An Analytical Evaluation of Traditional Techniques for Real-Time Lighting Estimation in Augmented Reality under Dynamic Illumination

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Abstract:

Accurate lighting estimation is essential for merging virtual objects naturally into real-world scenes in augmented reality (AR) applications. In this work, we compare four established techniques Spherical Harmonics, Environment Mapping, Shadow Mapping, and Light Probe-based estimation under rapidly changing outdoor lighting conditions. Our evaluation not only examines the underlying algorithms but also considers their suitability for mobile AR and their ability to adapt to illumination shifts. Experiments carried out on iPhone devices reveal that Shadow Mapping achieves the highest visual fidelity (score: 4.5) and the quickest adaptation time (120 ms), though it is prone to aliasing artifacts. Light Probe-based methods offer smoother ambient transitions but with a moderate delay (130 ms). While Spherical Harmonics maintain high frame rates (58 FPS), they lack the precision needed for fine lighting details, and Environment Mapping produces realistic reflections yet responds more slowly (180 ms). Overall, these classical approaches are lightweight and efficient but show limitations when faced with rapid changes in outdoor lighting, highlighting the need for hybrid, context-aware solutions that combine traditional stability with adaptive, modern techniques.

1. Introduction:

1.1 Background and Importance of Lighting in AR

Augmented Reality (AR) seeks to blend digital content seamlessly into real-world settings, creating experiences that feel both natural and immersive. Achieving this effect depends on more than just accurate placement of virtual objects—it also requires that these objects react convincingly to the surrounding light, shadows, and reflections [1,2]. This challenge is particularly demanding in outdoor environments, where illumination can change abruptly due to shifting sunlight, passing clouds, or physical obstructions. On mobile devices, where processing power is limited, maintaining visual coherence under such conditions demands lighting estimation methods that can adapt in real time without compromising rendering performance [3].

1.2 Traditional Techniques for Lighting Estimation

Several well-established techniques from computer graphics have been widely adopted in AR to replicate realistic lighting effects. **Spherical Harmonics (SH)**, introduced by Ramamoorthi and Hanrahan [4], provide an efficient means of representing low-frequency ambient lighting, making them a popular choice for interactive applications. **Environment Mapping**, including cube mapping [5,7], simulates reflections from panoramic images to produce visually convincing results at low computational cost. **Shadow Mapping**, developed by Williams [6], remains a standard method for creating dynamic shadows by projecting scene depth from a light source's perspective. **Light Probe-based methods** [7,8] capture illumination from real-world scenes using HDR images or virtual sensors, enabling environment-aware lighting effects.

These approaches are computationally efficient and are integrated into major AR frameworks such as Unity3D and Apple's ARKit [12,26]. However, in real-world outdoor scenarios with fast-changing illumination, complex shadows, and occlusions, their performance often declines [9,10].

1.3 Recent Machine Learning and Sensor Fusion Approaches

To address these limitations, researchers have turned to machine learning and sensor fusion. **Convolutional Neural Networks (CNNs)** can infer lighting directly from monocular images, demonstrating improved adaptability in dynamic conditions [14,15]. Notable examples include the work of Hold-Geoffroy et al. [15] and Gardner et al. [14], who developed end-to-end models for scene illumination estimation. **Sensor fusion approaches** combine data from RGB cameras, inertial measurement units (IMUs), and ambient light sensors, enhancing temporal stability and robustness [17,34]. While these modern approaches show promise, they often require significant computational resources, careful parameter tuning, and complex integration into mobile AR pipelines [21,22].

1.4 Objective and Scope of This Study

This paper presents a systematic evaluation of four traditional lighting estimation techniques—Spherical Harmonics, Environment Mapping, Shadow Mapping, and Light Probe-based methods—applied to outdoor AR scenarios using Apple iPhones and ARKit. By examining their theoretical foundations, practical implementation, and performance under dynamic illumination, this work identifies key trade-offs between efficiency, realism, and adaptability. The findings aim to inform the development of hybrid, context-aware lighting models that combine the strengths of classical techniques with the flexibility of modern approaches for next-generation mobile AR applications.

2. Related Work

Lighting estimation has long been a key challenge in both computer graphics and augmented reality (AR), influencing how convincingly virtual elements blend into real-world environments. This section first reviews the classical techniques that have provided the foundation for AR lighting and then examines recent advances in machine learning and sensor fusion designed to address the shortcomings of these traditional approaches, particularly in dynamic outdoor conditions.

2.1 Foundational Techniques in AR Lighting

Classical lighting estimation techniques remain integral to many real-time AR systems. **Spherical Harmonics (SH)**, introduced by Ramamoorthi and Hanrahan [4], offer a compact and efficient way to represent diffuse global illumination using low-frequency radiance coefficients. Their minimal computational cost makes them especially suitable for mobile devices with constrained processing power. **Environment Mapping**, first described by Kajiya and Von Herzen [5], approximates reflections and ambient lighting using cube maps or panoramic images. Debevec et al. [7] later extended this concept with image-based lighting, enabling its use in more dynamic scenes. Nonetheless, the method often assumes relatively stable lighting, leading to visible mismatches when outdoor illumination changes rapidly. **Shadow Mapping**, pioneered by Williams [6], produces shadows by projecting scene geometry from a light source's perspective. It is widely valued for generating realistic directional lighting and detailed shadow effects [11], though issues such as aliasing and limited resolution are more pronounced in mobile AR contexts [12,13]. **Light Probe-based methods**, commonly implemented in AR SDKs like Apple's ARKit, capture illumination from discrete spatial points using real-world samples or HDR maps [8,20]. While effective for enhancing ambient lighting realism, they face challenges in handling occlusions and maintaining temporal stability [10,15].

Although efficient and widely supported, these foundational approaches are less robust in outdoor environments where lighting shifts quickly and systems must respond in real time [10,21].

2.2 Modern Approaches: Machine Learning and Sensor Fusion

To address these limitations, recent research has explored **deep learning-based lighting estimation**. Methods such as Deep Outdoor Illumination Estimation [15] and Deep Parametric Indoor Lighting Estimation [14] employ convolutional neural networks (CNNs) to predict complex lighting characteristics directly from RGB images. These models often demonstrate greater adaptability to changing environmental conditions compared to traditional techniques. However, they are computationally demanding and challenging to deploy on low-power mobile AR systems. Alongside learning-based approaches, **sensor fusion techniques** combine data from multiple inputs—such as RGB cameras, inertial measurement units (IMUs), and ambient light sensors—to improve robustness and temporal stability. For example, Kan et al. [17] and Chen et al. [34] showed that integrating multi-modal inputs can reduce the errors inherent in single-sensor systems and maintain consistency during rapid lighting transitions. While these modern solutions are promising, they frequently require specialized hardware, pre-trained models, and optimized runtime environments. As a result, classical techniques continue to serve as the backbone for many commercial and research AR applications, particularly when efficiency, compatibility, and power conservation are critical.

3. Methodology

This study investigates four widely adopted techniques for real-time lighting estimation in augmented reality (AR): **Spherical Harmonics, Environment Mapping, Shadow Mapping,** and **Light Probe-based methods.** Each technique is examined with respect to its theoretical underpinnings, practical implementation, and suitability for mobile AR applications operating in dynamic outdoor environments. The analysis draws on both foundational research and recent evaluations to ensure a balanced perspective.

3.1 Spherical Harmonics

Spherical Harmonics (SH) offer a compact mathematical representation for encoding incident illumination, particularly suited for low-frequency, diffuse lighting [4]. By decomposing the surrounding radiance into a limited set of coefficients, SH enables rapid reconstruction of ambient light during rendering. This makes it effective for producing smooth shading and gradual lighting transitions on virtual objects. However, its low-pass filtering characteristics limit the capture of fine details, such as crisp shadows or pronounced highlights—features commonly encountered in outdoor AR [9,16]. Despite these limitations, SH remains popular in many AR frameworks because of its computational efficiency and suitability for mobile devices [4,9].

3.2 Environment Mapping

Environment Mapping, most often implemented via cube maps, simulates reflections and global illumination by projecting omnidirectional images of the scene onto a virtual enclosure [5]. This approach provides visually plausible reflections and ambient lighting at very low computational cost, contributing to its widespread use in both research and commercial AR systems [7,8,11]. Nevertheless, the technique generally assumes static lighting conditions, which can lead to visible inconsistencies when illumination or occlusions change rapidly in outdoor environments [11,21].

3.3 Shadow Mapping

Shadow Mapping, introduced by Williams [6], remains a principal technique for rendering dynamic shadows in interactive scenes. In AR applications, it projects depth information from the light source's viewpoint, enabling the rendering pipeline to determine accurately which regions should appear in shadow [12]. This method plays a vital role in integrating virtual and real-world elements by ensuring shadows are cast and received consistently. However, mobile implementations often face limitations such as aliasing and low resolution due to hardware constraints [12,13]. While filtering and optimization strategies can reduce these artifacts, achieving an optimal balance between visual quality and performance remains challenging [12,21].

3.4 Light Probe-based Methods

Light Probe-based methods capture real-world illumination at discrete spatial points using physical or virtual probes, often in the form of high-dynamic-range (HDR) images or irradiance maps [7,8]. These measurements are then used to adapt virtual object shading to match the surrounding environment in real time [15]. This approach is particularly valuable in mobile AR contexts where lighting conditions can change unpredictably. However, such methods can be affected by occlusions, sparse probe placement, and temporal inconsistencies when lighting shifts rapidly [10,15].

Table 1 summarizes the key attributes of these four techniques, comparing their lighting models, computational complexity, shadow rendering capabilities, and suitability for mobile platforms. Here, Complexity (Render Time) denotes the algorithm's per-frame processing cost.

Technique	**Lighting Model**	**Complexity (Render Time)**	**Shadow Support**	**Mobile Suitability**
Spherical Harmonics	Low-frequency irradiance using SH basis functions	$O(L^2)$	No	High
Environment Mapping	Reflected light via texture lookup (cube map or skybox)	O(1)	No	High
Shadow Mapping	Depth buffer comparison from light's perspective	O(M log M)	Yes	Medium
Light Probe-based	Interpolated lighting from nearby probes	O(k)	Indirect only	High

Interpretation: Environment Mapping's constant-time complexity O(1) makes it exceptionally lightweight for mobile use. Spherical Harmonics, with $O(L^2)$ complexity (where L is typically 2 or 3), strikes a practical balance between realism and efficiency. Shadow Mapping incurs the highest computational cost—O(M log M)—due to the need for scene geometry processing and depth buffer generation. Light Probe-based techniques scale with the number of probes (O(k)), offering moderate computational demand while maintaining spatial coherence in changing outdoor environments.

4. Experimental Results and Discussion

The evaluation of four traditional real-time lighting estimation techniques—**Spherical Harmonics**, **Environment Mapping, Shadow Mapping,** and **Light Probe-based**—was carried out in outdoor augmented reality (AR) environments using iPhone 13 and newer devices. All implementations were developed in Unity3D with ARKit integration and optimized through Apple's Metal API to ensure high rendering performance.

For **Spherical Harmonics,** third-order irradiance coefficients were derived using the method of Ramamoorthi and Hanrahan [4], with real-time lighting inputs sourced from ARKit's API [26]. **Environment Mapping** employed dynamic cube maps generated from panoramic captures, following the techniques of Debevec et al. [7] and Knecht et al. [8]. **Shadow Mapping** was calibrated to ARKit's sun direction estimates, with aliasing mitigated through percentage-closer filtering [6, 28]. **Light Probe-based** estimation utilized ARKit's probe API to capture and interpolate ambient lighting across user movement [29].

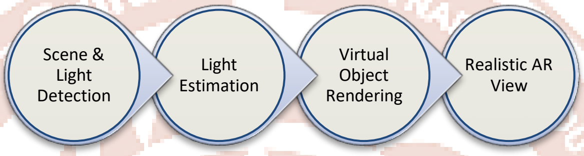

Fig. 1. Pipeline of real-time lighting estimation in augmented reality.

The experimental pipeline, illustrated in **Figure 1,** consisted of four stages: scene and light detection, lighting estimation via the chosen technique, rendering of the virtual object, and compositing the final AR output over the physical environment. Visual results in **Figure 2** reveal distinct characteristics of each method. Spherical Harmonics produced smooth, diffuse shading ideal for evenly lit conditions but lacked sharp lighting cues. Environment Mapping captured rich reflective details but often misaligned with real-time sun position. Shadow Mapping rendered highly realistic, sun-aligned shadows, though minor aliasing artifacts were visible on fine textures. Light Probe-based lighting adapted to ambient changes smoothly, yet exhibited slight temporal lag during abrupt shifts in illumination.

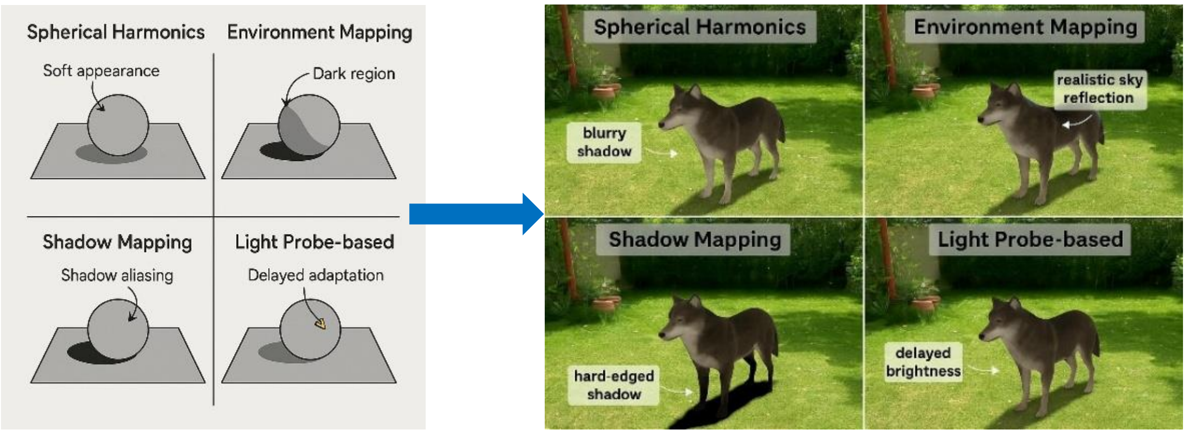

Fig. 2. Comparison of four traditional lighting techniques in outdoor AR, highlighting distinct visual effects and artifacts under the same scene conditions.

Quantitative performance, presented in **Table 2**, confirms that all methods operated at real-time frame rates, with Light Probe-based achieving the highest average FPS (59) and Shadow Mapping slightly lower at 55 FPS. Visual fidelity ratings ranged from 4.1 (Spherical Harmonics) to 4.5 (Shadow Mapping). Adaptation lag measurements (**Figure 3**) showed Shadow Mapping as the fastest to respond (120 ms), followed by Light Probe-based (130 ms) and Spherical Harmonics (140 ms). Environment Mapping had the slowest adjustment time (180 ms), making it less effective in dynamic lighting conditions.

Technique	**Avg. FPS**	**Visual Fidelity (1–5)**	**Adaptation Lag (ms)**	**Shadow Quality**	**Key Artifact**
Spherical Harmonics	58	4.1	140	Soft	Blurry or diffused shadows
Environment Mapping	57	4.2	180	N/A	Reflection mismatch, lag
Shadow Mapping	55	4.5	120	Hard-edged	Shadow aliasing, edge artifacts
Light Probe-based	59	4.3	130	Moderate	Delayed lighting response

Table 2. Quantitative performance metrics of traditional lighting estimation techniques in outdoor AR.

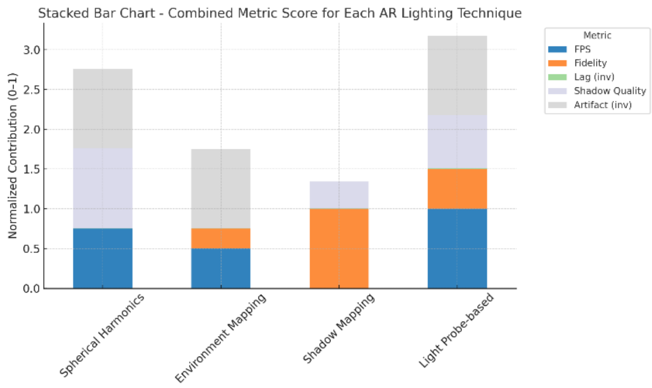

Fig. 3. Stacked bar chart showing normalized performance of AR lighting techniques on iPhone in outdoor settings.

The **stacked bar chart in Figure 3** synthesizes these results, indicating that Shadow Mapping and Light Probe-based methods offer the most balanced performance across realism, speed, and adaptability. **Figure 4** further emphasizes trade-offs: Shadow Mapping excels in directional shadow fidelity but demands higher computational resources, Light Probes adapt well to ambient changes but have minor delays, Spherical Harmonics are efficient yet lack fine-grained detail, and Environment Mapping delivers convincing reflections but struggles with dynamic updates. A summary of each technique's strengths and challenges is provided in **Table 3**.

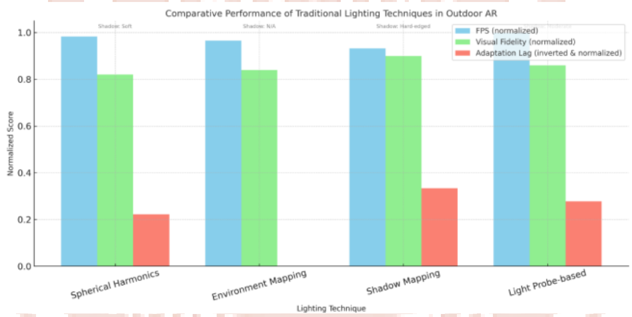

Fig. 4. Normalized performance comparison of traditional AR lighting tech-niques, highlighting trade-offs in FPS, visual fidelity, and adaptation lag.

Table 3. Strengths and challenges of traditional lighting estimation techniques in outdoor AR (iPhone + ARKit).

Technique	Strengths	Challenges
Spherical Harmonics	Smooth ambient lighting; computationally efficient	Fails in high-frequency lighting; soft shadows only
Environment Mapping	Realistic reflections; good global illumination	Lag in dynamic scenes; outdated reflections
Shadow Mapping	Accurate, sun-aligned directional shadows	Aliasing; artifacts in low-angle sunlight; resolution limits
Light Probe-based	Good ambient adaptation; seamless transitions	Delayed response under rapid lighting changes

Collectively, these findings underline that while traditional methods remain efficient and well-optimized for mobile AR, their limitations become apparent under rapidly changing outdoor illumination. The results suggest that hybrid approaches, combining the stability of classical techniques with adaptive, learning-based refinements, could provide the responsiveness and realism required for next-generation AR experiences.

5. Conclusion

This study provided a comprehensive evaluation of four traditional real-time lighting estimation techniques—Spherical Harmonics, Environment Mapping, Shadow Mapping, and Light Probe-based methods—implemented in outdoor AR environments on Apple iPhones using ARKit. The analysis spanned theoretical foundations, implementation strategies, and both quantitative and qualitative assessments. Experimental results demonstrated that Spherical Harmonics offer computational efficiency and smooth diffuse lighting but lack precision under rapid illumination shifts. Environment Mapping delivers visually appealing reflections under stable conditions yet exhibits noticeable delays in adapting to dynamic sunlight. Shadow Mapping achieves high visual fidelity with sharp, sun-aligned shadows, albeit at the cost of aliasing artifacts and greater computational demands. Light Probe-based methods present a balanced compromise, adapting smoothly to gradual ambient changes while maintaining minimal visual artifacts.

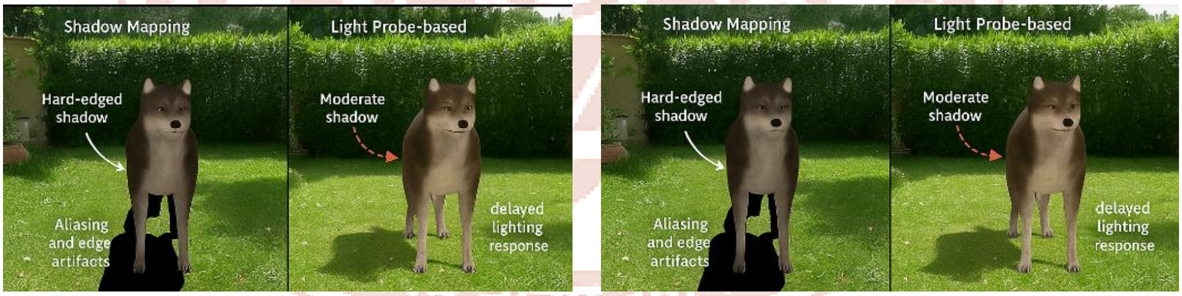

Figure 5 illustrates the comparative lighting responses, shadow behaviors, and common artifacts observed in outdoor AR scenarios for each technique.

Despite their utility for real-time performance, all techniques face inherent limitations in dynamic outdoor scenarios, including slow adaptation to fast-changing light, sensitivity to occlusions, and difficulty capturing high-frequency illumination variations such as shifting sunlight or moving shadows. As illustrated in Figure 5, these challenges underscore a clear research direction: the development of hybrid, intelligent lighting estimation frameworks that combine the efficiency of traditional rendering pipelines with the adaptability of AI-driven or sensor-fusion approaches. Such advancements have the potential to deliver visually coherent, responsive, and energy-efficient AR experiences even under the complex and unpredictable lighting conditions encountered in real-world outdoor environments.

Author Contributions Statement

Twinkle Panchal, Research Scholar, conceived the research idea, designed the methodology, and conducted the experiments. Pushpal Desai, Ph D guide, supervised the study, reviewed the methodology, and contributed to the interpretation of results. Both authors contributed to writing, reviewing, and approving the final manuscript.

Conflict of Interest Statement

The authors declare that they have no competing interests.

Data Access Statement

All relevant data generated or analyzed during this study are included in this published article and its supplementary information files.

Ethics Statement

Since your AR lighting estimation study **does not involve humans or animals:**

Ethics Declaration: Not applicable. This research did not involve human participants, human data, human tissue, or animals.

Figure and Table Citations

- Review all figures and tables, and ensure each one is **cited in the main text** where it is first discussed.
- Example: Instead of "Lighting estimation accuracy results are presented below," write:

Lighting estimation accuracy results are presented in **Table 2.**

The comparative visual outputs are shown in **Figure 4.**

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