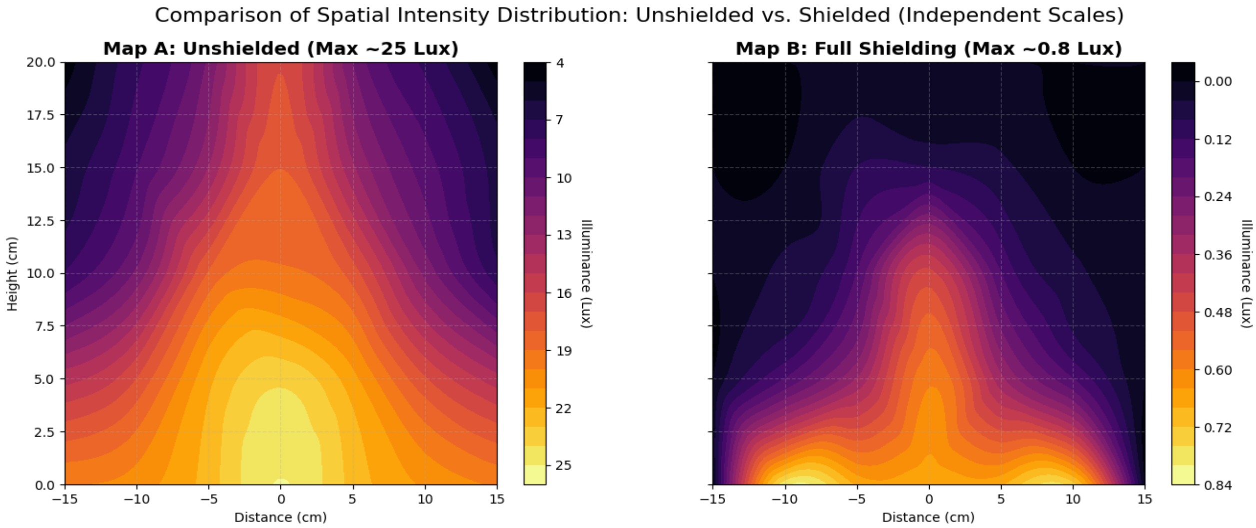


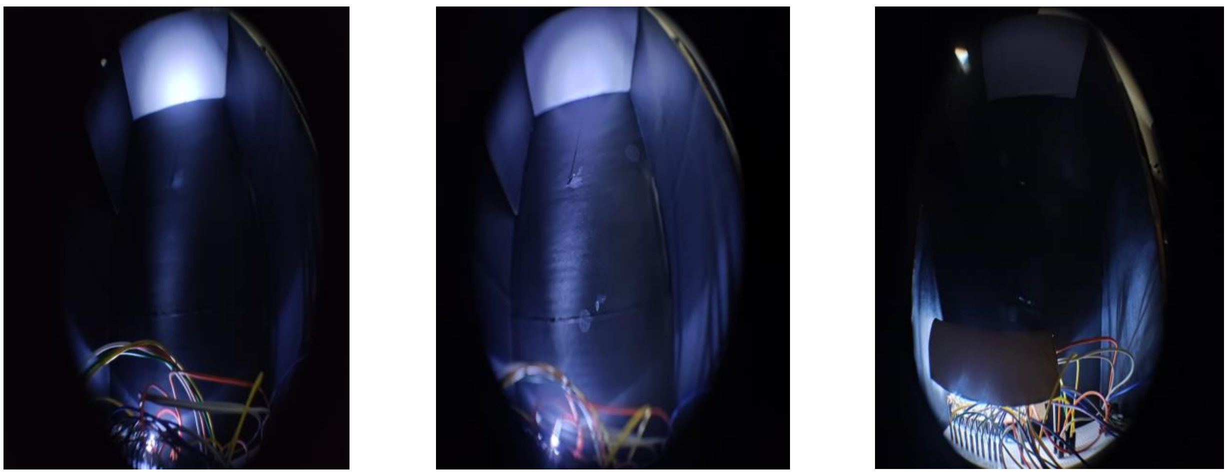
Fig. 9 Comparison Heat Map of Spatial Light Intensity Distribution for Unshielded vs Shielded with Independent Scales

Table 1 shows a comparative analysis of the effectiveness of geometric shielding in reducing light pollution. The average zenith illumination for the unshielded configuration was 1.48 Lux, compared to the average zenith illumination for the shielded configuration of 0.07 Lux. Therefore, a 95.27% reduction effectiveness was achieved with the use of full shielding.

The findings in Fig. 7 and Fig. 8 substantiate in the case of the unshielded configuration, the map displays a much more vertical distribution of luminaire light than the shielded configuration which demonstrates a concentrated distribution of luminaire light with most of the light being directed below 5 cm above the pavement surface. The results were consistent with [2], who determined that eliminating direct up light is the most effective way of eliminating skyglow. The information from the study shows that skyglow is determined largely by luminaire geometry and not necessarily by luminaire light intensity. Therefore, this provides evidence that fully cutting off fixtures can effectively assist in dark sky conservation.

The results show that shielding significantly reduces skyglow intensity. Partial shielding already produces a large reduction, while full shielding reduces lux by more than half. This behaviour reflects real-world studies where properly shielded luminaires are shown to substantially mitigate skyglow.

3.5 Visual Skyglow Analysis (Fisheye Imaging)



(a) (b) (c)

Fig. 10 Fisheye Image Overview of (a) Illuminance at Level 1, (b) Illuminance at Level 10 and (c) Fully Shielded Setup

Fig. 10 shows fisheye shots when the LEDs have varying values which indicate that there are significant variations in the brightness distribution. When the LED levels are low or at level 1, the diffuser gives little glow in the center. The image has a high central saturation and small radial dispensation of light. The fisheye images in the case of higher LED level, which is at level 10, show the diffuser and the entire inner box to be covered in the illuminance of the LEDs which gives a wider dispersion of light. In the case of the fully shielded setup of the LEDs, the model has demonstrated a remarkable reduction of the glare, less light distribution and gradient smoothness which is as well reflected from the observation in the picture and the data from the results. One thing to note is at (c), the angle at which the picture was taken seems to produce glare towards the lens in the picture which doesn't affect the observation of the illumination.

4. Conclusion

The Skyglow Investigation System development and testing have managed to address the research goals and offer a solid tool to consider the mechanics of light pollution in cities in a controlled setting. The experiment established that the intensity of the artificial source of light is linearly correlated with the measured skyglow with a correlation of about, which supported the use of TSL2591 sensor to simulate radiometric measurements. Most importantly, the experiments with the vertical attenuation profiles were able to reproduce the so-called Urban Canyon effect and showed the role of reflected light in raising skyglow levels at altitude, a process that is typically challenging to estimate in field experiments at large scale. More importantly, the feedback to this research was the quantification of the efficacy of geometric shielding to mitigate the effect. Experimental results showed that Full Cut-Off shielding was able to reduce the upward light flux on baselines by 95.27 percent. This result is empirical proof that the limiting of direct upward light is the most effective engineering solution to the minimization of urban skyglow. Moreover, sensor-based heat mapping and fisheye imaging also provided a complete approach to visualizing the "Light Dome" that fused to close this gap in the understanding of the quantitative radiometric data and visual perception. This study acknowledges certain limitations, primarily the use of a simplified reflective ceiling to simulate atmospheric scattering, which lacks the complex aerosol dynamics of real urban skies. Future work should focus on incorporating controlled aerosol simulations (e.g., mist or smoke) to model Mie scattering and conduct comparative outdoor field testing to calibrate the system against standard photometric instruments

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Yuvaneshwaran Srinivasan;* ***data collection:*** *Yuvaneshwaran Srinivasan;* ***analysis and interpretation of results:*** *Yuvaneshwaran Srinivasan, Afishah Alias;* ***draft manuscript preparation:*** *Yuvaneshwaran Srinivasan, Afishah Alias. All authors reviewed the results and approved the final version of the manuscript.*

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