

DYNAMIC DAYLIGHTING SIMULATIONS FROM STATIC HIGH DYNAMIC RANGE IMAGERY USING EXTRAPOLATION AND DAYLIGHT COEFFICIENT METHODOLOGIES

Mehlika Inanici

University of Washington, Department of Architecture, Seattle, WA, USA

ABSTRACT

This paper describes the development of a technique for extrapolation of dynamic daylighting simulations from a limited number of high dynamic range photographs. This technique allows us to photographically capture and measure per-pixel lighting quantities from existing spaces in a limited time frame; and the measured information is used to establish a statistics based daylight coefficient model for the studied scene. It negates the need to explicitly model the geometry, material and lighting properties in existing environments, as they would be required in a typical simulation and daylight coefficient computation. Statistics based daylight coefficients can be used to perform daylighting simulations under any generic, arbitrary or physically occurring sky conditions.

INTRODUCTION

High Dynamic Range (HDR) photography has become a commonly used technique for pixel scale luminance data acquisition. In this technique, multiple exposure photographs are taken with a digital camera, where each exposure captures a different luminance range in the scene. Using a HDR image assembly software such as Photosphere (Ward, 2005a), a unique camera response function is computationally derived, and used to fuse the multiple low dynamic range photographs into a single HDR image. This method has been validated for lighting measurement purposes (Inanici, 2006).

HDR photographs opened up new possibilities in lighting design, research, and consultancy as it is a low-cost, efficient, and effective technique to capture luminance maps. Any lighting professional can perform luminance measurements with a low-cost commercially available camera, and free software (Photosphere). However, HDR photographs capture the moment, and provide us lighting information under the conditions occurring at that time. For daylit spaces, it means that we analyze the space for the specific date, time, and sky condition; which is a tiny fraction of the lighting performance throughout the entire year. If the user has taken the HDR photographs in December under a cloudy sky, we can study the performance for that time frame, but it is not informative about the lighting conditions in June

under a sunny sky. Therefore, the usefulness of HDR photographs has been limited for analysis, as they fall short to provide long term performance information.

Meaningful evaluation of daylighting performance must take into consideration of dynamic variations under a wide range of naturally occurring sky conditions and sun positions. Time-series lighting performance can be determined through long term (annual) HDR measurements, but it is usually not feasible or possible due to the time constraints and accessibility restrictions of measured buildings.

DYNAMIC DAYLIGHTING SIMULATIONS

Dynamic daylighting simulations enable us to study the accumulated effect of lighting performance over a year-long period rather than to investigate the selected dates and times of the year. These simulations can be done with software such as DAYSIM (Reinhart, 2001) and Radiance *rtcontrib* (Ward, 2005b). *Rtcontrib* is recently rewritten and renamed as *rcontrib* (Ward, 2012). Different dynamic daylighting simulation techniques such as Useful Daylight Index (Nabil and Mardaljevic, 2005) and Daylight Autonomy (Reinhart et al., 2006) employ Daylight Coefficient (DC) method.

DC method has been originally proposed by Tregenza and Waters (1983). It is based on dividing the sky into finite number of discrete patches. DCs are calculated at measurement points as the normalized lighting values from each sky patch. Collectively the individual patches form the entire sky, and their contributions add up to the entire lighting quantity at the sensor point. DC embodies the unified impact of the site context, building form, and material properties on the distribution of normalized lighting values from each sky patch. It is a lighting property, which does not change as long as the site, building geometry, and material properties are not altered. The only parameter that will change the interior lighting conditions throughout the year is the value of each sky patch.

The established method in Daysim and Radiance is to perform a bundled simulation process to pre-compute the resulting effect of each sky patch at a single point. It is a bundled simulation as it is repeated for the number of sky patches utilized. The original DC

method is based on 145 Tregenza patches, but further subdivisions are currently utilized. These divisions may yield to 578, 1298 or 2306 patches (zenith patch in the original Tregenza division remains intact and all other patches are further divided into 4, 9, or 16 meshes, relatively). Another patch is added to account for contributions from the ground.

Given the pre-computed DCs, simple matrix calculations easily determine the luminance or illuminance values at the measurement point under any sky model without redoing new simulations. It is an efficient computation method to generate large number of predictions; therefore it enables us to perform annual daylighting simulations.

RATIONALE AND OBJECTIVES

Although the DC methods currently utilized are particularly successful for simulating spaces throughout design phases, it inherits challenges for evaluating existing environments due to the associated uncertainties of geometric and material modeling of building and site properties. Geometric measurements for real world spaces are tedious and time consuming, at best. Proper measurement and modeling of physically based material properties requires specialized and expensive equipment (such as spectra-reflectometer), and errors in material definitions lead to significant errors in simulations.

There are cases where complexity in geometry and material properties and their approximations could be detrimental to simulate the physical reality of the luminous environment. Example given in this paper is Hagia Sophia. Hagia Sophia, the Byzantine Church from 6th century BC, is regarded as one of the greatest architectural and structural achievements of all times (Mainstone, 1988). It is also a triumph of lighting quality that results from a unique and bold combination of complex forms, intricate use of surface materials (that include mosaics), and skillfully designed daylight apertures. Procopius described the lighting in Hagia Sophia in 6th century as an interior that “is singularly full of light and sunshine; you would declare that the place is not lighted by the sun from ‘without’, but that the rays are produced ‘within’ itself, such an abundance of light is poured into this church...” (Dewing, 1940). The building still provides a unique experience to visitors today, and it provides great challenges for lighting simulation, even for the most expert simulationists. The geometric complexity is ‘relatively’ easy to overcome, but material properties cannot be modeled in a feasible manner, while doing justice to the complexity of light reflection and transport within the structure (Figure 1).

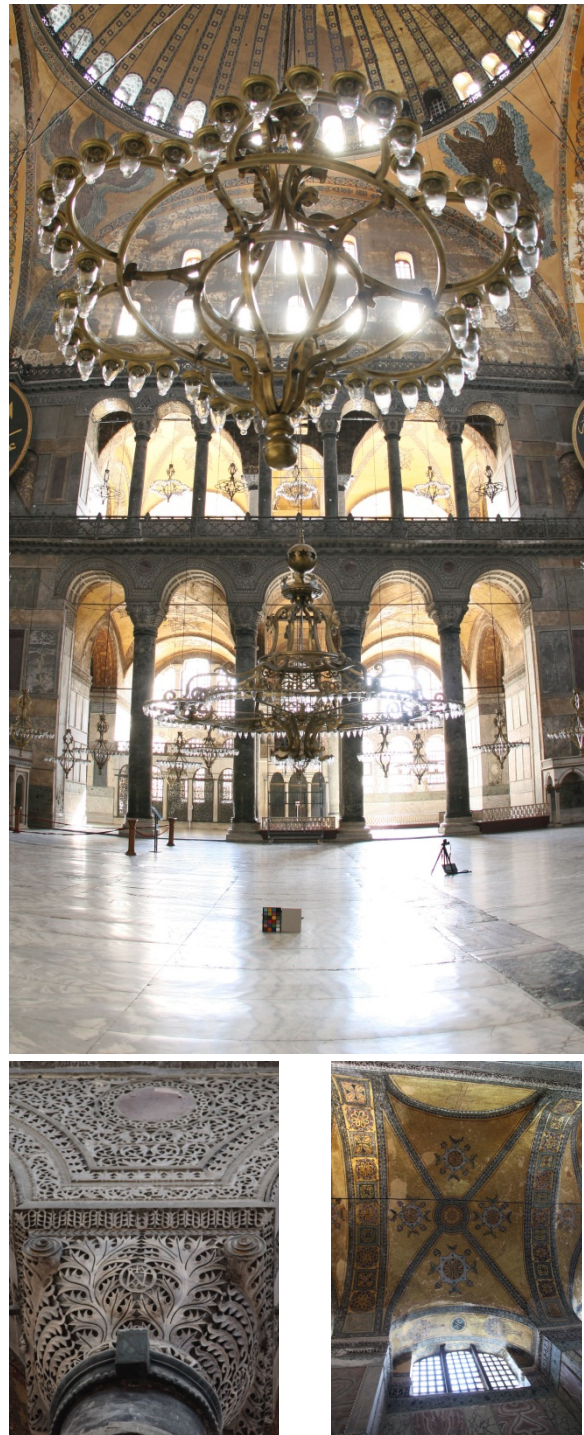


Figure 1 Geometric and material complexities in Hagia Sophia pose significant challenges for traditional simulation practices

The example of Hagia Sophia might be unusually demanding from a simulation point of view; however, it is hardly an isolated challenge. As adaptive reuse, remodeling, and refurbishing are becoming more common and promoted as part of sustainable practices, there is a need for a lighting simulation technique, which can start with the existing lighting information that can be captured

through HDR imagery, and predict long term lighting performance.

In situations where a complete simulation model of the building and the surrounding is available or feasible to generate, classical dynamic daylight situations are appropriate to evaluate the long term performance (using Radiance *rtcontrib* or Daysim). However, availability of a full simulation model for an existing building and the neighboring structures is quite the exception. In the absence of a faithful simulation model, the method demonstrated in this paper fills in the void.

The proposed methodology draws from the concept of DC. The goal of this research is to develop an HDR image based DC method (referred herein as HDRI based DC). Limited numbers of in-situ lighting measurements are done using HDR photographs under naturally occurring sky conditions. HDR photographs capture the end result of the complex interactions of light sources, materials, geometry, and site conditions. This information is used to extrapolate dynamic daylighting performance using a statistical model. The paper incorporates the development of the HDRI based DC method, demonstration and evaluation in a controlled simulation environment, and a real world application.

IMAGE BASED DAYLIGHT COEFFICIENTS

There are significant differences between the proposed HDRI-based DC methodology and its simulation based counterparts. The differences are summarized as follows:

- **Modeling:** The simulation based DC methods (Daysim and Radiance *rtcontrib*) require a simulation model that includes building and site geometry, material properties and a white uniform sky. The HDRI based DC does not require a simulation model. The HDR photographs are treated as the end result of the “simulation”.
- **Computation:** The simulation based DC methods (Daysim and Radiance *rtcontrib*) use Radiance engine to compute the contribution of each sky patch separately. HDRI based DCs are derived using a statistical model.
- **Sun and the sky:** The implementations of different simulation based DC methods vary, but as a general rule, simulation calculates the light transport in direct and indirect components separately for the sun. Contributions from the sky and ground are also separately computed (Bourgeois et al, 2008). Sum of all of these components are used as the final coefficient. In the HDRI based DC, naturally occurring sky conditions are captured. It is not possible to

dissect the diffuse and direct components.

The idea is to derive the accumulated effect of the sun, and the sky; i.e. the direct and diffuse components. The impact of this approach is further discussed in the Results section.

- Simulation based DCs can be used to generate either illuminance or luminance maps. However, both the Useful Daylight Index and the Daylight Autonomy methods are solely based on illuminance. HDRI based DC method is based on luminance.

In a nutshell, HDRI based DC methodology involves the following 5 steps:

1. HDR photographs of an interior spaced are collected throughout a single day in fixed intervals.
2. HDR photographs of the sun and the sky are captured simultaneously. Previous research demonstrate that using appropriate filters and two-aperture method, image based sky models can provide an accurate and efficient method for measuring the sun and the sky luminance distributions (Stumpf, 2004; Inanici, 2009; Inanici, 2010). Simultaneous captures of the interior and exterior conditions allow us to study the impact of changing outdoor conditions on interior luminance values.
3. The captured sky images are subdivided into discrete patches, as they are typically done in a classical DC method.
4. An iterative solver for least squares problems (Fong and Saunders, 2011) is employed for establishing a relationship between the sky patches and the resultant per-pixel luminance of the interior HDR scene. In the absence of a traditional simulation model, ray tracing method cannot be applied. DCs are derived and computed as a statistical model per pixel, which is a surrogate for the ray tracing method.
5. Once DCs have been determined, they can be used for all subsequent pixel calculations as a multiplier to the relevant sky patch to extrapolate interior luminance values to long-term dynamic lighting simulations under generic (CIE), arbitrary (Perez), or image based sky models.

Methodology

In the algorithmic development phase, it is necessary to study the feasibility and accuracy of the proposed methodology. Both HDR photographs and Radiance images provide the same information at a pixel level; i.e. RGBE (Red, Green, Blue, Exponent) values that are used to calculate luminance.

The testing of the methodology is therefore done using Radiance images, so that the method can be

properly tested in a controlled simulation environment, and absolute errors can be determined.

A room with a South facing side window and a skylight is simulated (Figure 2). Two sets of images are generated in Radiance software (using *rpict* method): a training set and a test set.

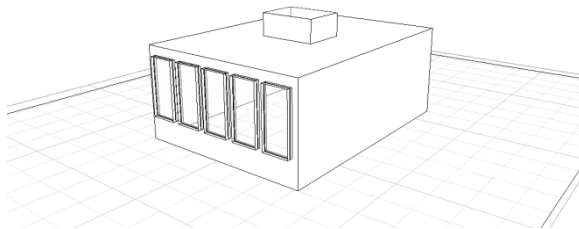


Figure 2 Test scene used for Radiance simulations

The training set encompasses a series of HDR images generated for a single day in fixed time intervals. A single day time period emulates the idea of collecting HDR photographs for one day. These images are generated for Seattle (47.6°N, 122.3°W) in 15 minute intervals from sunrise (6:15) to sunset (18:00) for September 21st under clear sky conditions. Two images generated under overcast sky conditions (12:00 and 15:00) are also included in the training set. The total number of training images is 50 (Figure 3).



Figure 3 An example image from the training set (September 21st, 10:00)

The test scenes are chosen to emulate the extreme lighting conditions in a yearlong period. They include December 21st with clear sky, December 21st with overcast sky, June 21st with clear sky, and June 21st with overcast sky conditions (all at noon).

The comparison for each date, time and sky condition is done with three different methods: 1) Original Radiance simulations (*rpict* method), 2) Radiance based DC simulations (*rtcontrib* method), and 3) the HDRI based DC method (i.e. iterative least squares).

Once training images are generated, Matlab software (Mathworks, 2012) is used to parse the data such that each pixel is represented as a matrix of 50 by 1 (50, being the number of training images). The total number of parsed matrices is equal to the total number of pixels. The images have a resolution of 335 by 240, so the total data is parsed into 80,400 matrices.

The sky model used to generate each image is also divided into sky patches. Radiance *genskyvec* program is used to generate 2306 patches of the sky (1 patch for the ground, 1 patch is for the zenith and the remaining 144 patches from Tregenza division are further divided into 16). The luminance of the sun is distributed among the nearest 4 patches. The resulting data is a matrix that encompasses the sky patches (2306) for all of the provided training cases (50). The high number of sky patches is preferred to reduce the image artifacts and to improve the accuracy of end result. There is not significant computation time difference between processing 146 and 2306 sky patches.

The DC problem is illustrated in Equation 1. L_{pixel} is the luminance matrix, where the luminance for a particular pixel is given in chronological order for all training sets. L_{sky} is the sky matrix that includes all patches for the training sets. The HDR images of the interior are generated/collected concurrently as the sky conditions are generated. Both the pixel luminances and sky patch luminances are known. What is needed to be determined is a function (DC) that will relate the sky luminances (2306 patches) to interior pixel values.

$$[L_{pixel}] = [L_{sky}] \times [f_{DC}] \quad (1)$$

Few rules are established to improve the robustness of the calculated DC function:

- It is necessary to use a function that will establish a correlation with as many sky patches as physically plausible. Basic least square methods return a correlation with few selected patches and zero correlation with many others. Obviously, this is not an acceptable algorithm. If the sun is in a zero correlation patch, this will yield to unacceptable errors.
- The successful function should not allow non-negative correlations. It is not physically possible to have a negative correlation between a sky patch and interior luminance value.
- Many different least square solvers were identified and evaluated in Matlab (statistic toolbox and curve fitting toolboxes) for the task. LSMR, an iterative method developed for solving least squares problems (Fong and Saunders, 2011) is found to be

sufficient to develop a model with the rules discussed above. It outperformed other solvers that were tested in terms of accuracy and speed. Therefore, it is adopted for this research as the DC solver.

- The HDR images do not encompass orientation information for daylight apertures (i.e. they do not geometrically reveal the patches of the sky visible from the windows). Without this information, and based on the rules given in the previous section, the algorithm will target to establish correlation with all patches in the sky. This is problematic for the studied space, as a northern patch will have little (due to reflections) or no impact on the south facing room. A weight factor is introduced to encourage the algorithm to establish stronger correlations with the sky patches facing the apertures. This is done based on azimuth and altitude of sky patches.

The calculated DC is a 2306 by 1 matrix. It determines the relative impact of each one of the 2306 sky patches on the pixel value. A separate function/matrix is derived for each pixel. The summation of the DC matrix multiplied by the corresponding luminance of sky patches at a particular instance returns the pixel luminance under that sky condition.

Results and Discussion

In comparison studies among the three methods, Radiance *rpict* is regarded as the base case and it is the high standard for accuracy and image quality. Radiance based DC simulations are done with 145 Tregenza subdivision, *genskyvec* function is used to generate the patches. Further details about this technique can be found in (Jacobs, 2010). Radiance based DC methods offer computational efficiency that enables dynamic daylighting simulations. However, there is a decline in image quality (i.e. image noise is often a problem). Additionally, since DC contributions are determined by a bundled simulation and they are not redone for different date and times, it is not possible to generate the sharp sun penetration and shadow patterns.

Figure 4 shows the false color images for December 21st at 12:00 under clear sky conditions with the three methods used for comparison. Figure 5 illustrates a numerical comparison of the per-pixel luminance values calculated by Radiance *rpict* and the Radiance DC (*rtcontrib*) methods. Comparison of these two methods produce a linear fit equation with a coefficient of 0.82 (95% confidence bounds and r-square is 0.90). Figure 6 illustrates a numerical comparison of the pixel values calculated by Radiance *rpict* and the HDRI based DC methods. The results match with each other well: linear fit yields a coefficient value of 0.98 with 95% confidence bounds. R-square is calculated as 0.88.

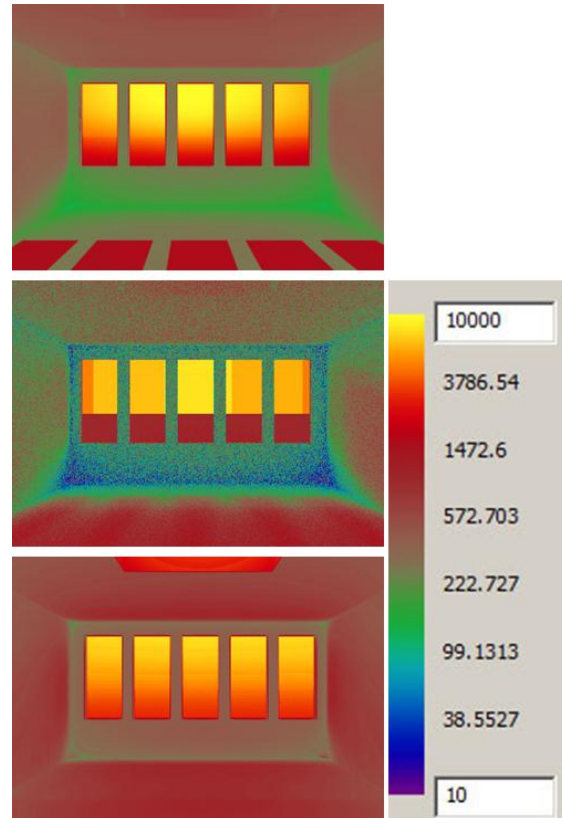


Figure 4 Dec 21, 12:00 under clear sky conditions: (top) Radiance *rpict* method, (middle) Radiance DC (*rtcontrib*) method and, (bottom) HDRI based DC method.

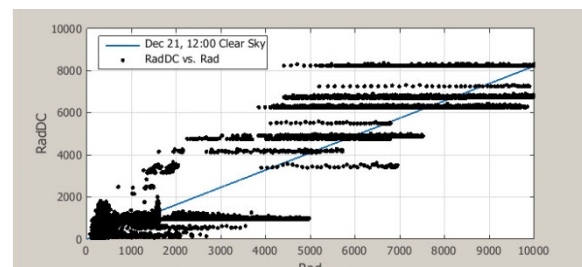


Figure 5 Comparison of luminance values calculated by the Radiance *rpict* method and Radiance DC method for December 21, 12:00 under clear sky conditions

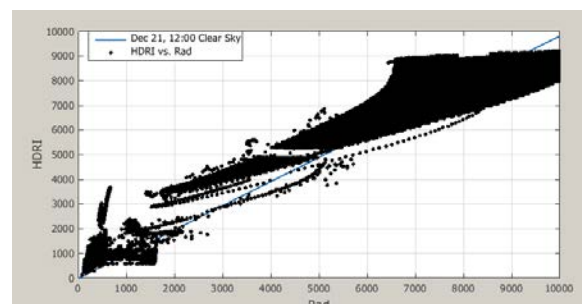


Figure 6 Comparison of luminance values calculated by the Radiance *rpict* method and HDRI based DC

method for December 21, 12:00 under clear sky conditions

HDRI based DC method shares the weakness of its simulation based counterpart in terms of ability to produce the sharp sun penetration and shadow patterns, but it is not as noisy (grainy) as the Radiance DC method. However, noise in Radiance DC method could be addressed by creating an oversampled (higher resolution) image that would be filtered down.

Similar comparison is done for June 21st at 12:00 under clear sky conditions (Figure 7). Figure 8 illustrates the correlation between the Radiance *rpict* and Radiance DC (*rtcontrib*) methods. In this case, linear fit equation yields a coefficient of 0.87 with 95% confidence bounds; r-square is 0.89. The comparison of the per-pixel luminance values calculated by Radiance *rpict* method and the HDRI based DC method (Figure 9) produce a linear fit (coefficient of 0.84 with 95% confidence bounds and r-square of 0.69).

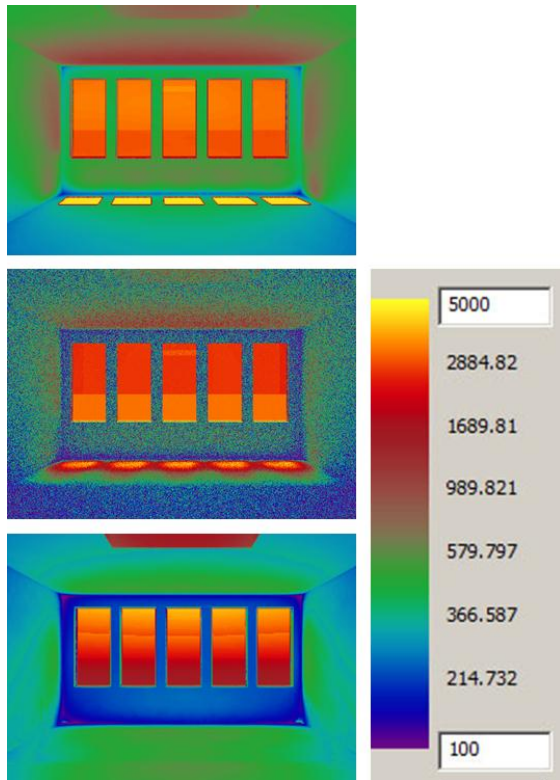


Figure 7 June 21, 12:00 under clear sky conditions: (top) Radiance *rpict* method, (middle) Radiance DC (*rtcontrib*) method and, (bottom) HDRI based DC method.

Overcast sky is a relatively simpler case. In fact, even basic (yet non-negative) least squares algorithms provided good results with the overcast sky conditions, and it is not required to apply weight factors since the overcasts sky is symmetric. Figure 10 shows the false color images for December 21st at 12:00 under overcast sky conditions. The numerical

comparison of the pixel values calculated by the Radiance *rpict* method and the HDRI based DC method (Figure 11) provide a very good match (the linear fit yields a coefficient value of 0.93 with 95% confidence bounds; r-square of 0.99). Similarly, comparison results from June 21st overcast sky conditions also lead to a linear fit of 0.93 with 95% confidence bounds; r-square of 0.99.

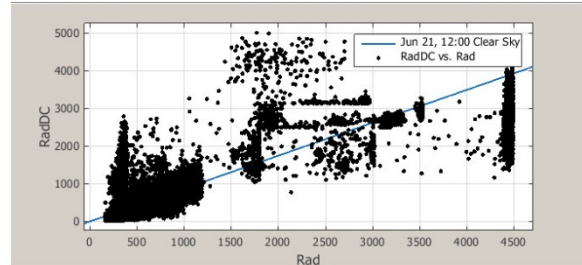


Figure 8 Comparison of luminance values calculated by the Radiance *rpict* method and Radiance DC method for June 21, 12:00 under clear sky conditions

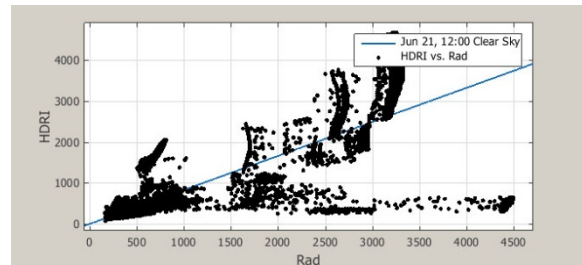


Figure 9 Comparison of luminance values calculated by the Radiance *rpict* method and HDRI based DC method for June 21, 12:00 under clear sky conditions

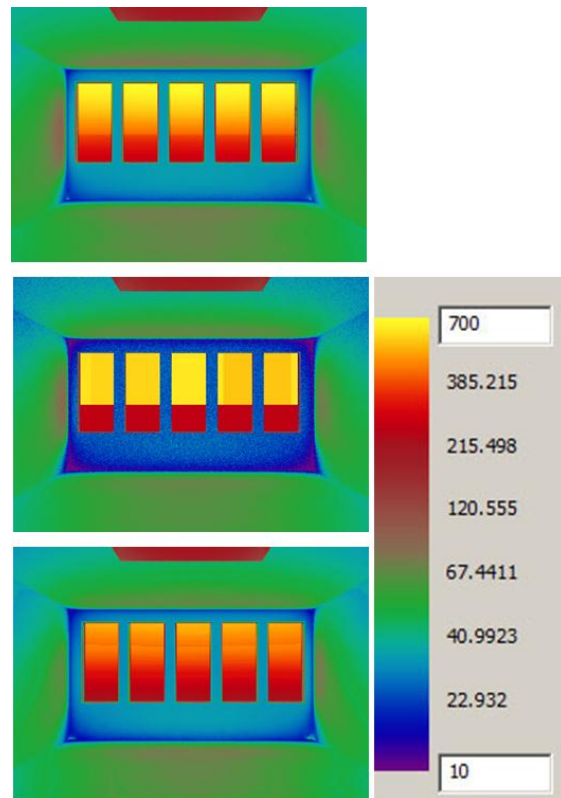


Figure 10 December 21st, 12:00 under overcast sky conditions: (top) Radiance rpict method, (middle) Radiance DC (rtcontrib) method and, (bottom) HDRI based DC method.

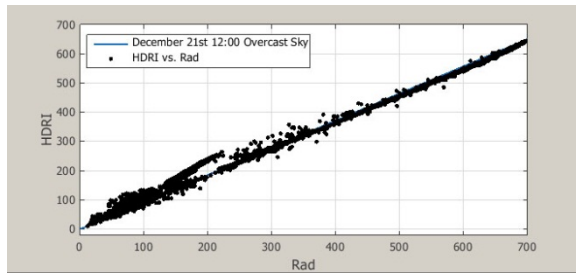


Figure 11 Comparison of luminance values calculated by the Radiance rpict method and HDRI based DC method for December 21, 12:00 under overcast sky conditions

APPLICATION

Currently, a study is in progress to determine the long term lighting performance in Hagia Sophia from HDR photographs. The data collection has been conducted over a day period (September 24th 2012) under clear sky conditions. As the interior HDR images were captured using a single aperture method (Figure 12), HDR sky images of Istanbul (41°N, 28.9°E) were simultaneously recorded using the two aperture method (Figure 13).

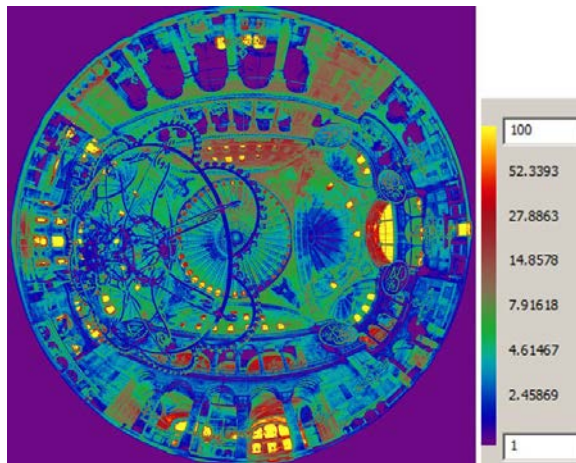


Figure 12 False color image of interior scene at Hagia Sophia, captured under the dome on September 24th at 13:00

In the data collection process, 36 images were captured from sunrise to sunset. 35 of these images were used for the training set, and one set was used as the test scene. The methodology described in this paper is used to derive HDRI based DC values. Figure 14 demonstrates the comparison between the measured (HDR photography) and the calculated (HDR based DC) luminance values for the test scene.

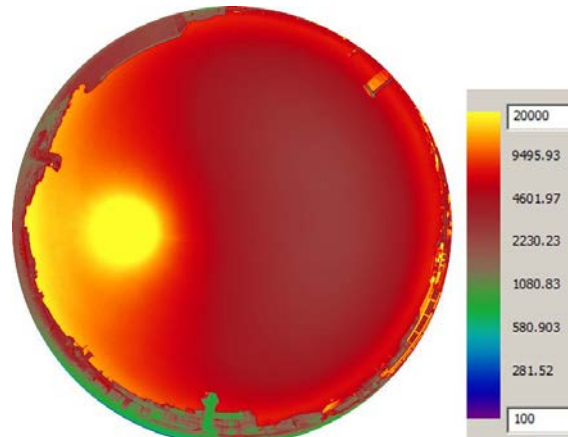


Figure 13 False color image of sky conditions in Istanbul on September 24th at 13:00

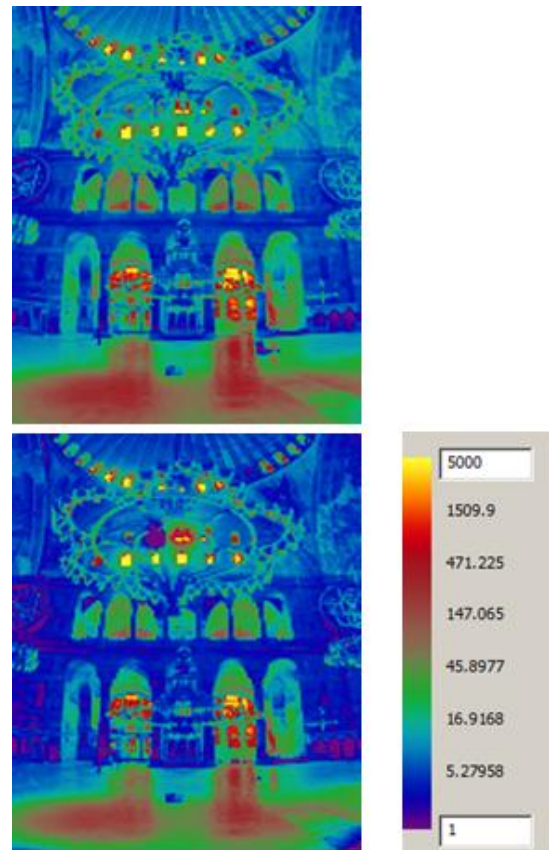


Figure 14 Comparison of pixel values measured by the HDR photography method and HDRI based DC method for September 24, 14:00 under clear sky conditions

CONCLUSION

This paper demonstrates the development of an image based DC methodology for extrapolating dynamic daylighting simulations from a limited number of HDR photographs. It is not a straightforward task to measure the geometry and material properties in-situ. HDR photography method

is a relatively easy lighting data acquisition method that encompasses the impact of geometry, material, and lighting properties in existing spaces. The starting point is short term lighting measurements in an existing space through HDR photography; where the collected HDR images act as the surrogate simulation model. The outcome is a predictive model of long-term daylighting simulations in any given intervals.

The results demonstrate that the methodology is particularly easy to extrapolate lighting information under overcast sky conditions. Clear and intermediate sky conditions benefit from additional information (i.e. orientation) that relates the apertures to the relevant sky patches.

The methodology described here is not a replacement for simulation based DC methodologies. It is suggested as a useful methodology in the absence of a faithful simulation models for existing spaces. It can be used to monitor built environments to study the efficiency of design decisions, and predict long term performances along with post occupancy evaluations. It can be used for assessing buildings that are candidates for adaptive reuse, remodeling, and refurbishing. It can also be utilized as guidance for lighting commissioning procedures. Comparative studies that utilize HDR photographs of different buildings are inherently problematic when they are mostly captured at different chronologies. This method is useful to study them under the same sky conditions. It is therefore an effective methodology for comparing different daylighting strategies.

Further research is planned to:

- 1) Study the impact of building geometry on the established method;
- 2) Study the impact of the data collection period on the outcome (i.e. whether shorter periods hamper accuracy, or longer data collection periods improve the outcome);
- 3) Study the impact of the time of the year or sky conditions on data collection; and
- 4) Test the technique on real world applications. This is particularly important as real world sky conditions are much more complicated than standard sky models in terms of luminance distribution patterns.

Although further investigation is warranted for wider adoption, this paper lays the foundation and demonstrates the feasibility of an HDR image based DC technique.

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