CALIBRATED SKY LUMINANCE MAPS FOR ADVANCED DAYLIGHT SIMULATION APPLICATIONS

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ABSTRACT

Reliable prediction of daylight availability in indoor environments via computational simulation requires reasonably detailed and accurate sky luminance models. In this paper, we compare three calibration methods to derive detailed sky luminance maps from digital sky images. The results imply that digital sky imaging calibrated with parallel measurements of overall horizontal illuminance levels, can provide an efficient basis for the generation of detailed sky luminance models.

KEYWORDS

Daylight simulation, sky luminance mapping, digital images, calibration

INTRODUCTION

Daylight simulation can support building design phase and assist model-based building systems control (Mahdavi 2001, Mahdavi et al. 1999, Mahdavi et al. 2005). However, the standard sky models, still used in most daylight simulation applications are not sensitive to transient luminance variations in different areas of the sky. Previous research efforts have shown that accurate sky scanning data can provide the basis for detailed sky models (Igawa et al. 1999). Moreover, sky-scanning measurements can be used in simulation tools to facilitate the creation of sky luminance distributions of real occurring skies (Mardaljevic 1999). However, high cost of sky scanners necessitates the deployment of more affordable technologies for obtaining accurate sky models for various locations and over statistically representative periods of time. The past research efforts (Roy et al. 1998, Spasojević and Mahdavi 2005, Mahdavi et al. 2006) have demonstrated that sky luminance mapping with digital photography can provide an alternative to high-end research-level sky scanners.

In the research presented in this paper, we further explored the use of a digital camera with a fish-eye converter toward provision of sky luminance maps of various real occurring skies. We used three calibration methods to derive detailed sky luminance maps from sky images. The calibrated sky luminance maps can consequently be used in daylight prediction tools as models of real occurring skies. The application of such sky luminance models increases the predictive accuracy of the computational daylight prediction tools.

APPROACH

Derivation of luminance maps from sky images

This paper presents an approach to obtain the sky luminance maps from digital images of the sky hemisphere with the help of simultaneous measurements of global horizontal illuminance. A digital camera equipped with a fisheye lens makes it possible to capture images of the entire sky dome. Figure 1 shows the digital camera with a fisheye converter, mounted at the TU Tower of the Vienna University of Technology to enable continuous sky imaging.

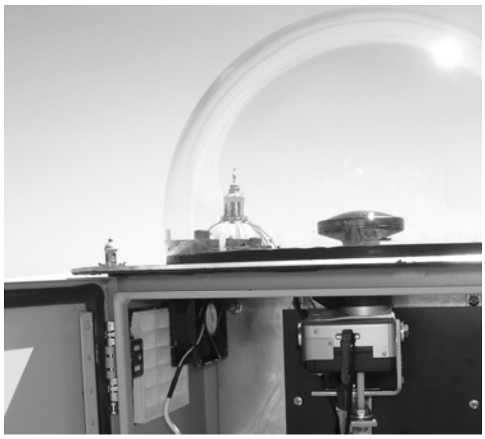

Figure 1
Digital camera with fisheye lens

Synchronous measurements of daylight levels are performed using a precision illuminance meter integral to our Department's weather station.

An algorithm proposed by Roy et al. (1998) allows deriving the luminance values of the particular portions of the sky dome using the RGB values of the image's pixels and the camera metadata such as shutter speed, f-stop number, and ISO number. This algorithm is used as the basis of the initial calculation procedure (Spasojević and Mahdavi 2005). We use a pattern of 256 patches to map sky luminance distributions. In this approach, the difference between the measured global illuminance and the horizontal illuminance obtained from initially calculated sky patch luminance provides a means for calibration of digital sky images.

A correction factor, defined as a ratio of the measured global illuminance to the horizontal illuminance obtained from initially calculated sky patch luminances, can be uniformly applied toward calibration of the sky luminance maps of cloudy skies without visible sun (Spasojević and Mahdavi 2005).

While experimental results showed that the uniform correction factor corresponding to the cloudy skies without visible sun does not exceed 1.1, it may be much larger in case of sunny skies. Thus, for sky conditions involving visible sun, the application of a uniform correction factor is not appropriate.

In order to arrive at a generally applicable calibration procedure to derive sky luminance maps from digital images, we considered a number of alternatives. Three such alternatives are compared in this paper, whereby the difference between measured and camera-based global horizontal illuminance levels is used to modify the initial luminance values of certain sky areas. The respective sky areas in these three cases are as follows:

i) CIRCUMSOLAR REGION: Five patches, one corresponding to the sun position and the four adjacent patches represent sun and its circumsolar region. The initial luminance values of the other 251 patches remain unaltered.

ii) SUN PATCH: A patch where the sun position has been detected is modeled as a source of direct illumination. The initial luminance values of the other 255 patches remain unaltered.

iii) SOLAR DISC: A small solid angle with an opening cone subtending 0.533 degrees (Duffie and Beckman 1991) is modeled as a source of direct illumination. Solar disc is separately modeled and added to the sky luminance map. The luminance of all 256 sky patches within the initial sky luminance map remains unaltered.

Three distinct experiments were conducted to compare the proposed calibration procedures:

A. Illuminance measurements with sky monitoring device

A sky monitoring device (see Figure 2), hosting twelve illuminance sensors, was placed on the roof of our Department's building to measure the horizontal illuminance resulting from twelve different sky sectors. The sky images were collected using the digital camera. A precision illuminance meter was used to obtain the global horizontal illuminance levels. The data set included 2547 sky images collected during a week in July 2003 and ten days in November 2005.

Figure 2 Sky monitoring device, digital camera with fisheye converter and illuminance meter

Figure 3 shows the projection of the twelve sky sectors "viewed" by the sky-monitoring device onto the fish-eye images obtained from the digital camera.

The sky luminance distribution maps derived from sky images were calibrated using the three aforementioned methods. The illuminance predictions resulting from calibrated sky luminance maps were compared to the respective photometric measurements.

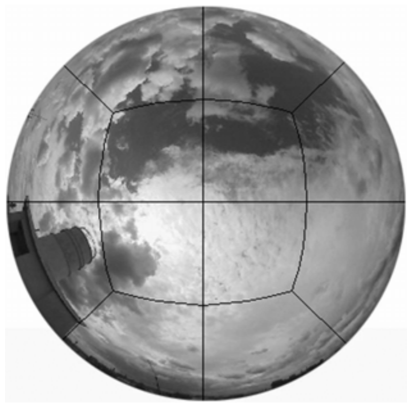

Figure 3 Fisheye projections of twelve sky sectors, "seen" by illuminance sensors

B. Illuminance measurements in a scale model

In this experiment, a scale model (1:5) of a simple rectangular room with one window opening (Figure 4) was placed on the roof of our Department's building. Illuminance measurements in this model were performed over the course of 10 days in November 2005. We also measured the outdoor illuminance levels and captured the sky dome state with the digital camera. The orientation of the scale model was changed a number of times so that the scale model's window opening faced both South and North directions.

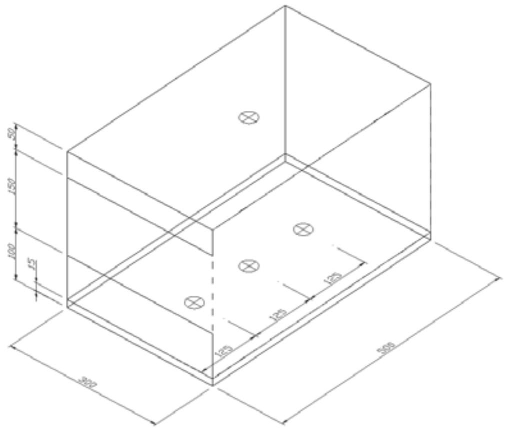

Figure 4 Scale model of the rectangular room

Using the lighting simulation system RADIANCE (Ward 1994, Ward Larson and Shakespeare 2003), we simulated the indoor illuminance levels for the same three positions in the scale model. Thereby, the sky luminance models were constructed using the camera-based sky luminance values as derived via the aforementioned three calibration methods. Subsequently, simulation and measurement results were compared.

C. Measurements of indoor illuminance in a real space

A sixteen-day experiment (fifteen days in May 2005 and one day in June 2005) involved illuminance measurements inside a test space at Vienna University of Technology (see Figure 5). This real office space has two casement windows equipped with movable blinds. The blinds were continuously moved through seven different positions and illuminance levels were measured for every blinds position using six sensors located on the desks (Figure 5, E_1 to E_6).

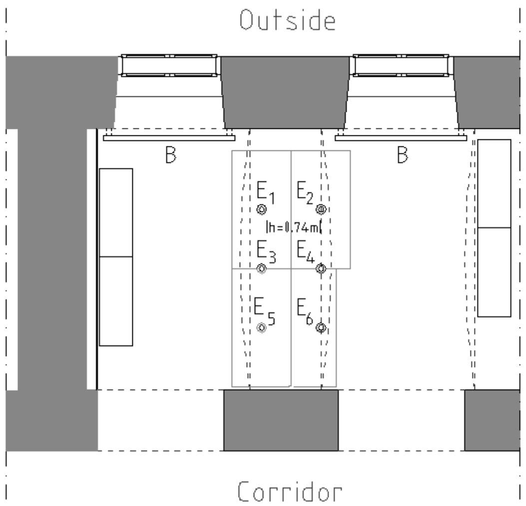

Figure 5 Test room with six measurement points

Simultaneously, the camera with the fisheye lens mounted at the TU Tower (Figure 1) was used to capture the sky images and the measurements of global illuminance were obtained from the Department's weather station. We compared the illuminance measurements (collected in 15-minute time steps and considering all seven blinds positions for each time interval) with the respective daylight simulation results. In this case too, the simulations were performed with the RADIANCE simulation system using calibrated image-based sky luminance models.

RESULTS

The three previously mentioned calibration methods (circumsolar region, sun patch, solar disc) were applied to the sky luminance maps of sunny skies and all calibration procedures involved uniform correction of the sky luminance maps of the cloudy skies.

Comparison using illuminance measurements with the sky-monitoring device

The following Figures (see Figures 6 to 8) illustrate comparisons of the measured illuminance values resulting from the twelve sky sectors for 2547 sky instances with the corresponding illuminance levels derived from camera-based luminance maps.

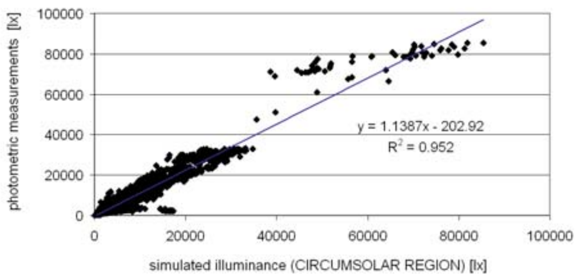

Figure 6 Comparison of measured external illuminance levels caused by twelve sky sectors with the corresponding camera-based values (CIRCUMSOLAR REGION)

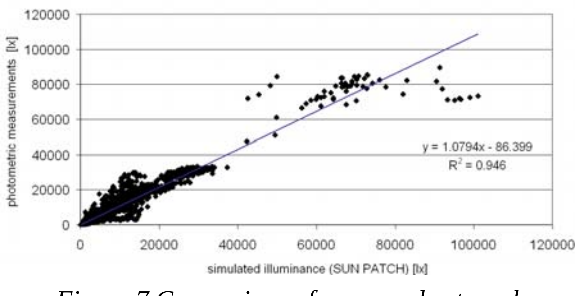

Figure 7 Comparison of measured external illuminance levels caused by twelve sky sectors with the corresponding camera-based values (SUN PATCH)

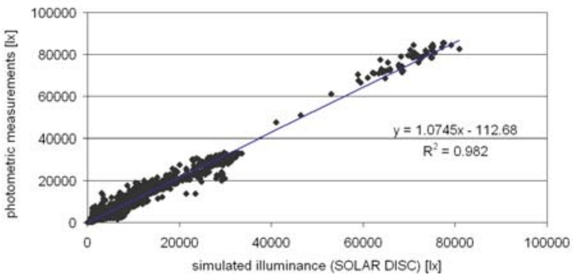

Figure 8 Comparison of measured external illuminance levels caused by twelve sky sectors with the corresponding camera-based values (SOLAR DISC)

Comparison using the scale model

The simulated illuminance levels at three points on the “floor” of the scale model were compared to the respective photometric measurements (see Figures 9 to 11).

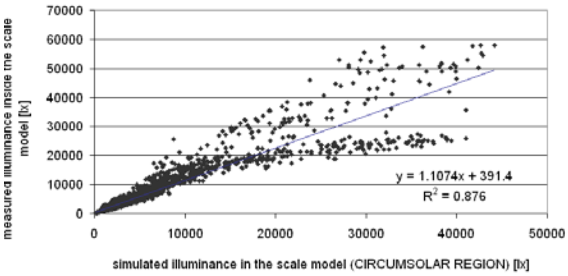

Figure 9 Simulated versus measured illuminance values in the scale model (CIRCUMSOLAR REGION)

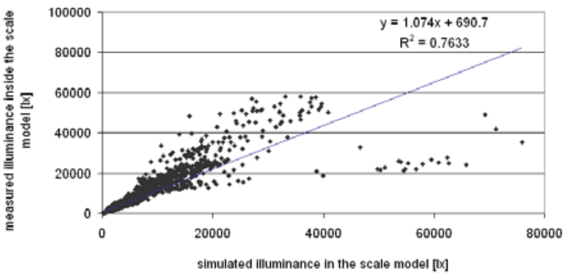

Figure 10 Simulated versus measured illuminance values in the scale model (SUN PATCH)

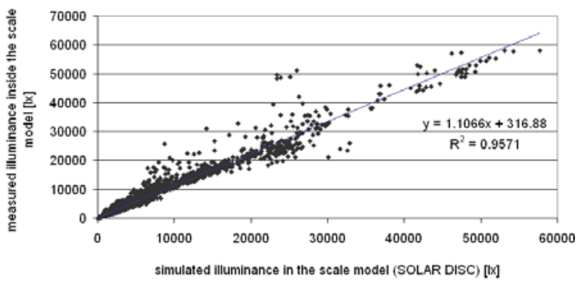

Figure 11 Simulated versus measured illuminance values in the scale model (SOLAR DISC)

Comparison based on measurements in a real space

We compared the illuminance measurements during a sixteen-day experiment for six measurement points on the working planes in the test room with the respective simulation results. The measurements involved the sensor readings in fifteen-minute intervals. For every time step the illuminance measurements corresponding to the seven different blinds positions were collected (one seven-state-cycle was completed within 4 minutes). A sky image at the beginning of each cycle was used to derive the respective sky luminance map. In total, 620 skies were considered. We used three sets of calibrated sky luminance maps within the RADIANCE lighting simulation system to obtain respective illuminance predictions. The comparison results are shown in Figures 12 to 14.

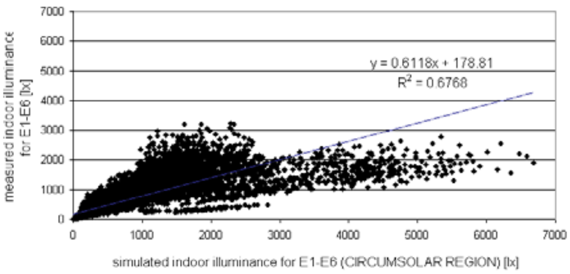

Figure 12 Comparison of simulated and measured indoor illuminance values in the test room (CIRCUMSOLAR REGION)

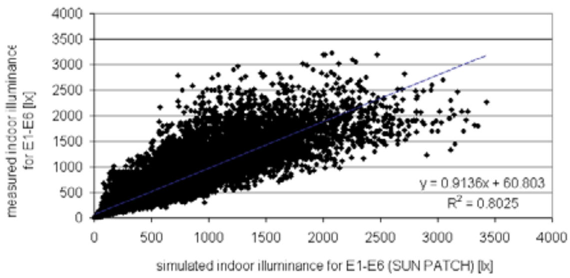

Figure 13 Comparison of simulated and measured indoor illuminance values in the test room (SUN PATCH)

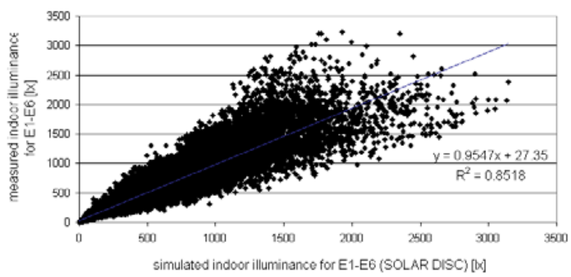

Figure 14 Comparison of simulated and measured indoor illuminance (SOLAR DISC)

DISCUSSION

The comparisons of measured and camera-based illuminance values suggest that – independent of the underlying experiment – the calibration method involving solar disc (use of smaller source of direct illuminance) performs best (see Table 1 with the comparison of the correlation coefficients for all calibration methods and experiments).

Table 1 Correlation coefficients regarding measured and camera-based illuminance values for the three experiments and the three calibration methods

	CALIBRATION METHOD		
EXPERIMENT	CIRCUM-SOLAR REGION	SUN PATCH	SOLAR DISC
Sky monitoring device	0.95	0.95	0.98
Scale model	0.88	0.76	0.96
Test room	0.68	0.80	0.85

The experiments involving the sky-monitoring device and the scale model had a more "controlled" character: The geometry of the monitoring device and the scale model are much simpler than that of the real space. Likewise, the simulation of light inter-reflections in a scale model (with a limited number of surfaces with well-defined reflection properties) is less error-prone. This explains the generally higher correlations between measured and camera-based values in these cases as compared to the respective results for the test room.

CONCLUSION

We compared three simple methods to calibrate sky luminance maps that are derived based on digital photography. These methods use the difference between measured and camera-based global horizontal illuminance levels to modify the initial luminance values of certain sky areas, namely

i) the CIRCUMSOLAR REGION;

ii) the SUN PATCH;

iii) the SOLAR DISC.

The comparisons were conducted in terms of three tests, using a

a) sky-monitoring device;

b) scale model;

c) real test space.

The results suggest that calibrated sky luminance maps derived based on digital photography can provide a reliable basis for locally representative sky descriptions in daylight simulation tools. Thus, the effectiveness of daylight simulation can be enhanced both to support design decision-making and model-based lighting control applications.

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