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# An investigation of the daylighting simulation techniques and sky modeling practices for occupant centric evaluations

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## ABSTRACT

Occupant centric performance approaches in daylighting studies promote design decisions that support human visual comfort, productivity, and visual preferences, along with more conventional energy efficiency criteria. Simulating per-pixel luminance values and luminance distribution patterns for the entire scene allows us to analyze the occupant centric metrics and performance criteria. However, there are a number of different sky models, complex fenestration models, and simulation techniques that produce either conventional point in time images or annual luminance maps. This paper discusses the similarities and differences between different techniques; and a comparison analyses provides insight about their impact on occupant centric lighting measures. The comparisons for sky modeling include the conventional CIE skies (Clear, Intermediate, and Overcast), measurement based CIE models, Perez all-weather skies, and high dynamic range image based skies. The comparison of simulation techniques include point in time simulations, image based lighting simulations, and annual luminance simulations (three-phase and five-phase methods). Results demonstrate that measurement based sky models match real world conditions with reasonable proximity, and generic CIE skies consistently underestimate the indoor lighting conditions. Annual simulation methods provide a large database of temporal luminance variations, where individual instances are comparable to point in time simulations. Long term luminance simulations provide opportunities to evaluate the percentage of the year that a given luminance based criteria is met or violated.

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## 1. Introduction

A large body of daylighting practices focus on energy savings, in which the design decisions are driven by illuminance based metrics and performance criteria. Recently, attitudes and research practices are shifting towards more occupant centric metrics and evaluations. The motives for the change rest upon many factors: i) Human beings are the most expensive assets in buildings; and their well-being, health, and satisfaction impact work force productivity and public health in general; ii) Predicted energy savings frequently do not correlate with the actual operations of the buildings, as the intended use of the building or the building systems are routinely altered in the presence of occupant dissatisfaction; and iii) The growing number of building designs that utilize large areas of glazing provide strong evidence for post-construction and post-occupancy problems that challenge the validity of deploying the

illuminance based professional standards and practices as the sole evaluation criteria.

The persistence and prevalence of the illuminance based daylighting metrics have a historical and technical basis. Both the measurement and the computation of illuminance values are less expensive compared to luminance quantities. Luminance measurements have become accessible in the past decade through the use of High Dynamic Range (HDR) photography technique [1–3], but the grid based illuminance simulations are still faster than their per-pixel luminance counterparts, simply due to the resolution of the calculation points. As a result, climate based daylight simulation techniques [4–6] have matured with the illuminance based metrics first, and annual luminance maps are emerging relatively recently [7–10]. The developments open up new opportunities for feasible production of annual luminance simulations, but they are currently mostly limited within the research communities due to their recent debut. However, a shift towards annual luminance metrics could be expected and facilitated in daylighting consultancy and practices, due to their ability to better predict occupant's responses that would reduce the costly and inconvenient post-construction

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alterations.

In a limited way, some of the illuminance based metrics have been developed or modified to provide surrogate techniques that attempt to address occupant centric performances. Useful Daylight Illuminance (UDI) metric utilizes the upper threshold (originally 2000 lux, modified to 3000 lux) with the rationale of limiting excessive levels of light that causes visual discomfort [5,11]. IES LM-83 daylight metrics proposes Annual Solar Exposure ( $ASE_{1000lx,250h}$  is the percentage of the illuminance grid that exceeds 1000 lux for more than 250 h of the year) to determine the extent of direct sunlight penetration, consequently, the discomfort glare [12]. Both of these two metrics are based on horizontal illuminances. Another and more significant shift is the measurement and the computation of vertical illuminances. Vertical illuminances can be aligned with the human line of sight and visual field. The human factors research studies demonstrate that vertical illuminances have higher prediction ability to detect visual discomfort [13–17]. However, given that total vertical illuminance is a single number (weighted over a cosine corrected hemispherical projection), it does not provide enough information about the luminance distributions and the contrast in the visual field. Analogue to metamers in color, it is highly probable for two scenes to have the same vertical luminance, and yet incorporate totally different luminance compositions. That is, the same vertical illuminance could be resultant of a uniform luminance in the visual field, or more likely non-uniform luminance distributions that may include a relatively high and concentrated source along with the low luminances. A more recent study [18] proposes the simultaneous utilization of two vertical illuminance criteria to control the visual discomfort; i.e. upper thresholds are specified for the total vertical illuminance and the direct vertical illuminance. This method effectively identifies the impact of high luminance sources, such as the sun; therefore, it is a promising addition to a singular vertical illuminance criterion. It accounts for the overall impact of the direct, diffuse, and total vertical illuminance, without specifying the location of direct beam within the field of view. A number of studies demonstrate that the vertical illuminance is an effective metric to detect discomfort glare as a result of overall high lighting levels in a given scene, but it is ineffectual on its own to detect discomfort glare as a result of high contrast among different portions of the visual field [19,20]. Luminance images and luminance based metrics and performance criteria provide more detailed information about the luminous scene, as they include the position of the source and luminance distribution patterns within the human visual field. A multitude of research studies demonstrate that luminance distribution patterns determine the visual appearance, visual appraisal, visual comfort and visibility in a given scene [17,21–25]. Adequate amount of luminance variation is essential to create a visually stimulating environment that supports occupants' activities; and inadequate amount of luminance variation leads to poor lighting conditions (such as dull environments with low variations, and glare prone settings with high variations).

Based on the evidence from research, it is clear that generating lighting visualizations and studying the per-pixel luminance values and luminance distribution patterns for the entire scene is necessary to evaluate and advance the occupant centric metrics and performance criteria. Given the recent developments that afford relatively feasible methods for simulating annual luminance maps, the objective of this paper is to compare sky modelling and daylight simulation techniques for the simulation of HDR luminance imagery that can be used for occupant centric evaluations. The comparison starts with conventional point in time simulation techniques with a collection of sky modelling practices; and extends to more recent annual luminance mapping simulation techniques that allow incorporation of complex fenestration systems. Studied sky models and simulation techniques are summarized in Table 1.

## 2. Sky models and daylight simulation techniques

### 2.1. Sky models

The accuracy of daylight availability is contingent on the ability of a sky model to reproduce the variations of the luminance distributions across the sky dome, based on the position of the sun and the dominant atmospheric conditions. In this paper the sky models are grouped into two categories.

The first category divides them as generic models and measurement based models. CIE sky (as referred as  $CIE_{basic}$ , hereafter) is a generic model that represents the sky brightness based on location, date, time, and sky type. CIE [26] classifies skies into 15 categories ranging from cloudless skies to overcast skies; but the sky types used in simulations are based on the historical definitions of CIE Overcast [27], Clear [28,29], and Intermediate skies [30]. Measurement based sky models include a variation of direct normal (or horizontal) radiation and diffuse horizontal radiation ( $W/m^2$ ). These models are the  $CIE_{BR}$ , Perez all-weather [31], and the HDR image based skies [32–35].  $CIE_{BR}$  utilizes the direct and diffuse horizontal radiation measurements along with the geographic information, date, and time. This sky type adapts a generic sky type ( $CIE_{basic}$ ) to instantaneous meteorological data. Similarly, Perez all-weather skies utilize solar radiation data. Both  $CIE_{BR}$  and Perez models implicitly represent sky clearness, sky brightness, solar elevation and cloud patterns; the difference of these models from  $CIE_{basic}$  is apparent in the representation of the size and intensity of the circumsolar region. Perez model is most commonly used as the irradiance is routinely available in hourly weather files, and it does not require specifying a particular sky type as CIE models do. However, neither model explicitly represents the boundaries of clouds that are predominant in actual skies. Skies are dynamic and cloud cover is transient in nature, but the location of clouds in relation to the sun and the abrupt changes around the boundaries of clouds could impact the daylight availability in significant quantities. Image based sky models are the captured fisheye images

**Table 1**  
Studied sky models and daylight simulation techniques.

| Sky Models                               | Simulation techniques                                                                           |
|------------------------------------------|-------------------------------------------------------------------------------------------------|
| Continuous sky Models                    | Point at a time                                                                                 |
| Generic CIE sky ( $CIE_{basic}$ )        | Default ray tracing                                                                             |
| Measurement based CIE sky ( $CIE_{BR}$ ) | Image based lighting (IBL)                                                                      |
| Perez all-weather sky                    | Secondary light sources ( <i>mkillum</i> ) with Bi-directional scattering distribution function |
| Image based sky                          |                                                                                                 |
| Discrete models                          | Annual simulations                                                                              |
| Tregenza subdivision                     | Three-phase method                                                                              |
| Reinhart subdivision                     | Five-phase method                                                                               |

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