# Daylight Prediction in Atrium Buildings: Measurement, Theoretical Analysis and Simulation

JIANGTAO DU, STEVE SHARPLES

School of Architecture, University of Sheffield, Sheffield, United Kingdom

*ABSTRACT: This paper investigates the impact of well geometry on vertical sky components in atria with square and rectangular forms under a CIE standard overcast sky. By comparing with scale model measurements and analytical theory the vertical sky components calculated using Radiance are validated. More simulated data of vertical sky components for a very wide range of atrium geometries are given. From the results the attenuation of the vertical sky component on the wall of a square atrium is explained and some empirical functions are derived. In addition, the results from atrium models with rectangular floor plan show the relationships between the vertical sky component and the Plan Aspect Ratio. Some guidelines for supporting design are presented.*

*Keywords: daylight, atrium, sky component, scale model, theoretical analysis, Radiance simulation*

## INTRODUCTION

The atrium, which is a significant architectural form, can help achieve many environmental benefits such as passive heating and cooling, ventilation and daylighting, which is particularly true in deep plan commercial and office buildings [1]. Daylight use in an atrium is particularly beneficial as the atrium well can allow natural light to reach potentially dark core areas, decrease energy use by artificial lighting energy use and improve the perception of the indoor environment.

Atrium shape is the first key factor in the preliminary stage of deciding daylight performance. Many authors have introduced a variety of results concerning the effect of atrium shape [2 - 4]. Most of them have tended to focus upon illuminance levels on horizontal surfaces such as the atrium well floor and working planes. However, the vertical surface daylight levels in atria are probably more important in terms of indicating the feasibility of spaces adjoining the atrium well being adequately daylit [2]. Compared with horizontal planes, the analysis of daylight levels on vertical surfaces in atria with different geometric proportions has received much less research attention. Only a few results are presented in the literature [5 - 7]. Even though they give some measured data and theoretical analysis about vertical daylight levels on atria walls, it is still necessary to carry out more effective investigations to achieve more detailed information and to establish reliable and simple prediction methods for the design stage of a project.

Well geometry can be quantified in terms of the well index (WI), which is a function of well length, width and height, and well-indexed depth (WID), which, in addition, considers the distance from the top edge of the atrium well [2] – see Figure 1.

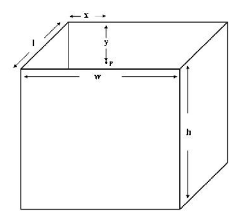


*Figure 1: WI and WID definitions*

$$WI = \frac{h(w+l)}{2wl};$$

$$WID = \frac{y(w+l)}{2wl} \text{ (rectangular atrium);}$$

$$WID = \frac{y}{w} \text{ (square atrium).}$$

WID is the main parameter used to describe the geometric characteristics of atria studied for vertical daylight levels. For shallow atria and upper parts of walls in deeper atria (WID << WI), sky component is the dominant factor. The measured data on this issue is limited [3]. Also, it is important to investigate light distribution on the whole atrium wall (and not just along a vertical central line) because areas not on the vertical centre would receive less light. For architects and engineers, it is essential to understand the daylight levels on these positions in order to set more daylit spaces as possible.

This study focuses on the impact of well geometry on vertical sky components on cuboid atria walls under a CIE standard overcast sky. There are two main parts in this study: the first is a comparative analysis between scale model measurements, analytical theory and computational simulation; the second is a further simulation analysis based on a wider geometric range of atrium models. No glasses or structure systems are included in this initial investigation. Future work will incorporate such systems.

## METHODOLOGY

Model measurements were made of the vertical sky component (SC*v*) on the walls of four – sided atrium models under CIE overcast sky conditions. Six atrium models were tested in an artificial sky, which consisted of a mirror – walled box capable of reproducing the luminance distribution of the CIE standard overcast sky. The colour of the atrium walls and floor was black with a low reflectance of 0.066. The plan size of this sky was 2.4m × 2.4m and its height from the 'horizontal surface' to the top of the mirrors was 1.2m. The six models had the same square plan of 200mm × 200mm and six different heights and WI values (Table 1). The measurement points on the walls were positioned on three vertical lines with horizontal distances from the corner edge to the vertical lines of 20mm, 60mm, 100mm respectively (i.e.10%, 30%, 50% of the atrium width, *w*). So, the vertical lines are named as: centre line, 30% line and 10% line, which are also used in the following analysis. The range of WID was decided by the measurement positions. The highest points were 25mm from the top edge with a WID of 0.13, whilst the lowest points were 187.5mm from the top with a WID of 0.94.

*Table 1: Scale atrium model configurations and WI values.*

| Model dimension and WI | | | | |
|---|---|---|---|---|
| No | w (mm) | l (mm) | h (mm) | WI |
| MODEL 1 | 200 | 200 | 50 | 0.25 |
| MODEL 2 | 200 | 200 | 75 | 0.375 |
| MODEL 3 | 200 | 200 | 100 | 0.5 |
| MODEL 4 | 200 | 200 | 150 | 0.75 |
| MODEL 5 | 200 | 200 | 200 | 1 |
| MODEL 6 | 200 | 200 | 250 | 1.25 |

Several theoretical functions quoted by Littlefair [8] were used for the calculation of vertical sky component (SC*v*) on the atrium wall. Their primary forms occur in an earlier paper on horizontal skylights and sky component [9]. In this study, the theoretical analysis applies these expressions to calculating the sky components along the vertical centre line, 30% line and 10% line of walls in the six atrium models mentioned above.

Radiance, a daylight simulation package using backward ray tracing techniques, was used for vertical sky component simulations. The simulation processes include two steps. The first simulation uses the same models as those in artificial sky measurements and theoretical analysis. The aim is to compare simulated results with measurements and theoretical calculations in order to validate the simulation. The next simulation was finished in a very wider range of atrium geometries.

## SIMULATION VALIDATION

When evaluating daylight levels in atrium buildings, WI and WID are generally used as parameters. The vertical sky component is just decided by sky conditions and the upper obstructions above measured points. So, WID is used as a function of vertical sky component when comparing measured data with simulation and calculated data with simulation.

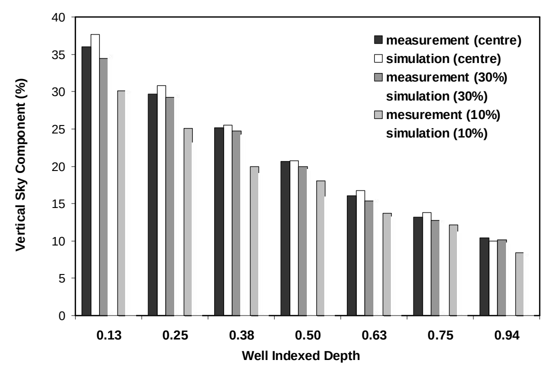


*Figure 2: Vertical Sky Component comparisons between measurement and Radiance simulation.*

Figure 2 illustrates the comparisons between the measured data and the simulated data of sky components along the centre, 30% and 10% line. For the centre line the maximum and minimum percentage difference are 4.4% and 0.3% respectively. The mean percentage difference is just 3.2%. It is apparent that in the WID range of around 0 to 1 the simulated data at the centre line were very close to the measured results. For the 30% line there also a good with a maximum percentage difference of 5.1% and a mean value 2.7%. Near the corners of the wall (10% line), measured data slightly overestimate the sky component compared with simulated results. The maximum, minimum and mean percentage differences are 11.9%, 0.5% and 5.4% respectively.

The maximum average deviation in the data of the three groups is less than 5.5%, which obviously displays the validation of the simulations for sky component on the atrium walls, especially in the centre area. The divergence is due to the fact that photometric characteristics between physical models in measurement and virtual models in simulation have some disagreements [10]. The surface of scale models cannot be perfectly 'black' (reflectance 0), which means there is still some reflected light when measuring the sky component. The measured points on the centre wall receive more light from the sky with fewer obstructions, whilst the points near the corners are blocked by more walls. So, corner areas receive more reflected light from the floor and other walls. This might explain the relatively bigger difference occurring in the corner area. In addition, the inexact geometrical correspondence between the two models could cause some other deviations.

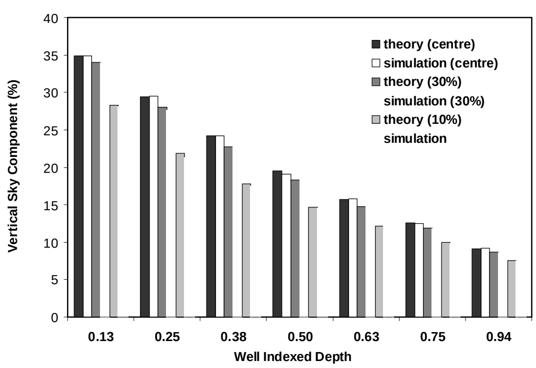


*Figure 3: Vertical Sky Component comparisons between theoretical calculation and Radiance simulation.*

Figure 3 illustrates the comparison between the theoretical data and the simulated data of sky components along the centre, 30% and 10% line. For the percentage difference of sky component at the centre line between simulation and theory the maximum, minimum and mean values are 2.1%, 0, and 0.8% respectively. The percentage differences at the 30% line are: 1.9% (maximum), 0.26% (minimum) and 0.9% (mean), whilst the values for the 10% line are 2.6% (maximum), 0.8% (minimum) and 1.5% (mean). Similarly, data in the corner area display a slightly larger difference than those in the middle area.

The maximum average deviation of 1.5% in the data of the three groups shows a better agreement between simulated data and theoretical data than that between simulated data and measurement. This again enhances the validation of the simulation for vertical sky component calculations in atria. The small divergence might be explained by the random nature of the ray tracing process that is used by Radiance.

This section has demonstrated that Radiance simulations could be a reliable method to carry out calculation of the sky component on atrium walls.

## SKY COMPONENT INVESTIGATIONS

Radiance simulations were used in this section to further analyze vertical sky components across atrium walls. The geometric range of the atrium models was greatly extended so that the WI range of square atria was from 0.25 to 2.5 and the new WID range was from 0.13 to 1.88. Several atrium models with rectangular plans were also studied and the typical PAR (plan aspect ratio = well width / well length) values were 0.8, 0.67, 0.5 and 0.4 respectively.

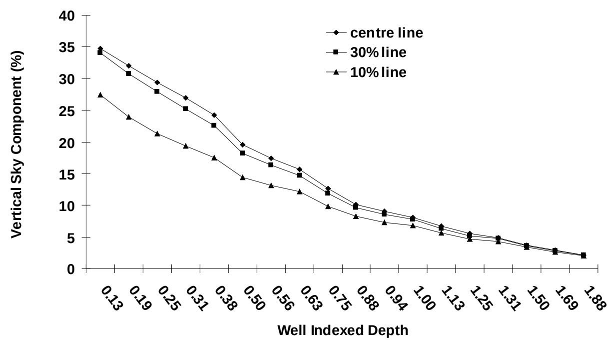


*Figure 4: Simulated Vertical Sky Component at the centre, 30%, and 10% lines of square atrium.*

The first part investigated variations of vertical sky components with WID along the centre, 30% and 10% line of a square atrium (Figure 4). For atrium models with square plan, the WID could be expressed as: WID = atrium height / atrium width. So, SAR (section aspect ratio = atrium height / atrium width) equals WID. With the increase of WID the sky component would approach zero, which means there will be little light from the sky on lower parts of the atrium wall. The curve of the centre line lies on the top and has the biggest values. Although the 30% line deviates from the centre line for WID < 1, the average divergence percentage is just 4.6%. The form of the 30% line is similar to the centre line. Figure 4 shows that the points on the 30% and centre lines (the central area of the wall) receive similar amounts of light from the sky. For WID < 1.25, the 10% line disagrees with the other two curves - the smaller the WID the greater the divergence. This shows that the corner areas receive less light from the sky compared to the central areas of the walls of shallow atria or higher parts of deeper atria walls.

Theoretically, the unobstructed vertical sky component is approximately 0.4. This means the sky illuminance on the vertical surface is 40% of the unobstructed global illuminance on a horizontal surface under CIE standard overcast sky. The vertical sky component will tend to 40% when WID approaches zero. From the top edge to the lower areas on atrium wall, six points were selected as typical positions to examine the attenuation of the sky component along the vertical line: WID 0.25 (atrium height = 1/4 atrium width), WID 0.5 (atrium height = 1/2 atrium width), WID 0.75 (atrium height = 3/4 atrium width), WID 1 (atrium height = atrium width), WID 1.25 (atrium height = 5/4 atrium width), WID 1.5 (atrium height = 3/2 atrium width). Table 2 gives the ratios of sky components in these positions along the vertical lines to the unobstructed vertical sky component (0.4). When

*Table 2: Ratios of sky components along the three vertical lines to the unobstructed vertical sky component (0.4).*

| WID | Centre line | 30% line | 10% line |
|---|---|---|---|
| 0.25 | 73.4% | 70.0% | 53.2% |
| 0.5 | 49.0% | 45.4% | 36.0% |
| 0.75 | 31.6% | 30.0% | 24.5% |
| 1 | 20.3% | 19.5% | 17.2% |
| 1.25 | 13.8% | 12.8% | 11.7% |
| 1.5 | 9.3% | 9.0% | 8.4% |

the distance to the top edge is 1/4 atrium width, the illuminance in the centre area of the wall would be about 70% of the unobstructed vertical illuminance, whilst the illuminance in the corner area of wall is only half of that. The sky components of the positions in the central area with a distance of one atrium width become around 20% of the unobstructed vertical sky component. At the same height, the sky component in the corner area is 17%. All the sky component ratios approach around 9% at a lower position of 3/2 width. It is very interesting that in the position WID 0.5 (a distance of 1/2 atrium width from top edge) the sky component is approximately 0.5 of the unobstructed vertical sky component.

By using curve fitting analysis three regression functions can be derived from the simulated data for the three vertical lines. In terms of the exponential form of decay, which coincides with one theoretical analysis [11], the regression lines are:

$SCv = 49.89e^{-0.16WID} \times 100\%$ ( $R^2 = 0.98$ centre line)

$SCv = 46.91e^{-0.16WID} \times 100\%$ ( $R^2 = 0.99$ 30% line)

$SCv = 34.89e^{-0.15WID} \times 100\%$ ( $R^2 = 0.99$ 10% line)

Alternatively, the regression lines could be described virtually as well by polynomial functions:

$SCv = (0.095WID^2 - 3.76WID + 39.36) \times 100\%$ ( $R^2 = 0.99$ centre line)

$SCv = (0.099WID^2 - 3.74WID + 38) \times 100\%$ ( $R^2 = 0.99$ 30% line)

$SCv = (0.073WID^2 - 2.81WID + 29.48) \times 100\%$ ( $R^2 = 0.99$ 10% line)

The discussions above explain the attenuation of vertical sky component on the wall of a square atrium model according to different SAR values. Apparently, the centre area (including the centre line and 30% line) is the principal region for daylighting applications. The area with SAR < 1 (higher parts of deep atria or shallow atria) is dominated by the vertical sky component.

The second part introduces variations of vertical sky components along the centre, 30% and 10% line of rectangular atria with different PAR values and SAR values. The SAR range of 0.13 to 1.88 follows that of a square atria. According to the definition about rectangular plan aspect ratio [2], the PAR is chosen as: 0.8, 0.67, 0.5, and 0.4.

For the short wall in an atrium with a rectangular plan (Figure 5) the sky component increases with the decrease in PAR (plan becoming narrower). However, the sky component values at different heights (SAR) are different. Generally, when the SAR becomes big (toward lower positions of wall), the sky component value increases. For example, on the centre line, with SAR < 0.5 (distance to top edge < ½ width) the relative difference of sky component between square plan (PAR 1) and the narrowest plan (PAR 0.4) is less than 15%, while the value with SAR 1 and SAR 1.88 are 60% and 173% respectively. The data for the 30% line show the same results as for the centre line. Furthermore, for the 10% line, with SAR 0.5, the relative difference of sky component between square plan and narrowest plan is 20%. In the deeper positions, the value becomes 64% (SAR 1) and 166% (SAR 1.88). This analysis shows that when PAR changes the sky components at three different lines change in a similar way; the changing magnitude of sky component is larger with large SAR and becomes smaller with a decreasing SAR.

For the long wall in an atrium with a rectangular plan (Figure 6), there is the same trend as for the short wall: when the PAR is smaller the sky component is bigger. However, there is no obvious relationship for the change in the form of the curves. Compared with the results for the short wall, the relative difference of sky component between square plans and the narrowest plan here increases for SAR < 1, whilst it slightly decreases when SAR > 1. For example, with SAR 0.5 the values of centre line, 30% line and 10% line are 30%, 35% and 33% respectively. With SAR 1, the values become 64%, 61% and 40% respectively. Also, the values achieve 105%, 93% and 69% respectively when SAR equals to 1.88. This demonstrates that PAR changes produce bigger impacts on sky component values in the central area compared with the corner area; the changing magnitude of sky component is larger with large SAR and becomes smaller with the decreasing of SAR.

The discussions above explain the fact that vertical sky component on the wall of rectangular atrium model would change according to different PAR values. For all the walls of rectangular plan, the decreasing PAR values

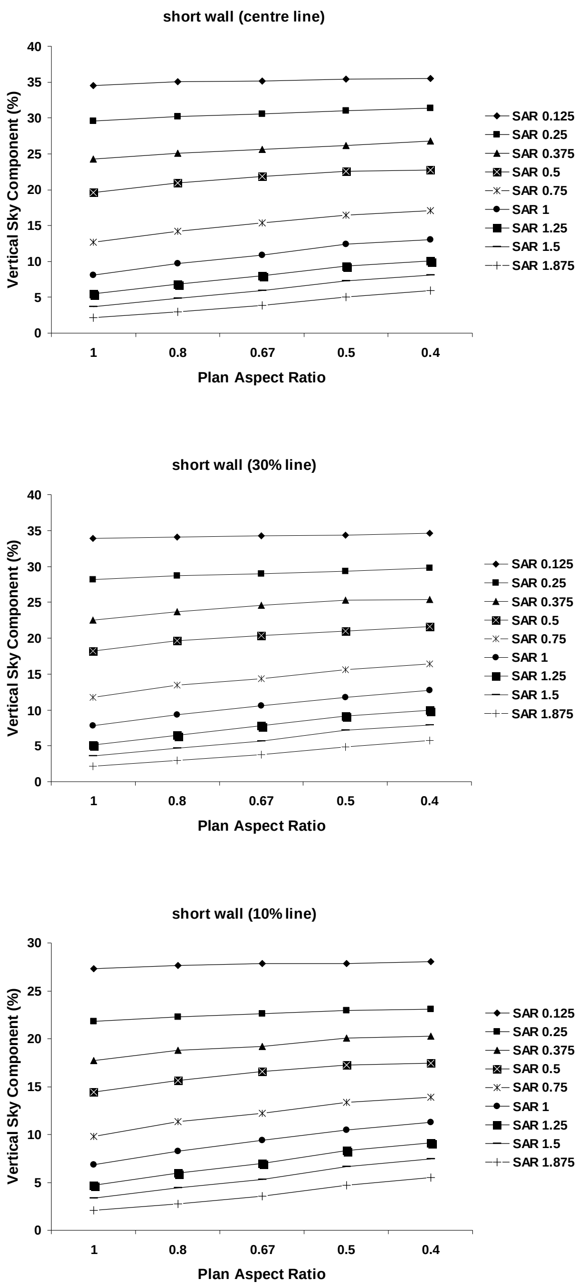


*Figure 5: Simulated Vertical Sky Component at the centre, 30%, and 10% lines of short wall in rectangular atrium.*

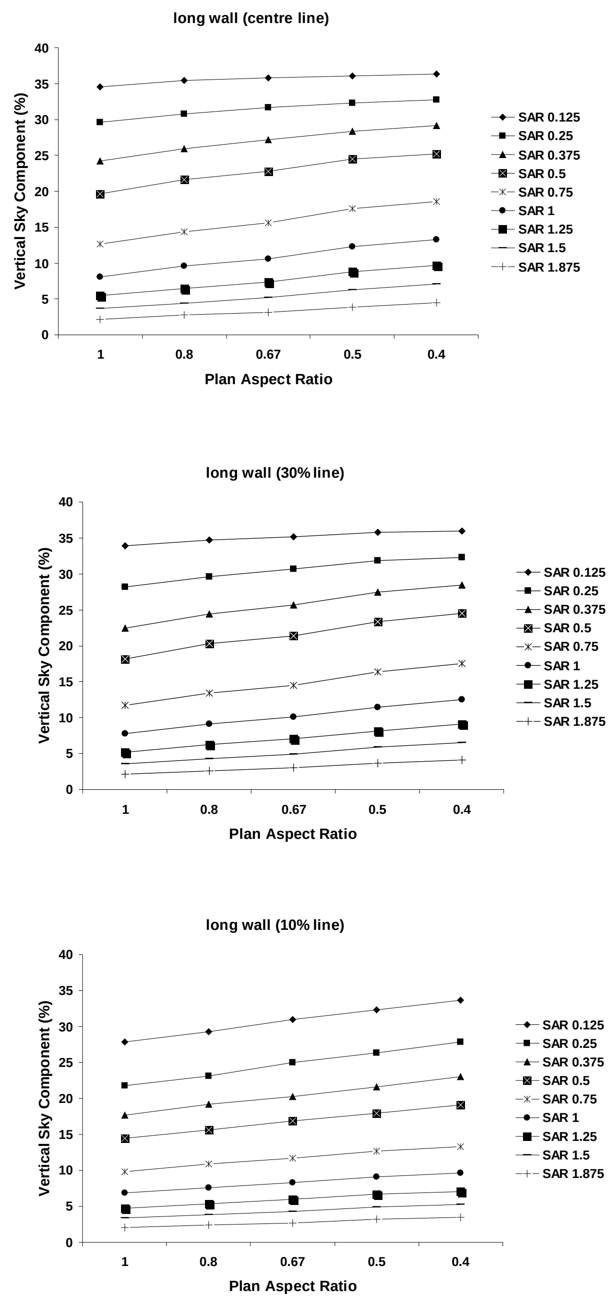


*Figure 6: Simulated Vertical Sky Component at the centre, 30%, and 10% lines of long wall in rectangular atrium.*

mainly influence the sky components at the lower parts, although they receive much less light from sky than higher positions; for long walls of rectangular plan, the PAR changes would bring much more impact on the sky components in the centre area (including centre line and 30% line) than those in the corner area.

## KEY OBSERVATIONS

(1) The wall area in the middle of two vertical lines with a distance of the 30% atrium width to corner has the largest sky components and has the biggest possibility to naturally light spaces adjacent to the atrium well.

(2) The wall area between the top edge of the atrium and the horizontal line at a distance to top edge equal to the atrium width is mainly dominated by sky component.

(3) For a given SAR, decreasing the PAR of an atrium could improve the sky component on the wall, especially on the lower parts of the wall, which are still influenced by the sky light.

(4) For a given SAR, decreasing the PAR of an atrium will produce an increase, of a similar magnitude, in the sky components in the centre area and corner area on the short wall; however, sky components in the centre area on the long wall will increase much more than those in the corner area of the long wall.

## CONCLUSIONS

In this study the impact of well geometry on vertical sky components in square and rectangular atria under a CIE standard overcast sky has been investigated. By comparing the outputs from scale model measurements and analytical theory the predicted vertical sky components from Radiance simulations were shown to be accurate. More simulations to determine vertical sky components for a much wider geometric range of atrium models were then performed. The vertical attenuation and horizontal distribution of sky components on atrium walls have been analysed and some guidelines presented.

These conclusions are obviously limited to the specific geometries investigated. Total atrium wall daylight level (including sky component and internal reflected component) will be the subject of future work.

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