Daylight Simulation: Validation, Sky Models and Daylight Coefficients

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This thesis is dedicated to the memory of

Professor Neil Bowman

Director of the Institute of Energy and Sustainable Development

1994 to 1999

Abstract

The application of lighting simulation techniques for daylight illuminance modelling in architectural spaces is described in this thesis. The prediction tool used for all the work described here is the *Radiance* lighting simulation system.

An overview of the features and capabilities of the *Radiance* system is presented. Daylight simulation using the *Radiance* system is described in some detail. The relation between physical quantities and the lighting simulation parameters is made clear in a series of progressively more complex examples. Effective use of the inter-reflection calculation is described.

The illuminance calculation is validated under real sky conditions for a full-size office space. The simulation model used sky luminance patterns that were based directly on measurements. Internal illuminance predictions are compared with measurements for 754 skies that cover a wide range of naturally occurring conditions. The processing of the sky luminance measurements for the lighting simulation is described. The accuracy of the illuminance predictions is shown to be, in the main, comparable with the accuracy of the model input data. There were a number of predictions with low accuracy. Evidence is presented to show that these result from imprecision in the model specification - such as, uncertainty of the circumsolar luminance - rather than the prediction algorithms themselves. Procedures to visualise and reduce illuminance and lighting-related data are presented.

The ability of sky models to reproduce measured sky luminance patterns for the purpose of predicting internal illuminance is investigated. Four sky models and two sky models blends are assessed. Predictions of internal illuminance using sky models/blends are compared against those using measured sky luminance patterns. The sky model blends and the Perez All-weather model are shown to perform comparably well. Illuminance predictions using measured skies however were invariably better than those using sky models/blends.

Several formulations of the daylight coefficient approach for predicting time varying illuminances are presented. *Radiance* is used to predict the daylight coefficients from which internal illuminances are derived. The form and magnitude of the daylight coefficients are related to the scene geometry and the discretisation scheme. Internal illuminances are derived for four daylight coefficient formulations based on the measured luminance patterns for the 754 skies. For the best of the formulations, the accuracy of the daylight coefficient derived illuminances is shown to be comparable to that using the standard *Radiance* calculation method.

The use of the daylight coefficient approach to both accurately and efficiently predict hourly internal daylight illuminance levels for an entire year is described. Daylight coefficients are invariant to building orientation for a fixed building configuration. This property of daylight coefficients is exploited to yield hourly internal illuminances for a full year as a function of building orientation. Visual data analysis techniques are used to display and process the massive number of derived illuminances.

Acknowledgements

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The following all deserve mention. Dr. Mike Heath (Marine Laboratory, Aberdeen) who showed consideration above and beyond what might be normally expected. Dr. Derek Raine (Astronomy Dept., Leicester University) who, some time ago, encouraged me to write my own (active-galaxy X-ray) illumination model and, unwittingly, provided the foundation for this work. Marilyn Uffner Alan (Morgan Kaufmann, San Francisco) for assistance with the book chapter and obtaining permission to reproduce it here, and David Bartholomew (BEPAC) for doing the same for Chapter C. Ian Ashdown (Ledalite, Canada) for bringing me in on the first Siggraph (1995), and Rob Shakespeare for just being there at both of them.

It (almost) goes without saying that I owe the greatest debt of thanks to Greg Ward and all of his alter-egos.

Finally, I must thank Shona for her patience and understanding. Her words on hearing that this thesis was (at long last) finished were, unfortunately, unrepeatable. Especially in front of Elspeth!

I declare that the content of the submission represents solely my own work.

John Mardaljevic, December 1999.

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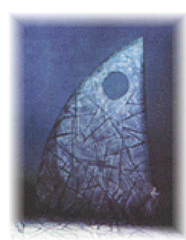
“Das licht! Das licht!”

Tristan und Isolde, Act II

Richard Wagner



Chapter

1 Introduction

"I read part of it all the way through"

SAM GOLDWYN

The goal of the work described in this thesis is the accurate simulation of hourly internal daylight illuminance levels for a full year under naturally occurring meteorological conditions. The prediction tool used for all the work described in this thesis was the *Radiance* lighting simulation system [Ward 98]. Chapter 2 is an introduction to daylight simulation using the *Radiance* system. This chapter was originally published in the book **Rendering with Radiance: the Art and Science of Lighting Visualization**.[1] This chapter introduces to the reader the fundamentals of using *Radiance* for exacting daylighting simulation work. The chapter covers a range of topics from daylight factor prediction for simple spaces to creating renderings of highly complex architectural designs. Throughout the chapter, a strong emphasis is placed on the relation between physical

1. Note that the originator of the *Radiance* system has been known variously as: Greg Ward, Greg Larson and Greg Ward Larson. Despite this, and several changes of employment, he has yet to escape recognition as the (effective) sole originator/creator of the *Radiance* system. As of late-1999, 'Greg Ward' is the name to use.

quantities and the lighting simulation parameters. The use of the ambient calculation for inter-reflected light, generally considered to be one of the more perplexing features of the *Radiance* system, is carefully described. The examples given in this chapter demonstrate how the performance of the ambient calculation can be optimized by judicious examination of the scene prior to attempting any simulations. This chapter was conceived as a 'tutorial' on daylight simulation for those already familiar with, at least, the basics of the *Radiance* system.[2] The chapters that follow are concerned with the validation of the illuminance calculation and the formulation, application and proving of techniques for daylight illuminance prediction.

The validation of the *Radiance* illuminance calculation under real sky conditions is described in Chapter 3 (Preparation) and Chapter 4 (Results). The validation dataset is based on simultaneous measurements of the internal illuminance in an office space and the luminance distribution of the sky.[3] The internal illuminance was recorded at six locations along the length of the office, and the sky luminance was measured at 145 points evenly distributed across the hemisphere. The validation dataset contains measurements - internal and external - for 754 unique skies that cover a wide range of naturally occurring conditions: from heavily overcast, through intermediate to clear. The sky brightness patterns used in the lighting simulation were based directly on the sky luminance measurements. A hypothesis regarding potentially unreliable photocell-sky combinations in the validation dataset is advanced. Chapter 4 begins with a summary presentation of the validation results. Thereafter, the validation results are subjected to a range of investigations. These analyses are gradually refined and evidence is presented to support the hypothesis advanced in Chapter 3. On the strength of this evidence, the photocell-sky combinations in the validation dataset are partitioned into 'reliable' and 'potentially unreliable'

2. For a practical introduction to Radiance, readers are directed to Chapters 1 to 4 of the book *Rendering with Radiance.*

3. Validation data were supplied by the Building Research Establishment.

sets based on the visibility of the circumsolar region from the photocell location. The accuracy of the illuminance predictions for the 'reliable' set is taken to be the intrinsic accuracy of the illuminance calculation.

The use of sky models for lighting simulation is investigated in Chapter 5. For this, the validation exercise was repeated but now the sky luminance patterns are based on sky models. The sensitivity of internal illuminance predictions to sky model type is evaluated. In all, four different sky model formulations and two sky model blends are assessed.

An implementation of the daylight coefficient approach for *Radiance* is described in Chapter 6. With the daylight coefficient approach, the internal illuminance for arbitrary sun and sky conditions can be evaluated by re-using pre-computed daylight coefficient values for a discretised sky. Five candidate daylight coefficient formulations for *Radiance* are examined. One of these is found to be potentially very inaccurate and it is eliminated from further consideration. The accuracy of the remaining formulations is tested using the validation dataset. Illuminance predictions for the office space are derived from daylight coefficients using the measured sky luminance patterns for all 754 skies in the validation dataset. The accuracy of daylight coefficient derived illuminance predictions are compared against measurements and those obtained using the standard *Radiance* calculation method. This chapter then shows how daylight coefficients can be used to predict the annual daylighting potential of an architectural space. A methodology for the efficient evaluation of annual daylighting potential as a function of building orientation is presented. Several possible applications for these new techniques are discussed. The thesis concludes with a list of suggestions for the practical application of the new techniques and recommendations for future work.

Familiarity with the *Radiance* system is a desirable, though not essential, prerequisite for critical reading of this thesis. It is hoped that many of the findings described here will be of interest, to a greater or lesser degree, to all those concerned with daylight prediction.