The new Belgian single-patch sky and sun simulator and its validation

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1. Abstract

A new type of sky and sun simulator has been developed in Belgium. This paper presents this new sky and sun simulator and the mirror box built as a complementary tool of this one. The simulator, made of 91 halogen lamps placed in a hexagonal shape, is based on the modelling of one patch of the Tregenza sky hemisphere distribution. Thanks to this concept, the illuminance evaluation of one geometric configuration made from one measurement set is usable for every sky model. The sun simulator, which is also made of halogen lamps placed in a hexagonal shapes is also described. This paper presents the parallax error measurements. The very intensive validation work is also summarised; it shows that the tools are powerful and present very low errors.

2. Introduction

Daylighting is one of the key elements of all architectural projects. Architects have used scale models for centuries in order to evaluate their projects under 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.

It has been 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 choice 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 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 the second is an original, new single-patch sky simulator combined with a single-patch sun simulator.
Validation studies have shown good uniformity and a low parallax error.

3. The Mirror Box

The mirror box sky has the great advantage of providing direct results and views, and is therefore of great didactic interest. This sky is mainly intended for didactical purpose.
The mirror box is a wooden cube of 3.30 m wide. The vertical walls are covered by mirrors. The first validation’s measurements showed that the luminance values were too poor at low elevation angles (between 0° and 15°). The mirrors were thus curved at their bottom in order to reach the CIE overcast sky luminance distribution.
Fig. 1 illustrates the luminance distribution before and after curving the mirrors, compared with the CIE overcast sky theoretical luminance distribution.

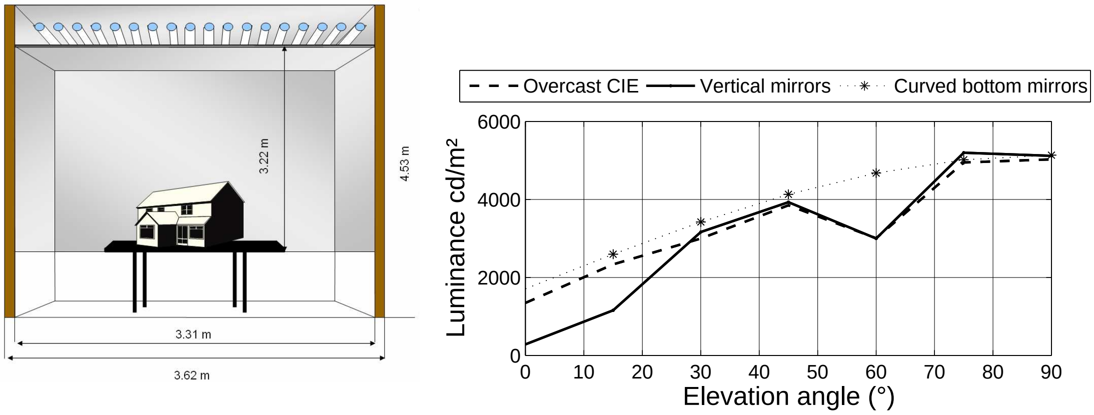

Fig. 1 :The mirror box and its luminance distribution

The ceiling is made of 101 TL lamps (6500 K) behind a diffusing plate providing an horizontal illuminance of about 10 000 lux on the floor of the Mirror Box. The uniformity of the floor horizontal illuminance is higher than 92 %. The luminance of the walls viewed from the centre of the mirror box was also measured for different heights and for a 360° horizontal rotation. Fig. 1 clearly shows that the measured values follow the theoretical values exactly, except at 60 degrees altitude. This disturbance is due to some inter-reflexions at the junctions of the vertical walls and the ceiling.
The presence of models inside the Mirror Box has an effect on the luminance distribution of the sky. Some of the mirrors are obstructed and the inter-reflexions are disturbed. Those effects have a significant impact on the measured values (but not yet precisely evaluated). For this reason, the model's height is limited to 0.7 m. For practical reasons, the scale model's base is limited to 1.1 m x 1.1 m.

4. Single-patch simulator

4.1. Description

The single-patch sky is based on the reduction of the complete dome sky to one part of the hemisphere; only one patch of the modified Tregenza distribution (2) is modelled. The here applied method is based on the daylight coefficient principle (3). In the Tregenza distribution, the vault is covered by 145 circular patches assuring by this a global covering rate of 68% and providing an acceptable discretisation of the sky vault. Due to this consideration, the measured values may be considered as the image of the real illuminance value (scaled at 0.68) avoiding any extra covering rate problem. Each patch is characterised by a unique position as a function of the centre of the half sphere and all superimposition is avoided. In order to approach the real sky conditions, an additional software correction sets the covering rate to 100%.
The main advantages of this choice are a low cost, a limited calibration procedure, an easy control of the lamp flux variation during the measurement (inherent to the power supply) and the limited area required for the installation, allowing greater apparent diameter of the dome.
An additional advantage is the independent light flux weighting of each patch from 0 to 100% because of the numerical weighting that is applied on the measured illuminance value (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 rotating table. This table has two orthogonal

rotation axes. The two axes allow definition of 145 positions, simulating the 145 diffuse sky patch positions.

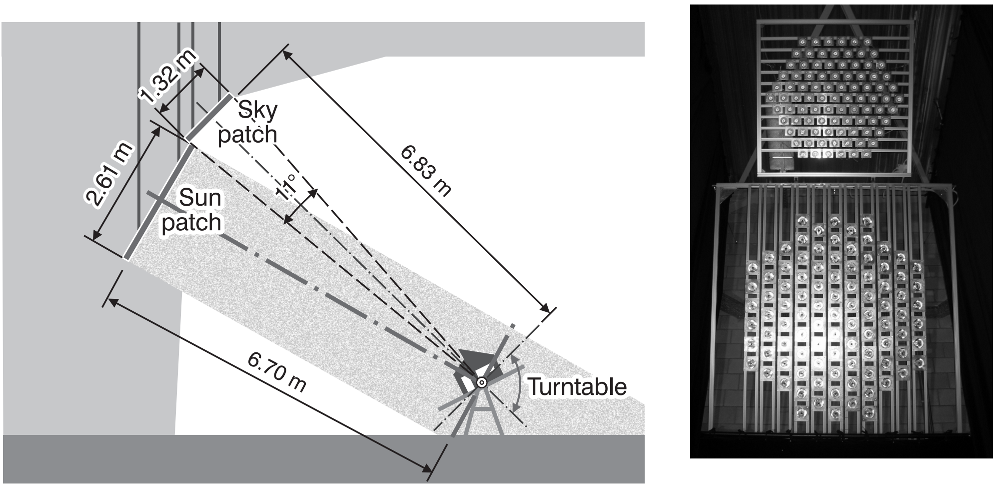

Fig. 2 : Single-patch sky and sun simulator

The realisation of such a partial system also allows a larger diameter for the installation. The construction of a patch of 1.4 meters viewed at an opening angle of 11° makes the diameter equal to 13.5 meters. The use of only one patch reduces the area needed to less than 35 m^2 at floor level.

The main disadvantage of such a configuration resides in the image treatment of the measurements. This system is based on many computer calculations that could make the system not very attractive for non-specialists. This concept was not applicable until recent computer development that allows now fast calculation procedure.

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 1h15 time varies in function of the number of illuminance meters and the exposure).

The design of the light sources was based on Radiance and manual lighting calculations. 91-halogen-lamp are placed according an hexagonal array. The lamps used are 50 W - 12 V low pressure halogen lamps that provide 3500 lux on plate with a uniformity of 97 %, when the turntable is parallel to the light source (the normal axis of the turntable is parallel to the normal axis of the light source).

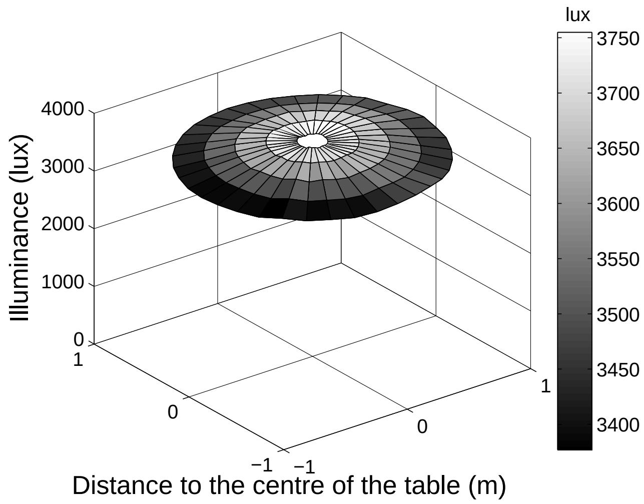

Fig 3.: Illuminance provided by the sky patch on the turntable which is parallel to the sky patch

4.2. Parallax Errors

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

The Simple parallax error (4) was characterized for the standard CIE overcast sky and Fig. 4 shows that the Simple parallax error (S_{PE}) 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 1m x 1m x 0.7 m.

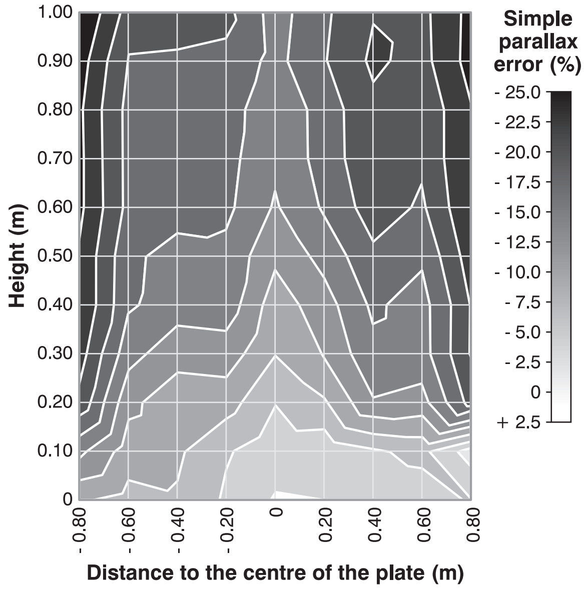

Fig. 4 : Simple Parallax error in a vertical plane passing at the origin

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 ≈ 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 meter 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 the dome at University College London (UCL, UK) (4).

The compound parallax error occurs when the unobstructed horizontal illuminance, necessary for the daylight factor calculation, cannot be measured at the origin, due to the presence of the scale model (4). The single-patch simulator of the Belgian Building Research Institute avoids this error by calculating the daylight factor using the absolute illuminance level measured without any model on the plate and the illuminance values measured in the scale model. In order to work under constant light flux, a correction is made on the light source flux.

5. Single patch sun simulator

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 extremely high illuminance on the plate. When the turntable is perpendicular to the sun rays, its central illuminance is greater than 8500 lux. This illuminance value stays quite constant within a circular zone of 1 meter diameter (uniformity greater than 90%). But, outside this circle the illuminance is not uniform at all and more than 40 % of the illuminance value is lost. This limitation is acceptable due to the size limitation on the models.

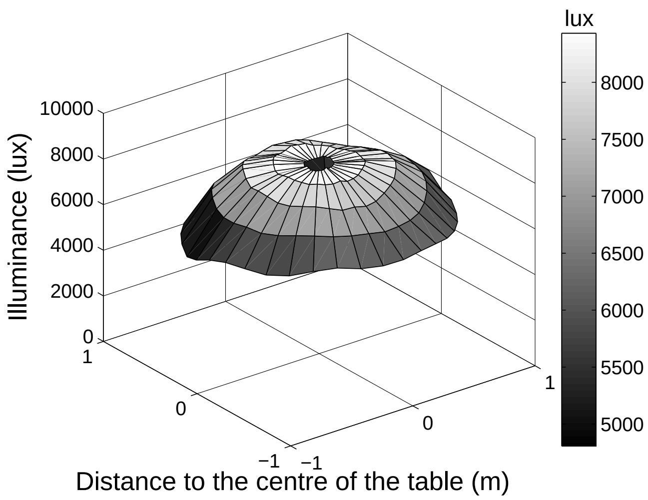

Fig. 5 : Illuminance provided by the sun source on the turntable which is parallel to the sun source

The turntable allows rotations of the scale model, simulating by this the sun's displacement. The algorithm used for modelling the sun curve is the one developed by Szokolay (5).
Following the software user's specifications, the illuminance values are directly measured and weighted to the appropriate value (i.e. 80.000 lux) or are combined with other illuminance measurements under the diffuse sky source in order to get the simulation of the CIE Clear sky with sun. The use of a camera also allows visualisation of the sunlight penetrating the model.

6. Validation Measurements

6.1 CIE overcast sky

Validation measurements were performed on the single-patch sky and sun simulators.

To validate the CIE overcast simulations, measurements were done in a model, for 33 different geometrical configurations (429 observations). The DF measurements were realized under the Mirror Box and the single-patch sky simulator. The measured values were compared to Superlite simulations (6) and are very close to the software simulations results (less than 1% absolute difference for the DF).

Statistical calculations have been done and show that there is a very good correlation between measurements and calculations. Tab. 1 shows the mean bias error (MBE), the root mean square error (RMSE) and the correlation coefficient between, respectively, the Superlite calculation results and the Mirror-box measurements, the Superlite calculation results and the single-patch sky measurements and the mirror box and the single-patch sky measurements.

	Gross values			After correction			After logarithmic correction		
	MBE (%)	RMSE (%)	Cor. coef. (%)	MBE (%)	RMSE (%)	Cor. coef. (%)	MBE (%)	RMSE (%)	Cor. coef. (%)
Superlite-Mirror box	5,70	19,30	98,15	0,80	13,00	98,15	0,76	12,30	98,99
Superlite – single patch sky	4,30	17,70	98,10	0,52	12,40	98,10	0,29	12,60	98,90
Mirror box – single patch sky	10,00	7,60	99,74	1,12	9,5	99,74	0,67	8,70	99,59

Tab. 1 : Mean bias error (MBE), Root mean square error (RMSE) and correlation coefficient (cor. coef.) between the Superlite calculation results, the mirror box and the single-patch sky measurements, under overcast sky.

The values calculated from the gross values are given in columns (2 to 4). If a correction is done, thanks to the linear regression coefficients, lower MBE and lower RMSE are obtained, except for the comparison between the mirror box – and the single-patch sky, for the RMSE (see column 5 to 7). After a logarithmic transformation of the data's, very low MBE and very high correlation coefficients are obtained, for the three comparison cases.

6.2 CIE Clear sky without sun

Validation measurements have also been done for CIE clear sky simulations, with and without sun, under the single-patch sky simulator, for the localisation of Brussels. The illuminances were measured and calculated for different days (21 December, 21 March, 21 July) and for different solar hours (9:00, 12:00 and 15:00), (1053 observations).

The Tab. 2 shows the mean bias error (MBE), the root mean square error (RMSE) and the correlation coefficient (cor. coef.) between the Superlite calculation results and the single-patch sky measurements.

	Gross values			After correction			After logarithmic correction		
	MBE (%)	RMSE (%)	Cor. coef. (%)	MBE (%)	RMSE (%)	Cor. coef. (%)	MBE (%)	RMSE (%)	Cor. coef. (%)
Superlite – single patch	9,76	15,30	97,94	4,15	14,05	97,94	0,90	13,11	98,60

sky									

Tab. 2 : Mean bias error, Root mean square error and correlation coefficient between the Superlite calculation results and the single-patch sky measurements, under clear sky without sun.

The MBE and the correlation coefficients are slightly lower than the ones calculated under the CIE overcast sky but are still very good.
The Fig. 6 shows an example of illuminance values obtained on 21 March, at noon, under a CIE clear sky.

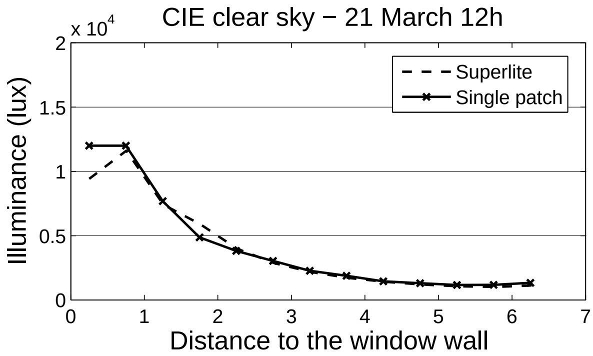

Fig. 6 : Example of validation results (Illuminance – CIE clear cky with sun)

6.3 Direct sun light

Validation measurements made under the single-patch sun simulator gave good results. The only restriction to mention is the non uniformity of illuminances measured on the model which is due to the sun source composition. This problem is especially marked for low sun elevation. The fig. 7 presents the results obtained for the 21st of June at 12h.

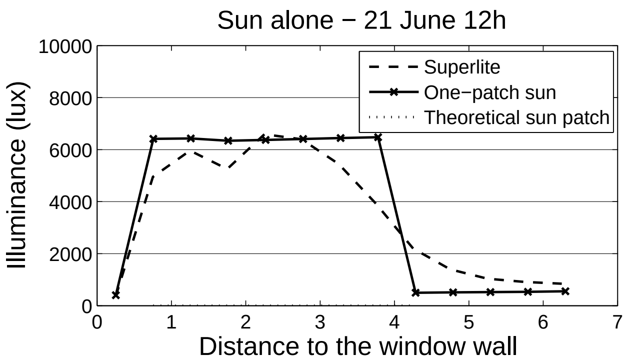

Fig. 7 : Example of validation results (Illuminance –sun alone)

Quantitative results also show the limitation of the sky for low sun elevation. In those cases, the illuminance values have to be weighted for two reasons:

- For low illuminance values, the illuminance meters are less accurate
- The illuminance meters error measurement is inversely proportional to the light incidence angle (sun altitude in our case).

7. Conclusion

The BBRI and UCL 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 with a high precision level and is complementary to the more teaching-oriented Mirror Box.

The single-patch sky simulator realised is a very powerful tool presenting low errors. The 13.5 meter apparent diameter allows the study of quite large models (0.1 m x 0.1 m x 0.7 m) while keeping the simple parallax error below 12.5%. Full dome reconstruction requires about 1h15 and allows modelling of all sky type 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 errors on measured illuminances are very low and can be highly correlated with simulation results.

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 (sky + sun) and give an image of the illuminance distribution. 3D-images of the interior scene are also available, which helps designers to understand light distribution within models.

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