Lighting Res. Technol. 38,1 (2006) pp. 73–89

Design of a new single-patch sky and sun simulator

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Received 22 December 2004; revised 25 March 2005; accepted 16 May 2005

The design of a new sky simulator and its construction are described in detail. The simulator, comprising 91 tungsten halogen lamps placed in a hexagonal array, is based on the modelling of one patch of the Tregenza sky hemisphere distribution. This concept allows illuminance measurements from one geometric configuration to be used for every sky model. The sun simulator, which is also comprised of halogen lamps placed in a hexagonal array, is also described. Parallax error measurement and validation studies show that the sky presents low errors. The paper includes a review of existing skies and suns.

1. Introduction

Daylighting is one of the key elements of all architecture projects. Architects have used scale models for centuries in order to evaluate their projects under a real sky. For many years,[1] the development of artificial skies has made the studies less dependent on factors like the weather and the time of the year. Various projects can now be compared among themselves, whatever their location, for example. Of course, during these years, the evolution of lamps and the development of new electronic techniques have increased the accuracy of the measurements carried out under artificial skies.

The Architecture department of the Université Catholique de Louvain and the Belgian Building Research Institute have decided, with the support of the Belgian government, to encourage the use of daylighting in buildings, and therefore, to provide architects and building designers with tools that could help them to improve daylighting penetration and distribution in their buildings.

Following an analysis of the advantages and disadvantages of the various types of daylighting study tools, the decision was made to design a sky and sun simulator, which had not existed before in Belgium. The new instruments are located at the Belgian Building Research Institute (BBRI), in Limelette, Belgium.

The artificial sky and sun were also designed to achieve certain teaching and research goals. That is why, after a detailed study of the design possibilities, the researchers chose to build two artificial skies. The first is a mirror box, a well known concept, which can model a CIE overcast sky and will not be described further. The second is an original, new single-patch sky simulator combined with a single-patch sun simulator.

2. Review of existing artificial skies

2.1 Full covering skies and partial skies

There are two categories of artificial sky. The first category can be called 'full covering' sky and the second category contains what is called 'partial' sky. For the 'full covering' sky

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10.1191/1365782806li157oa

category, the scale model is placed under the sky and the illuminances are directly measurable and observable in the model. Mirror boxes, sky domes and the spotlight sky simulators are ‘full covering’ skies.

In the ‘partial’ skies, the sky vault is recomposed by successive rotations of the scale model or of the source, co-ordinated with an appropriate distribution of the source intensities. The illuminances and luminances for the whole sky are calculated by software. These calculations can be very simple (addition) or more complex, as in the case of the Belgian ‘single-patch’ sky simulator, which is based on the ‘daylight coefficient’ concept.[2] A more detailed description of the measurement and calculation method applied in Belgium is described in section 4.

Sector skies, Spotlines and the ‘One lamp’ sky are partial skies.

2.2 The mirror sky or mirror box

A mirror box[3,4] consists of a luminous ceiling with mirrored walls. The light source is a white diffusing material illuminated by lamps from behind. The mirrors, arranged vertically all around the periphery of the box, produce an image of the lit ceiling by reflection and inter-reflection to infinity. The main advantages of a mirror sky[5,6] are its moderate cost and its low horizon error, while the main disadvantages are that only the CIE overcast sky[7]is reproduced and that the scale model interferes with inter-reflections. An artificial sun can be placed in a mirror box, as at the Copenhagen school of Architecture,[8] but it interferes with the distribution of the sky luminance. Darlington *et al*., have developed an alternative compact box made of lateral mirrors combined with a Fresnel lens which eliminates the horizon error.[9]

2.3 Sky dome

In sky domes,[10–13] the required luminance distribution is obtained by light projected onto a reflective hemisphere acting as the sky vault.[4] The referenced sky domes[10–13] have a diameter between 3 m and 9 m.[5] They may be a diffusely reflective opaque dome surface illuminated from below, or a translucent dome (hemispherical) with lighting equipment mounted behind. An artificial sun can be installed in a sky dome. The most important disadvantage of sky domes is that inter-reflection within it means that a uniform wash of light is superimposed on the required luminance distribution, reducing the spatial gradient of luminance and making the sky luminance distribution too uniform. Some sky luminance distributions can only be obtained through limitation of the dome reflectance.[14] Another disadvantage of sky domes is that the dome needs to be large to limit the parallax error. Moreover, a horizon error can occur: points at the top of the model receive some light from below the horizon. The calibration is lengthy and difficult (from 1 day to 1 week) and the maintenance has to be done frequently.

Stupple *et al*.,[12] have outlined two alternative designs of conventional sky domes: the first is a specular paraboloid which can drastically reduce parallax and horizon errors and causes negligible inter-reflection problems. The second uses the more traditional matt hemisphere, but with a time-saving computer technique to optimize the simulation of the required luminance pattern.

2.4 Point sky simulator

The hemispherical sky vault comprises a multitude of small light sources—in comparison to the size of the dome—incandescent, halogen or compact fluorescent lamps.[15] Any type of sky can be reproduced. The calibration and maintenance are complicated by the different ageing patterns of the sources. There are also sharp changes in luminance and multiple shadows.

2.5 Sector sky

In the existing sector skies,[16–18] the complete dome is reduced to one part of the hemisphere. Extended light sources are used.

This sky is based on the measuring format proposed by Tregenza.[19] As this distribution is split by imaginary vertical planes into six symmetrical parts of 60°, the building of one sixth of the hemisphere is sufficient to recompose the entire sky vault by six rotations. This sky can reproduce any sky distribution. The calibration is relatively easy and fast and the sky requires less maintenance than a complete sky vault. The construction costs are lower than those for a complete sky. The disadvantage of this sky, and of all the 'partial' skies, is that the illuminances and luminances, as well as images, have to be computed and generated by data processing. Another disadvantage of this type of sky is that inter-reflections can occur between the lamps.

2.6 Spotline sky

The spotline[20] sky works on the same principle as the sector sky with the difference that the sector is reduced to a line made of small light sources, mounted in a quarter-circle arc. The advantages of this sky are that any sky luminance distribution can be modelled, the equipment is smaller and cheaper than a complete dome and the problem of inter-reflection between the lamps does not occur. The main disadvantages are that direct view and measurement are not possible, measurement is slow and the accuracy is inherently limited by the division of the sky into finite elements.

3. Review of existing sun simulators

The criteria to be considered when designing a sun simulator are the following: the luminous source has to provide beams that are as parallel as possible and the illuminance has to be uniform on the ground in order to give correct and representative measurements (more than 20% illuminance difference is not acceptable). The sun patch has to be large enough to allow measurements on the whole model and the light source's spectrum has to be similar to the sun's spectrum.

Only a small amount of literature exists on sun simulators: most systems have been developed for spacecraft applications by specialized companies[21,22] and are not applicable for daylighting studies because they are too small, too complex and very expensive.

However, several design concepts can be used for the building of a sun simulator. They are now detailed.

3.1 Lamp and optical corrections

The systems equipped with light sources and optical corrections are made of a single light source corrected by Fresnel lenses, providing nearly parallel beams.[23,24] These systems give high illuminances and high uniformity. Usually, the light source is not mobile: a system like a heliodon is required to rotate the model.

3.2 Parabolic reflector

For this system, the light source is placed at the focus of the parabolic reflector.[25] Owing to its optical properties, the parabolic reflector provides nearly parallel beams on the scale model if the light source is small enough. The easiest way to simulate the solar displacement is to move the scale model but other applications can use a moveable source coupled with a moveable parabolic reflector.

3.3 Halogen lamps

The sun simulators made of halogen light sources providing near parallel beams are based on more basic concepts.[26] They are made of one or more lamps that light the model directly. Some kinds of lamps may contain reflector systems to reduce beam spread.

Light sources arranged in a honeycomb structure are quite large and are usually fixed. The sun movement is simulated by rotation of the model.

3.4 Fluid optics

Recently, fluid optics reflectors[27] have been developed. A dynamic fluid optics reflector is an optical system made up of a container containing a fluid moving in liquid state and traversed by light radiation.[28] These components have very particular optical properties: they have a natural disposition to make the light coming from wide sources, which may be multiple, more collinear while filtering out, in a radical way, a defined part of the energy produced by these sources, especially the infrared energy. This technology seems interesting but not enough information and no concrete experience with fluid optics was available at the beginning of our study.

4. Single-patch sky simulator

4.1 Description

4.1.1 Concept

The single-patch sky is based on the same principle as the sector skies described earlier. The difference is that only one patch of the modified Tregenza distribution[19] is modelled. The method applied here is based on the daylight coefficient principle.[29] In the Tregenza distribution, the vault is covered by 145 circular patches, thereby assuring a global covering rate of 68% (set to 100% by a rule of 3) and providing an acceptable discretization of the sky vault. In view of this consideration, the measured values may be considered as equivalent to the real illuminance value (scaled at 0.68) avoiding any extra covering rate problem. Each patch is characterized by a unique position as a function of the centre of the hemisphere and all superimposition is avoided. To approach the sky conditions more accurately, additional software corrects the coverage to 100%.

The main advantages of this choice are a low cost, a limited calibration procedure, easy control of the lamp flux variation due to variation in the supply voltage during the measurement, and the limited area required for the installation, allowing a greater apparent diameter of the dome.

An additional advantage is that it is possible to weight the flux from each patch independently from 0% to 100% by a weighting factor that is applied to the measured illuminance (there is no dimming of the lamp).

As it is much easier to move the architectural model than to move the lamps, it was decided to fix the lamps and to place the model on a turntable. This table has two orthogonal rotation axes. The two axes allow definition of 145 positions for simulating the equivalent number of sky patch positions (see Figure 1).

For each position (azimuth, elevation), of the patch (k), the illuminance E_k is measured at the desired point. To work under constant light flux, the measured illuminances under patch k ($E_{mes,k}$), shown in Figure 2, are corrected as a function of the illuminances measured by an additional fixed monitoring illuminance meter looking at the light source and providing information on light flux variation when measuring (E_k).

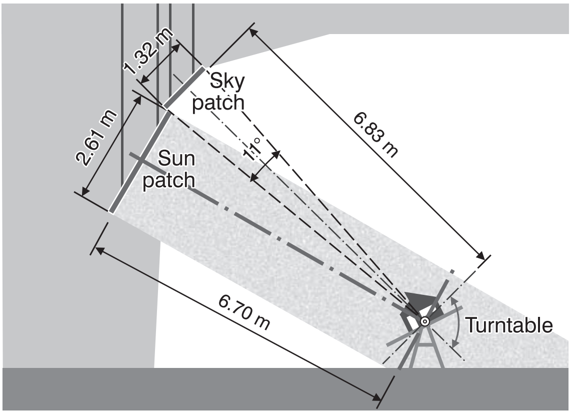

Figure 1 Single-patch sky and sun simulator

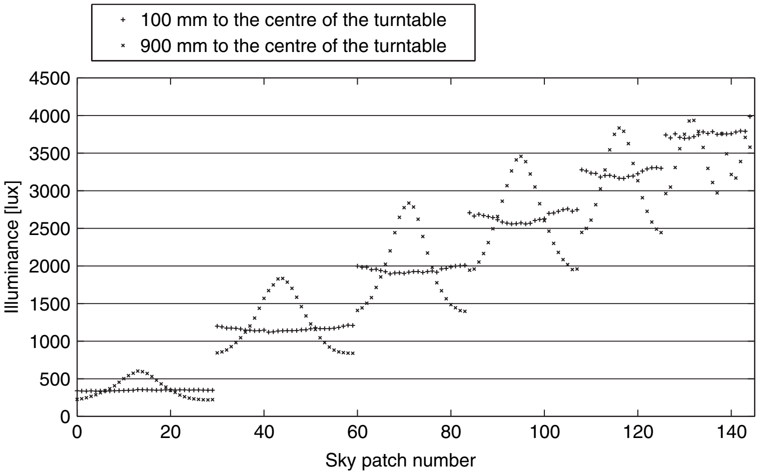

Figure 2 Horizontal illuminance on the turntable for the 145 patches

$$E_{cor,k} = \frac{E_{ref\_captor,1}}{E_{ref\_captor,k}} \times E_{mesk} \tag{1}$$

with:

$E_{cor,k}$: illuminance under patch k (k varies from 1 to 145)
$E_{ref\_captor,k}$: illuminance measured on reference meter under patch k
$E_{ref\_captor,1}$: illuminance measured on reference meter under patch 1
E_{mesk}: illuminance measured under patch k

After the measurements have been made and the corrections for the 145 positions applied, each illuminance measurement is multiplied by its weighting factor c_k(azimuth, elevation), which is a function of the patch position and the sky luminance distribution. Table 1 gives the weighting factors (c_k) for the standard CIE overcast sky.

The total illuminance value E at point P is the weighted sum of the 145 corrected illuminances ($E_{cor,k}$) for this point.

$$E_P = \sum_{k=1}^{145} c_k \times E_{cor,k} \tag{2}$$

The calculation of the daylight factor (DF) is made by dividing the total illuminance by the absolute illuminance measured in the centre of the plate without any model, which has been previously stored in the computer memory.

$$\begin{aligned} DF_P(\%) &= \frac{E_P}{E_0} \times 100 \\ &= \frac{1}{E_0} \times \left(\sum_{k=1}^{145} c_k \times E_{cor,k} \right) \times 100 \end{aligned} \tag{3}$$

with: E_0, the total horizontal illuminance at the centre of the free turntable, under the same diffuse light flux as the one of the patch 1 measurement. The total illuminance value E_p measured on the turntable (based on the 145 separated values combined with the 145 weighting factors) can be up to 220 000 lux. Figure 3 shows that the daylight factor measured along the diameter of the turntable has less than 3% variation in its central zone (circle of 1 m diameter), which represents a very high uniformity level.

Other sky models can be modelled by using appropriate weighting factors (ie, CIE clear

Table 1 Weighting factors for each of the 145 patch positions (CIE overcase sky)

Strip	Elevation angle (horizon = 0°) [°]	Number of patches	Horizontal angle between the patches [°]	Weighting factor = (1 + 2sinE)/3
1	6	30	12	≈0.403019
2	18	30	12	≈0.539345
3	30	24	15	≈0.666666
4	42	24	15	≈0.779420
5	54	18	20	≈0.872678
6	66	12	30	≈0.942364
7	78	6	60	≈0.985432
8	90	1	—	1

sky). The determination of these weighting factor values is based on the calculation of the average luminance of each sky patch of the Tregenza distribution.

The average luminance of each patch (L_k), is determined on the basis of the corresponding sky vault element's luminance, which is a function of its altitude and elevation. The (L_k) average value is obtained by summing the luminance of all the points in the vault element and by dividing this value by the number of points in that vault element. The discretization of the vault element is a function of its position because it is based on a calculation of the azimuth and altitude (see Figure 4).

The number of steps for the discretization is not the same for each element and is a function of the altitude of the element. For instance, the First patch of the First row—from 0° to 20° azimuth and from 0° to 12° altitude—is based on 273 luminance values (21 × 13), the first patch of the seventh row—from 0° to 60° azimuth and from 72° to 84° altitude—is based on 793 luminance values (61 × 13).

The sky luminance is thus determined for each azimuth and each altitude value; 32 401 relative luminance (360 × 90 + 1) values ($L_{i,j}$) are calculated.

$$L_k = \frac{\sum_{j=1}^{m}\left[\sum_{i=1}^{n} L_{i,j}\right]}{m \times n} \tag{4}$$

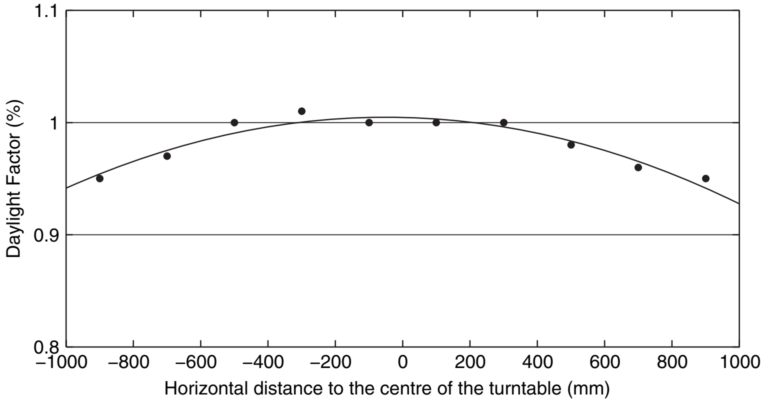

Figure 3 Measured daylight factor on the plate (%)

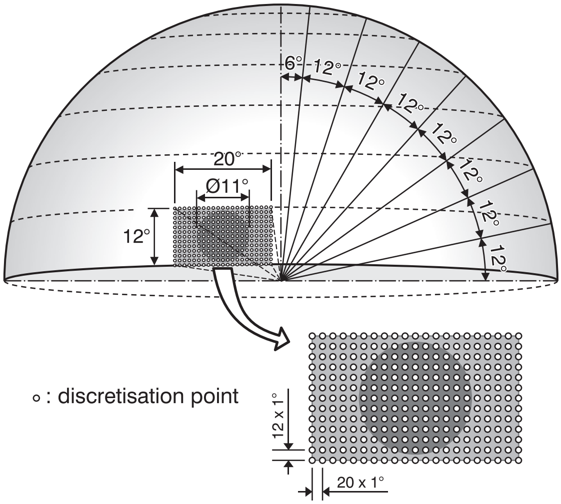

Figure 4 Discretization of a patch element

with:

L_k: average luminance of patch k
m: number of calculation points on horizontal subdivision
n: number of calculation points on vertical subdivision
$L_{i,j}$: the luminance of point i, j calculated by following the CIE formula.
For CIE overcast sky, $L_{i,j}$ is function of the elevation (γ_p) of the point.
For CIE clear sky, $L_{i,j}$ is function of the elevation (γ_s) and azimuth (α_s) of the sun, and of the luminance of the zenith ($L_{zcl}(\gamma_s)$)

All the L_k luminance values are then divided by the average luminance of the zenith patch $L_{k,zenith}$. These 145 values are the reduction factors F_k, given by:

$$F_k = \frac{L_k}{L_{k,zenith}} \tag{5}$$

These reduction factors are combined with the corrected measured ($E_{cor,k}$) values to give the illuminance contribution of the patch. After combining these 145 values, a scale factor (S) is applied to give the real illuminance.

This scale factor is obtained by dividing the simulated horizontal illuminance calculated for the centre of the turntable (E_0)—without any model—by the illuminance value measured on the top of the model (E_{top}), at the vertical of the turntable centre.

$$S = \frac{E_0}{E_{top}} \tag{6}$$

where: E_0 is the illuminance at the centre of the turntable.

This value is presently an external output but will soon be automatically displayed and provided by the installation system.

$$E_{top} = \sum_{k=1}^{145} (F_k \times E_{top,k}) \tag{7}$$

where: $E_{top,k}$ is the illuminance value measured on the top of the scale model under patch k.

The calculation of the total illuminance at point P (E_P) is obtained by:

$$E_P = S \times \sum_{k=1}^{145} \left(\frac{L_k}{L_{k,zenith}} \times E_{cor,k} \right) \tag{8}$$

Or

$$E_P = E_0 \times \sum_{k=1}^{145} \left(\frac{L_k}{L_{k,zenith}} \times \frac{E_{ref\_captor,1} \times E_{mes,k}}{E_{top,k} \times E_{ref\_captor,k}} \right) \tag{9}$$

4.1.2 Practical considerations

For a given size of available space, this system allows a larger diameter for the installation. The construction of a patch of 1.4 m viewed at an opening angle of 11° makes the diameter equivalent to 13.5 m.

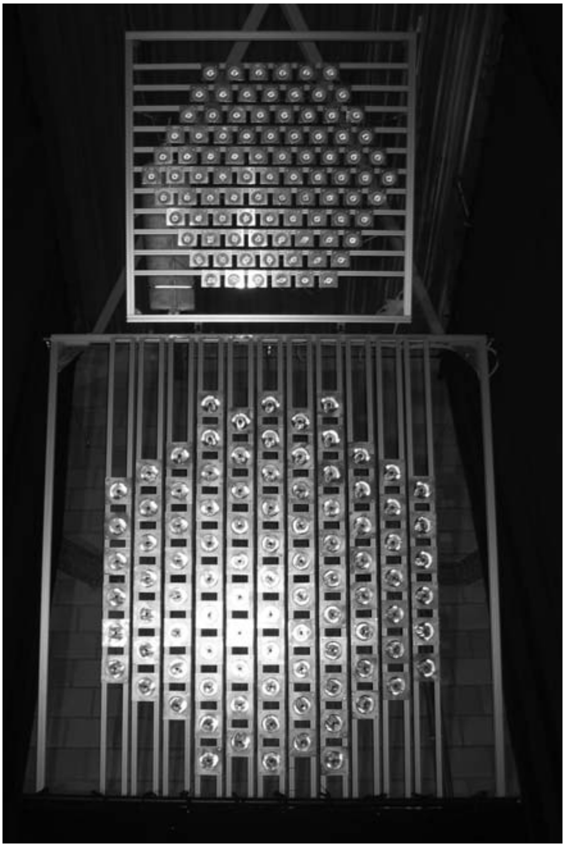

Figure 5 Single-patch sky (above) and sun simulator (below).

The use of only one patch reduces the area needed to less than 35 m^2 at floor level.

The main disadvantage of the single-patch simulator is in the production of images. Complex calculations are required for this, which until the recent development in computer technology were beyond the reach of the non-specialist.

But this disadvantage is also linked to one of its main advantages: once the measurements are done for one geometrical configuration of the model, any kind of sky may be simulated by modifying the weighting factors of the 145 illuminance patches with the computer (one geometrical configuration measurement requires about 1 h 15 min—the time varies as a function of the number of illuminance meters and the exposure).

As it was not possible to find a 1.6 m diameter lamp, we used small lamps, geometrically placed to give the most uniform horizontal illuminance possible.

The choice of the lamps and of their layout was based on Radiance[30] and manual lighting calculations. Different lamps (tungsten–halogen lamps of 19°, 30°, 38°, 40° beam width and with peak intensities of 1800 cd, 950 cd, 1800 cd and 400 cd, respectively) and different geometrical arrangements (hexagons, squares, circles, optimized circles) were modelled in order to simulate the most uniform luminous patch possible. From the different geometrical configurations analysed, the one that gave the best uniformity is the 91-halogen-lamp hexagonal array. The lamps used were 50 W—12 V low voltage and low pressure halogen lamps (38° beam width, 1800 cd peak intensity), which provide 3500 lux on the turntable with a uniformity of 97%, when the turntable is parallel to the plane containing the light source (see Figures 5 and 6).

The horizontal illuminance provided by the sky source is measured for each of the 145 positions. These values are a function of the inclination angle between the plate and the light source and of the distance between the

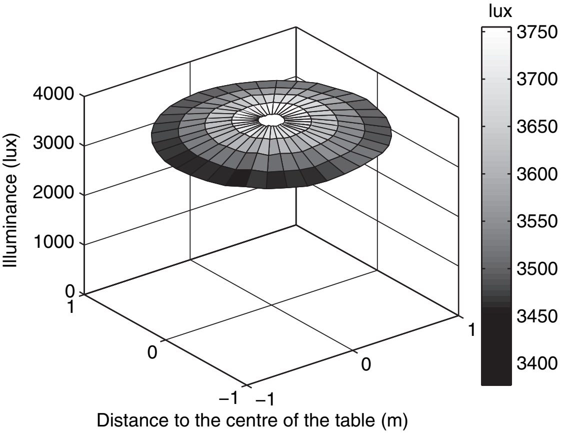

Figure 6 Illuminance provided by the sky patch on the turntable which is parallel to the sky patch

light source and the measured point. For each strip there is a variation of the average horizontal illuminance. When the elevation angle of the patch increases, the average horizontal illuminance increases as well. Inside each strip the measured illuminances vary in relation to the distance to the light source (as a function of the 360° rotation inside this strip). The variation is much less for the points located near to the centre of the table, which is logical. These variations are greater for points at the extremity of the plate (0.9 m distance to the centre).

4.2 Parallax errors

To evaluate the performances and the limits of the acceptable models, the parallax error was evaluated by measuring the vertical and horizontal illuminance in the plane containing the two rotation axes.

4.2.1 Simple parallax error

Simple parallax error (S_{PE}) is an important parameter; it characterizes the quality level reached by the artificial sky and specifies the maximum scale model dimensions. As explained by Mardaljevic,[31] the simple parallax error is a function of the vertical illuminance measured at the origin (centre of the turntable) and of the vertical illuminance measured at the point where this error is computed.

$$S_{PE}(\%) = \left(\frac{V_p - V_O}{V_O}\right) \times 100 \qquad (10)$$

where:

V_P is the vertical illuminance value at the point P (where the S_{PE} will be characterized)

V_o is the vertical illuminance value at the origin (centre of the turntable).

Measurements were taken in the vertical plane passing through the origin of the turntable and containing the two rotation axes. The vertical illuminances were measured every 200 mm horizontally and every 100 mm vertically, which represents a total of 99 points.

The S_{PE} error was characterized for the standard CIE overcast sky and Figure 7 shows that the S_{PE} error increases with the distance to the centre of the turntable (horizontally and vertically). A maximum absolute error of 18% was measured in this plane. To get correct sky simulations, a maximal 12.5% S_{PE} will be accepted and, due to the symmetrical aspect of this error, the models will be limited to 1 m × 1 m × 0.7 m.

This relatively low parallax error is linked to the D-ratio (the diameter of the plate divided by the apparent diameter of the artificial sky: 1.8 m/13.6 m $\approx$0.132). The greater the D-value, the greater the parallax error. So, to limit the parallax error on the measurements, the models must fit within a 1 m diameter circle. The D-value is then equal to 0.073, which is between 0.062, the D-value of the dome at Welsh School of Architecture (Cardiff University, UWCC) and 0.100, the D-value of

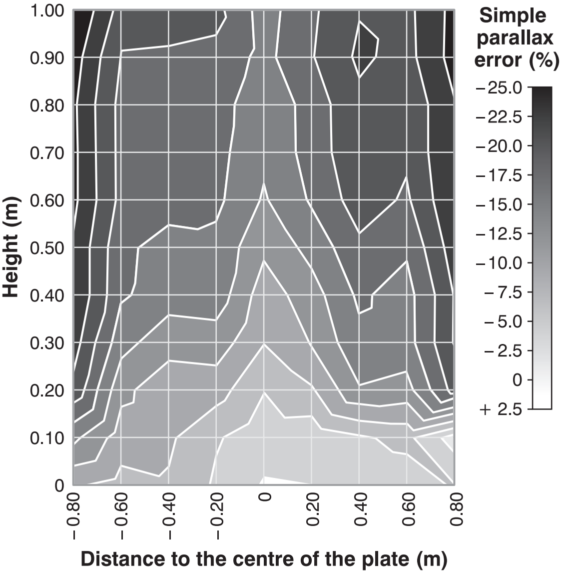

Figure 7 Simple parallax error in a vertical plane passing through the origin

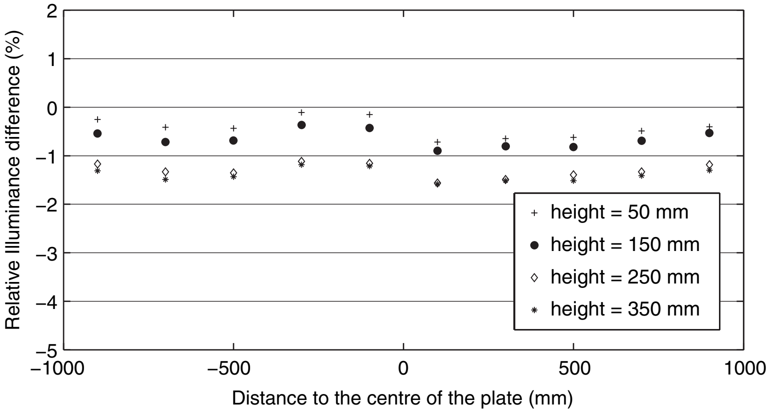

Figure 8 Horizontal illuminance difference in relation to the distance from the centre for several heights of the turntable

the dome at University College London (UCL, UK).[31]

To achieve the best accuracy, the height of the turntable can be adjusted so that the centre of the window may be made to coincide with the geometrical centre of the dome (if the model has multiple light apertures, it is best to superimpose the geometrical centre of the model and the centre of the dome). Additional studies have shown that the vertical displacement of the plate has no significant influence on the measurements (1% illuminance variation for 350 mm height variation of the plate) see Figure 8.

4.2.2 Compound parallax error

Compound parallax error occurs when the unobstructed horizontal illuminance, necessary for the daylight factor calculation, cannot be measured at the origin, owing to the presence of the scale model.[31] The single-patch simulator of the Belgian Building Research Institute avoids this error by allowing the calculation of the daylight factor by using the absolute illuminance measured without any model on the turntable, and the illuminance values measured in the scale model. To work under constant light flux, a correction is made to the light source flux.

5. Single-patch artificial sun

As demonstrated by the previous review, only two sun simulator models were realizable at reasonable costs: a lamp with optical corrections and a halogen lamp.

According to the sky lamp concept, the sun simulator is made of a hexagonal array of 95 halogen 50 W 12 V lamps (4° beam width).

This installation provides an extremely high illuminance on the turntable (see Figure 9).

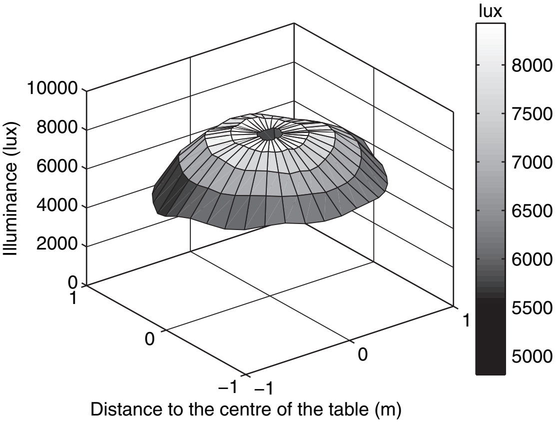

Figure 9 Illuminance provided by the sun source on the turntable which is parallel to the sun source

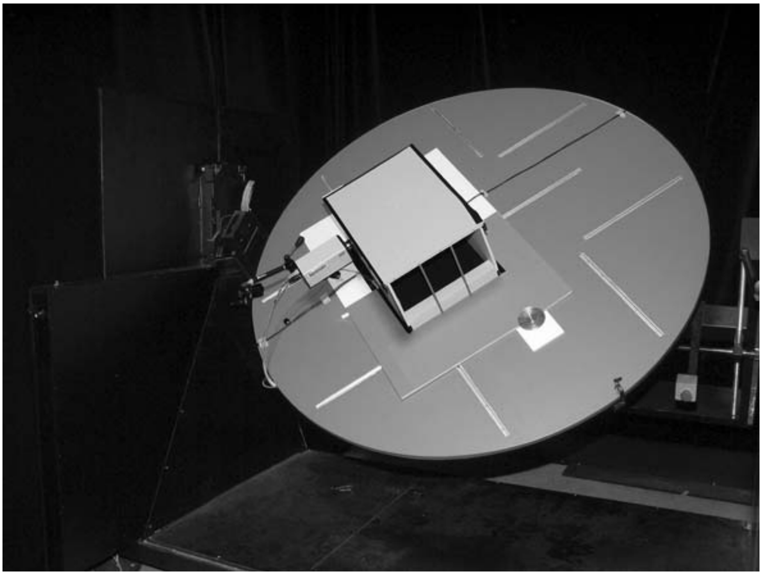

Figure 10 The turntable

When the turntable is perpendicular to the sun's rays, its central illuminance is greater than 8500 lux. The illuminance uniformity is higher than 90% within a circular zone of 1 m diameter. But, outside this circle the illuminance is not uniform at all and the illuminance reduced by more than 40%. This limitation is acceptable owing to the size limitation on the models.

The turntable allows rotations of the scale model, thereby simulating the sun's displacement. The algorithm developed by Szokolay was used for calculating the sun's position as a function of the localization, the date and the hour.[32]

The illuminance values are directly measured by following the software user's specifications and weighted to the appropriate value (ie, 80.000 lux) or are combined with other illuminance measurements under the diffuse sky source to achieve the simulation of the CIE Clear Sky with sun.

The use of a camera also allows visualization of the sunlight penetrating the model.

6. Measurement tools

Two kinds of measurement are possible: illuminance and luminance. Twenty illuminance meters, cosine corrected and corrected to have a $V(\lambda)$ response, are available to make measurements on the table.

Interior ambiances are also available. Indeed, the CCD movie camera takes a picture for each position of the luminous patch and, after completion of the 145 rotations, a numerical combination provides the interior view of the model. The numerical combination of the 145 pictures is arrived at in the same way as the illuminance combination explained in section 4.1: a weighting factor based on the average luminance of the patch is used for each of the pictures. Black and white or colour pictures are available and may be presented as an animation sequence in order to visualise the displacement of the sunlight in the model. The use of these pictures is currently 100% visual and qualitative but further developments would enable one to use this camera

Figure 11 Interior view of models

to be used as a video-luminance meter. Also quantitative data and views (colour charts with luminance distributions) could be obtained. For a picture of the turntable see Figure 10, for an interior view of the models see Figure 11.

7. Validation measurements

After building the single-patch artificial sky and sun, validation measurements were performed.

To validate the CIE overcast simulations, measurements were taken on a model for 36 different geometrical configurations. The DF measurements were realized under the mirror box and the single-patch sky simulator. The measured values were compared to software simulations, carried out with Superlite software,[33] that are very close to them (less than 1% absolute difference for the DF) (see Figure 12).

Validation measurements have also been done for CIE clear sky simulations under the single-patch sky simulator. The illuminances were measured and calculated for different

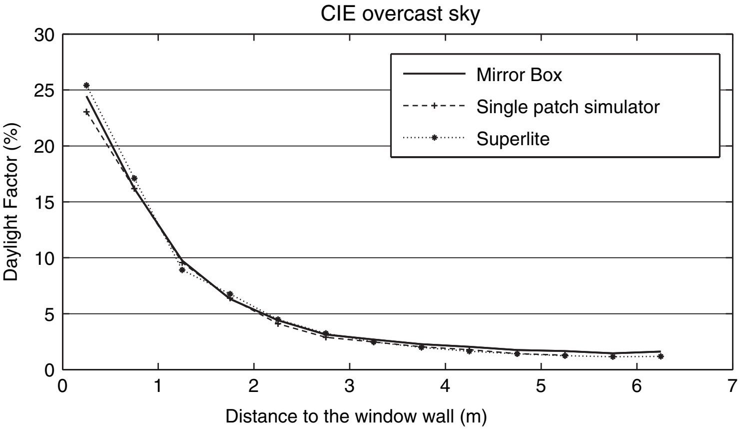

Figure 12 Example of validation results (Daylight Factors)

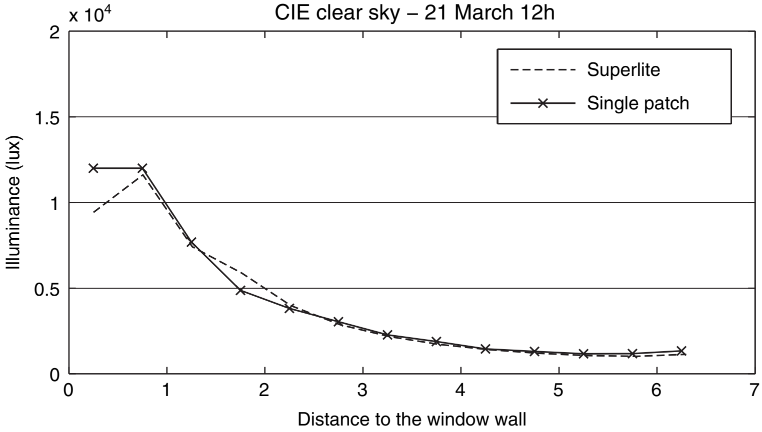

Figure 13 Example of validation results (Illuminance—CIE Clear sky)

dates (21 December, 21 March, 21 July) and for different solar hours (09:00 h, 12:00 h and 15:00 h) (see Figure 13).

Additional validation measurements were also taken under the single-patch sun simulator.

All these results are available and will be presented in a future publication.

8. Conclusion and future work

The BBRI and the 'Université Catholique de Louvain' have developed a single-patch sky and sun simulator that is unique. This basic concept is simple but its realization was not possible before the development of numerical technology. This advanced tool simulates the sky to a high precision.

The 13.5 m apparent diameter allows the study of quite large models, measuring 1.0 m × 1.0 m × 0.7 m, while keeping the simple parallax error below 12.5%. Full dome reconstruction requires about 1 h 15 min and allows modelling of all sky types for one geometrical configuration without any additional measurements.

The global recombined turntable illuminance distribution reaches a high uniformity and is very close to the theoretical values. The differences between the theoretical and measured values on the turntable are less than 3% at 700 mm from the centre of the turntable.

An additional single-patch artificial sun allows simulation of the sun-curve as a function of the orientation, the latitude, the time and the date. Combinations of both kinds of measurements are possible and give an image of the illuminance distribution. Three-dimensional images of the interior scene are also available, which helps designers to understand light distribution within models.

Future work will aim at achieving complete interior luminance measurements for all possible cases. It will also compare the results obtained with those obtained under other artificial skies.

Acknowledgements

The authors wish to thank the Walloon and Flemish governments for their support in funding the simulators design and construction. The validation work has been funded by the Walloon Government.

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Discussion

Comment 1 on 'Design of a new single-patch sky and sun simulator' by M Bodart, A Deneyer, A De Herde and P Wouters

P Raynham (The Bartlett School of Graduate Studies, University College London, UK)

The authors of this paper are to be congratulated on the way that they have systematically reviewed artificial sky design and developed their own sky for which they have characterized the main operating parameters. Clearly they have developed a system that can assess natural light in architectural models to a relatively high degree of accuracy.

As an operator of a lighting simulation facility, I regularly use a large variable luminance sky with architectural models as well as using lighting simulation software. Whilst I am aware of the improved accuracy of the simulation results that I get when using software I still find that architectural models are very useful for certain types of work. The key advantage of the physical modelling appears to be the intuitive nature of the model and its lit appearance. This makes it very easy for the user to interact with the model and make modifications to the model and instantly see the results in terms of a change of lit effect. Whilst we photograph and measure illuminance inside the models this information tends to be only used as record of events in the sky rather than forming part of the design process.

I was very interested to read this paper on this new single-patch sky, however I was a little concerned that some of the intuitive relationship between the designer, the model and its lit appearance may have been lost as it as not as easy to visualize changes in the lit appearance. It would be very informative to have the authors' views on the use of this sky and how it compares to generating the same lighting performance data using lighting simulation software.

Comment 2 on 'Design of a new single-patch sky and sun simulator' by M Bodart, A Deneyer, A De Herde and P Wouters

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Considerable capital investment has been made in the construction and operation of full-hemisphere sky simulator domes for the evaluation of daylight in physical models. The authors present an intriguing development in this area with a design that is based on a single patch of sky. As noted by the authors, the single-patch sky simulator is in effect the physical embodiment of Tregenza's daylight coefficient (DC) approach. And therefore suitable, in principle, for the prediction of annual daylighting profiles founded on hourly meteorological data.[1,2] Full-hemisphere sky domes could also be used to determine DCs through the sequential switching of lamps ie, using only one lamp at a time. However, the single-patch sky simulator should offer a far more cost-effective means of determining DCs than a full-hemisphere sky simulator. Operational factors may also favour the single-patch sky since only a steady output is needed. The differences are not just with the capital cost of equipment, the volume of space required for a single-patch sky simulator is much less than that of a full-hemisphere sky. It may be argued that the full-hemisphere skies offer a tangible advantage where the model interior can be directly viewed. As far as I am aware, full-hemisphere domes cannot reproduce absolute illumination values. Nor can the illumination effect of the sun be modelled simultaneously with that of the sky, at least not without reducing the absolute illumination from the sky lamps to miniscule levels to maintain the correct relative level with that from the sun lamp. I suspect that most of us would struggle to notice the difference in visual appearance between a model illuminated by a full-hemisphere sky simulator and the same model under an improvised 'sky' comprised of some muslin cloth and a few lamps. (Unfortunately, no such comparison has ever been carried out as far as I am aware.) In consequence, I remain sceptical that viewing a model illuminated by a sky simulator dome can offer any meaningful insight. Indeed, the perceived benefits of model viewing under seemingly 'controlled' conditions are, I believe, largely illusory, and if it must be done, then it may as well be under a real sky with a real sun. If one shares these views, then the single-patch sky simulator seems to have the upper hand over its more amply endowed full-hemisphere cousins—at least for quantitative illuminance modelling provided that it can be shown to be reliable.

A question however remains: why use physical modelling at all? The single-patch sky simulator reduces the parallax error which is an inherent problem with finite-sized skies. Scale models, however, are subject to construction errors that result in significant divergences between illuminances measured in an actual building and its scale model representation.[3] Cannon-Brookes study showed scale model illuminances to be consistently 200% or more greater than those in the actual building under real sunny sky conditions. In contrast, the *Radiance* validation under real sky conditions (ie, the BRE-IDMP dataset) showed illuminance predictions to be generally within 20% or less of the measurements.[4] Accordingly, I believe that the case for physical modelling needs to be demonstrated unambiguously: what are the advantages and disadvantages over computer simulation in terms of accuracy, reliability, practicality, and flexibility? Closely related is the deeper issue: what should a daylight evaluation consist of? Should it be qualitative or quantitative, images or numbers, daylight factor or climate-based, or some combination? Daylight evaluation is at a crossroads, and there is disenchantment in many quarters with the standard approaches (eg, daylight factors). Thus the developers of new tools have the opportunity to influence the future of daylight evaluation. I look forward to the author's comments on this discussion.

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Authors' response to P Raynham and J Mardaljevic

M Bodart, A Deneyer, A De Herde and P Wouters

The divergence of opinion which appears in the comments from Mr Raynham and Dr Mardaljevic reflects the current tendency for disagreement between the daylight studies based on architectural models and daylight studies based on computer simulations.

We think that both methods have their advantages and disadvantages but our experience indicates that it is essential for architects to personally appreciate the luminous environment of a space and to compare several solutions qualitatively.

This intuitive appreciation obtained by a scale model cannot currently be obtained by use of computer simulations.

Moreover, some authors state that scale models still represent a standard method for the assessment of the daylighting performance of buildings and even generally supersede computer models for common practical daylight design.[1]

The single patch sky does not allow a direct view in the model. This weakness led us to build a mirror box sky as a complementary tool, which was much appreciated by architects. This enabled us to test and compare several architectural solutions, under a CIE overcast sky. In practice, the single patch sky is mainly used for quantitative results and for sun illumination studies. In future it will be used for prediction of annual electric lighting consumption by using the methodology developed by Reinhart in Daysim.[2]

Concerning the accuracy of scale model measurements under sky simulators, Cannon-Brookes study showed that the two main sources of errors are dimensional and those due to photometric properties of materials used in interiors.[3] These two sources of errors can each be divided into survey errors and model errors. The survey error also occurs in computer calculations. The errors in scale models can be minimized by choosing an appropriate scale for the model and by strict conformity to the dimensions. The choice of appropriate materials is crucial to minimize the photometric model error; for this reason, we are developing a web tool that helps the architects in the choice of the scale model materials. This web tool is based on photometric measurements of full scale and scale model materials, included in a database.

If the model is built accurately, the measurement results can achieve high accuracy. The comparison we made on a simple office room gives a low root mean square error (maximum 17.7% for CIE overcast sky and 16.8% for a CIE clear sky) and high correlation between the single patch sky results and the Superlite simulation results (more than 96.9% for all types of sky).

In response to Mr Mardaljevic's question, a daylight evaluation should consist of a combination of qualitative and quantitative results that leads to images and numbers, even if the scientific community does not agree on which figure we should study and which value we should reach.

Moreover, in the current context of sustainable development, it is essential to be able to compare several architectural solutions, in order to evaluate the potential for annual electric energy savings to be achieved with a good daylighting design.

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