

# Assessing a rapid technique for estimating the daylight transmittance of atrium roofs

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**ABSTRACT:** This paper describes the development and testing of a technique which could rapidly assess roof transmittances in existing atrium buildings. The technique involves the analysis of a hemispherical photograph of the roof to establish the proportion of visible sky seen from the photograph viewpoint. The method was demonstrated on two atrium buildings in the UK city of Sheffield and was shown to be fast and user friendly. More illuminance measurements in real buildings will be necessary to further validate the technique. Potentially, a large transmittance database of existing roofs could be established with considerably less effort than through real illuminance measurements or simulation.

Keywords: daylight, energy, atrium

## 1. INTRODUCTION

Electric lighting consumes 20% of all generated electricity within the United Kingdom [1]. Significant financial and energy savings could be made by harnessing 'free' daylight from the sky, as was historically the way in architecture. Furthermore, the quality and variability of daylight is generally preferred by building users, and in some cases has shown to significantly improve occupant performance [2]. The atrium is one building form that could potentially be used to displace artificial lighting as the principle means of illumination in medium and large scale buildings. Previous studies concerning daylight and atrium buildings were usually undertaken using scale models, and as such, generally investigated the geometry and surface properties of the well. The roof of the atrium, being much harder to model, remains the least understood area of atrium design with regard to daylighting [3]. The few studies implicitly examining the transmittance of the roof, for example [4], are quite dated and hard for architects to apply to the design process.

The roof configuration has been demonstrated to be the single most influential factor of atrium design with regard to daylight direction and intensity [5]. As a general rule, at the earliest stages of the design process flexibility is at its greatest. As the process develops, changes become harder and more costly to implement. It would therefore seem important for designers to be able to access appropriate and reliable information at the early stages of the design. It may be more useful to have approximate but early information rather than precise information which comes too late. There are essentially two approaches - using a tool that simulates the desired space, or through comparison to other schemes that are similar in form. Whilst using time intensive processes such as accurate scale or computer modelling may not be an efficient means of

performing daylight analysis on a roof at the early stages of a design, there do exist other options. The user-friendly program SkyVision is free to download and has fast input and output times which makes it well suited to the early stages of a design [6]. However, although the program has been validated against simple scale models it has not been tested against a range of real building measurements, which do differ from scale models. Also, the level of roof structure is input as a 'frame factor', that is to say, the proportion of the opening perceived as blockage when looking from above. This means that two significantly different arrangements of roof, which could behave differently with respect to daylight transmittance, might return identical output from SkyVision. Coupled with this, the depths of the structural members are not taken into account. This may lead to divergences from actual behaviour, especially if considering positions close to the roof. It has already been shown in previous studies that the Plan Area of Obstruction (PAO), which is effectively the same as the frame factor, understates daylight losses [7], [8].

The second type of tool looks at similar typologies i.e. examining precedents. With regard to the daylight transmittance of roof, there is a scarcity of information derived from illuminance measurements taken in real buildings. In order to assess only the effects of the roof measurements must be taken above the well (i.e. at roof plane level) such that illuminance contributions from the surfaces of the well do not distort the logged readings. This is practically challenging in atria, as areas immediately beneath the roof normally correspond to a large physical drop, and as such the fixing of measuring equipment for sustained periods of time is impractical. Measurements made from other positions, such as at the base of the well or in adjacent spaces will be useful in gauging daylighting potential around that specific building, but the universal applicability would be diminished.

Fontoynt [9] details 60 European case studies in terms of geometry, daylight factors, material characterisation, visual comfort, homogeneity of distributions, photographs, user comments and energy calculations. A resource with a similar clear format examining the transmittance of various existing roof forms would be useful to designers. Through empirical experimentation this study has attempted to derive a method that could rapidly assess the transmittance of atrium roofs. This paper surmises the principle methods used in the study, and demonstrates the practical application of its findings. More details on the techniques used are given in [10]

## 2. ATRIUM MEASUREMENTS

### 2.1 Measured Daylight Transmittances in Atria

In order to assess the validity of the proposed rapid method it was necessary to obtain some physical daylight transmittance data for comparison purposes. Two case study buildings were selected in Sheffield, United Kingdom (53°23'N, 1°27'W). The first of these was covered by an A-framed atrium roof and had approximate dimensions of 27m (L) x 6m (W) x 19m (D). Figures 1 shows an internal view of the building.



**Figure 1:** Internal view of A-frame atrium roof

The other atrium building was larger (approximate dimensions 50m (L) x 18m (W) x 16m (D)), and was covered by a monopitched roof which was supported by a space frame structure. The monopitched atrium was significantly overshadowed by an adjacent 12-storey building. An internal view is shown in Figure 2. For both roofs, the openings were double glazed, with the metallic structure painted white. The average transmittance across a roof plane immediately beneath a skylight is the ratio of illuminance under the skylight to illuminance if the skylight were not there. In this study internal illuminance was measured at one point only. This was due to the limited measurement positions possible due to the practical challenge of suspending a photocell above the well. Simultaneous measurements were recorded of the external illuminance. The ratio of internal to external illuminance describes the daylight factor at the point



**Figure 2:** Internal view of monopitch atrium roof

of the internal measurement point. In order to convert this value to average roof plane transmittance, illuminance levels across the whole roof plane, together with the contribution of well reflective surfaces (walls, floor etc.) are needed. It was not physically possible to measure this. A method to obtain this information using computer simulations with Radiance is described in [11].

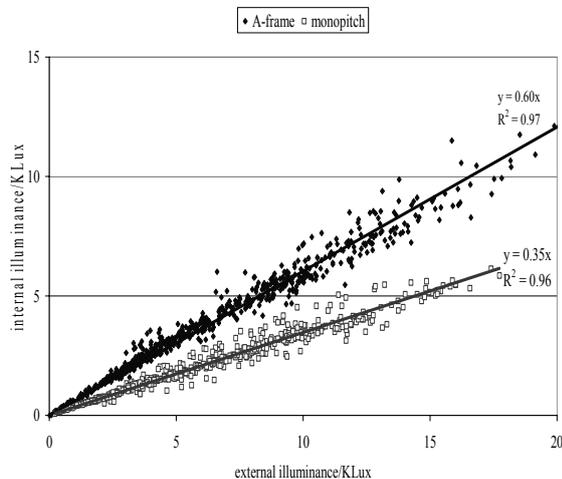
Illuminance was measured using cosine corrected Skye Lux sensors (SKL 310) attached to standalone DataHog 2 loggers. The internal photocell for the A-frame roof sat on a timber support which was cantilevered from a window cleaning gantry over the well (Figure 3). The internal photocell for the monopitched roof was fixed to a customised tripod immediately beneath the roof on top of a small block of accommodation. For both scenarios the external photocell was positioned on the roof of the buildings, with an unobstructed view of the sky vault.



**Figure 3:** Photocell positioned in A-frame atrium

Overcast skies were considered in this study as they represent the most common sky condition for the geographic location of this study and are often used for design purposes as a worst case scenario. The recorded data gave 972 data points for the A-frame roof, and 481 for the monopitched roof. The internal and external illuminance results were plotted against

each other as can be seen in Figure 4. The gradient of the lines is representative of the daylight factor at the point of the internal photocell. In the case of the A-frame roof, this was 60% ( $R^2=0.97$ ), whilst for the monopitched roof this value was 35% ( $R^2=0.96$ ).



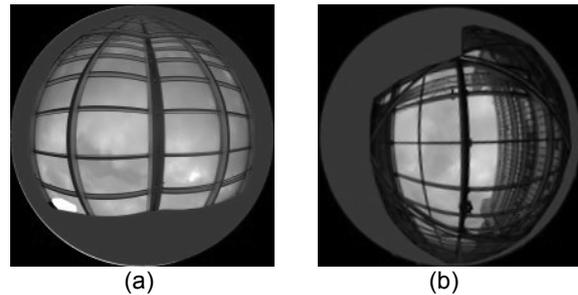
**Figure 4:** Internal and external illuminances measured in the A-frame and monopitch atria

## 2.2 Photographic Technique

Real buildings represent a potentially rich source for studying transmittance through skylights, yet physical illuminance measurements are time consuming, often impractical and are dependant upon building owners granting permission. Modelling is also time consuming, and potentially inaccurate. Capturing a digital photographic image of the roof using a camera is a simple and rapid process. Analysing the proportion of visible sky may prove to be more representative of roof transmittance than the PAO, as the roof is considered in three dimensions. HemiView [11] is a computer program that was originally developed to study sunlight transmission through tree canopies. HemiView can calculate the proportion of visible sky in a hemispherical image. In adopting a polarised stance of either 'gap' or 'blockage', an assumption is made that all gap is 100% transmissive whilst all blockage completely absorbs light. In reality, the glazing will reflect and absorb a proportion of light flux, whilst the structural blockage will reflect a fraction of incident light.

## 2.3 Methodology

Hemispherical images aimed vertically upwards were taken of the atrium roofs using a Nikon 950 Coolpix digital camera with fisheye adaptor. Non-roof areas (i.e. well surfaces etc.) were painted red in a standard paint program. This was so that HemiView could 'ignore' such regions in its calculation. These images are shown in Figure 5. Images are classified by determining a threshold intensity above which a pixel is classified as visible sky and below which is classified as blockage. For this reason, the photographs were taken under overcast sky conditions such that variance across the sky was minimised, facilitating the classification process. In



**Figure 5:** Fisheye images of (a) A-frame and (b) monopitch roofs

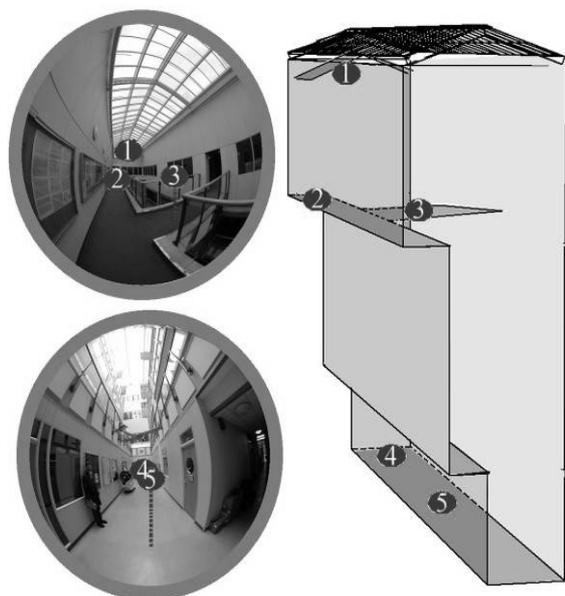
some cases, user intuition was required to offset dark regions of the sky which had been classified as blockage with bright areas of structure which had been classified as gap. In such a way, a representative value for the overall roof 'visible sky' was derived.

## 2.4 The Photocell Position

The illuminance at the internal measurement point is dependant on the view seen by the photocell. Photographs were taken in both case study buildings from the position of the internal photocell. The value for visible sky obtained from the photocell position in the A-frame building was 60%. This is an exact match to the daylight factor measured at that point. The fact that the two numbers are congruent is coincidental. The area classified as visible sky does not provide the corresponding illuminance levels compared to if there was an open top well, due to reflectance and absorption by the glass. Likewise, the area designated as blockage in actuality does contribute to the illuminance measured at the photocell due to inter-reflections from the surfaces. In this case these factors are equal, though in others the same can not necessarily be stated. For the monopitch roof the proportion of visible sky seen from the photocell position was 31%. This is 4% lower than the measured daylight factor. In this case gains from perceived blockage (i.e. the structure and the large facade of the over-shadowing obstruction) outweigh the losses due to attenuation at glazing. Until the exact relationship between the glazing transmittance value and structural reflectance value can be assessed, it is not possible to implicitly state the relationship between the proportion of visible sky as seen from a point and the daylight levels at that point.

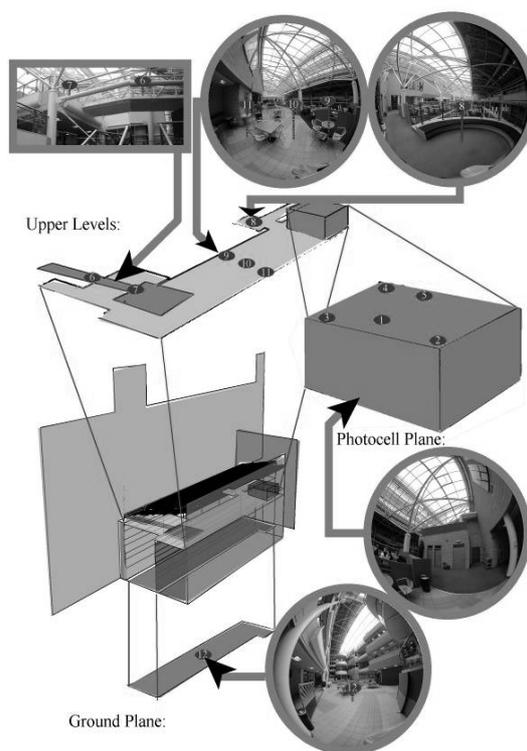
The principle advantage of this proposed photographic method for obtaining transmittance information of atrium roofs in real buildings over more traditional measurement of modelling processes is its speed and simplicity. In most cases it will not be possible to obtain a photograph from immediately beneath the skylight. For this reason, photographs in the two case study buildings were taken in supplementary positions to the photocell position (A1 and M1 respectively), so as to establish criteria for photograph viewpoint when applying the technique to other buildings. In the A-frame building, four further positions were chosen. Two on the top floor walkway (one at the corner of the well (A2) one in the centre

(A3)), and two at ground floor level (one at the end (A4), one at the centre (A5)) (Figure 6).



**Figure 6:** Camera positions in A-frame atrium

In the monopitch building, photographs were taken in eleven supplementary positions. Four of these were on the same plane as the photocell position, each seeing a slightly different arrangement of roof structure overhead (M2-5). Two more were taken from a walkway crossing the well at the other end of the well to the photocell position, at roof plane level (one halfway across the walkway (M6), one at the end of the walkway (M7)). Four more were taken on the top floor of the well (M8-11), and one was taken from the centre of the base of the well (M12) (Figure 7). The proportions of visible sky seen from the various viewpoints together with the relative difference from the photocell position can be seen in Table 1. In the A-frame building the values obtained from the upper floor positions (A2 and A3) were relatively close to the A1 value. The slightly lower value at A2 is due to the lateral displacement of viewpoint towards the side of the well, resulting in a more sectional view of the prominent central purlin, and a reduced view of visible sky. The slightly higher value at the central position is due to less of a perceived loss at the ends of the image. In the central position the structural members only converge for half the distance as from the end position. There is therefore less compressed region in the central image. Both these differences are relatively minor, and can be explained as a result of viewpoint position in the lateral plane. The values from the ground positions (A4 and A5) are significantly lower than at the photocell position. There are two reasons for this: firstly, as the distance between viewpoint and target (the roof) increases, the focal point moves towards the infinite, which are the conditions for a plan projection. In this respect, we would expect the visible sky value to equal [1-PAO]. This value for the



**Figure 7:** Camera positions in monopitch atrium

**Table 1:** Visible sky as seen from varying positions within the two case study atria.

Position	Visible Sky	% Difference from A1/M1
A1	59.6%	0%
A2	58.4%	-2.0%
A3	63.8%	7.0%
A4	76.9%	29.0%
A5	78.7%	32.0%
M1	30.9%	0%
M2	32.9%	6.5%
M3	33.9%	9.7%
M4	23.7%	-23.3%
M5	32.1%	3.9%
M6	23.5%	-23.9%
M7	37.2%	20.4%
M8	24.9%	-19.4%
M9	28.9%	-6.5%
M10	30.9%	0%
M11	32.3%	4.5%
M12	49.7%	60.8%

A-frame roof was measured to be 73%. In both cases, the visible sky values actually exceed this figure. This is due to the second reason, a loss of information at increased depths within the well. As the distance from the roof increases, so its size within the hemispherical field of view diminishes. This stretches the capabilities of the camera to the limit, and results in omitted detail and aliased ('jagged') elements. Improvements in camera technology since the start of this experiment could make this error redundant in future experiments. Similar patterns

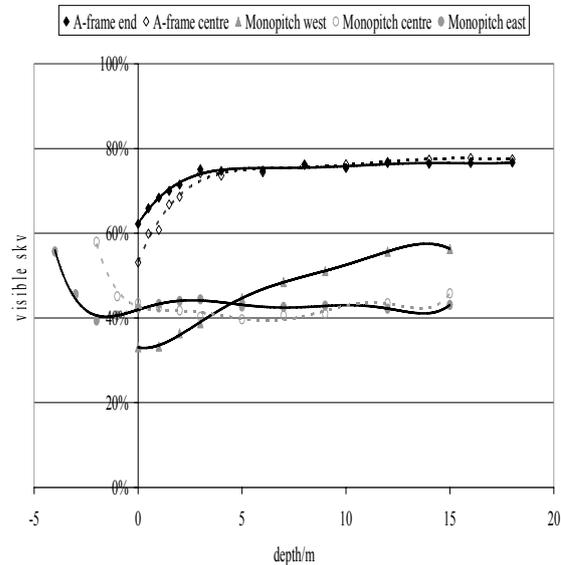
concerned with localised field of view can be seen when comparing positions M1-3 in the monopitched atrium. Each of these positions is in close proximity to one another, resulting in the relatively small deviation from M1. Positions M6 and M7 see a greatly different proportion of visible sky than M1. The low value at M6 is due to the immediate overhead juncture of several principle structural components. The value from the ground floor, M12, is once again significantly greater than at roof plane level. This is due to the previously discussed increase in focal length resulting in plan-like conditions, though in this case, the image is still an angular projection (the [1-PAO] value being 71%).

### 3. USE OF COMPUTER-CREATED IMAGES

#### 3.1 Investigations using computer-generated images

There are several physical limitations to field captured photographs that can be addressed through the computer generation of images from a model of the same space. Generating a rendering from a computer model of the space enables viewpoints from any point in space, whilst resolutions are limited only by the computational time cost of the rendering. An even light source defines objects within the scene unambiguously, whilst non-relevant factors are omitted from the model. The two atria were modelled and fisheye views generated using Radiance [12]. The wells were heavily simplified and did not include the overhead walkways, stairwells etc. A uniform sky was specified as the light source. Through pre-rendering simulations, a resolution of 4096x4096 was found to be sufficiently accurate to display the roof with no omitted or aliased elements of structure at the deepest depths within the well. This resolution contains almost twelve times the quantity of pixels as in the 1200x1200 images capable from the digital camera used. In the A-frame roof images were generated along central and end paths, at depths between 0 and 2m (at 0.5 m intervals), 3m, and between 4 and 18m (ground) (at 2m intervals) from the roof plane. In the monopitch roof images were generated along paths at the central, lower end of the monopitch (1/8 the width of the well from the western edge of the well) and upper end of the monopitch (1/8 the width of the well from the eastern edge of the well) at depths of 0, 1, 2, 3, 5, 7, 9, 12 and 15m (ground) from the roof plane. In the central and eastern paths, images were generated within the volume of the roof, at depths of 1 and 2m, and in the case of the eastern path, 3 and 4m too. The visible sky values for both case study buildings are shown in Figure 8. The values of visible sky within the A-frame case study demonstrate the trends discussed from the physically captured photographs. At depths close to the roof plane, the visible sky values are at their lowest. As depth increases, and due to the change in projection at which the structural members are viewed, more visible sky is seen. The sharpest increases in value occur between 0 and 4m. The rate of increase in visible sky from 4m up to the base of the well (18m) is minor. At depths near the roof plane, more sky can be seen from the central position

than the end position, due to less compressed area of roof from the image at the centre of the well. At greater depths, lateral displacement of viewpoint has a diminished effect upon visible sky values, as the configuration of blockage to structure in the field of view of the image becomes more uniform.



**Figure 8:** Visible sky values moving viewpoint along vertical paths within the two case study buildings

Both roofs have a similar PAO (27% in the A-frame building and 29% in the monopitch building). However, the magnitudes of visible sky seen from viewpoints within the monopitch building are markedly lower. This is due to the large over-shadowing façade in the monopitch building, which in plan constitutes no obstruction, yet when viewed in three dimensions is of great significance. The presence of this external obstruction masks the phenomena of increased visible sky with increasing distance from the roof. Only along the west axis does visible sky increase moving towards the well base. This is the edge closest to the external obstruction, and so relatively low marginal drops in depth result in a more significant reduction in influence of the obstruction when compared to the central and east axis. Painting the external obstruction white and recalculating the visible sky values confirmed that the proportion of structural blockage does diminish with increased distance from the roof in the same way as the A-frame building. The monopitch roof was more complex than the A-frame roof in that the space frame structure extended into the volume of the well. For this reason, moving the viewpoint at increments into the well revealed parts of the structure at greater depths that were beneath the field of view for viewpoints higher up in the well. Only beneath the depth of the entirety of the roof structure did the patterns begin to emerge. Moving into the roof as was done in the central and eastern axis resulted in higher visible sky values. This is due to the localised effect of the lateral position of the axis, beneath an area of glazing rather than structure. At sufficient depth (i.e. distance from the roof), the entirety of the

roof can be seen and thus localised biasing is reduced. At much greater depths, it would be expected that the visible sky would rise to the [1-PAO] value of 71%.

#### 4. DISCUSSION

The aim of this research has been to find a means to rapidly assess the transmittance of real atrium roofs through taking a photograph of said roof. Taking a photograph from the position from which internal illuminance was measured produced values for visible sky that were similar to the daylight factor. The amount of 'visible sky' measured is also only a guide to likely illuminance levels, as contributions from the visible sky will be less than a no roof scenario due to the light attenuation of glazing and light reflection from structural members. Likewise, under differing sky conditions, transmittance properties of a roof system will vary, and in that sense, visible sky can only be considered to be a crude guide to transmittance. Practically measuring the average roof illuminance levels and parametric effects of glazing transmittance values and structure reflectance values in real buildings are likely to be overly challenging. More feasible would be the use of modelling, either scale model or computer. In terms of accurately inputting the model geometric and photometric properties, as well as ease of testing multiple parameters, computer modelling represents the best means of continuing the investigation. The aim of this next step should be to form definite measurable links between the visible sky value from the photocell position, and the average roof plane transmittance with regard to glazing transmittance and structural reflectance. A critical part of any proposed method would be the appropriate selection of viewpoint position. This can be considered in terms of position on the horizontal plane, and depth. In most cases, it would not be possible to take the photograph immediately beneath the roof. As distance from the roof increases, the location in the horizontal plane becomes less critical, as a more representative view of the entire roof can be achieved, without localised biasing factors. At any given depth, stipulating that the view encompasses a representative view of the general arrangement of the roof should return consistent results (e.g. not directly beneath a major structural joint). The visible sky value is dependant on depth. At increased depths, it was shown that the value approaches the [1-PAO]. This pattern was clearly visible in the A-frame case study, though was not immediately apparent in the monopitch case study due to the overbearing influence of the immediately adjacent obstructing facade. It is possible to quantify the relationship between depth and visible sky through use of a polynomial equation in the A-frame building. In applying the findings to future buildings, the term depth should be expressed as relative depth, that is, the cross sectional width of the roof divided by the depth. Through further empirical investigation of depth and visible sky, it will be possible to examine further roof forms.

#### 5. CONCLUSIONS

Through the measurement of daylight levels in two case study buildings, and analysing photographs of the atrium roofs, several conclusions can be drawn. Using the results available, it was not possible to state a definitive relationship between roof transmittance and visible sky as seen from a photograph. This was due to the fact that it was not possible to measure average roof plane transmittance, and that the quantitative effects of the glazing transmittance and structure reflectance remained unknown. A methodical investigation of these parameters using computer simulations and the integration of the findings to the photographic method forms the next part of the investigation. This further investigation will include the relationship of depth to the visible sky values such that the photograph may be taken in any position within the well. Once a working method has been established, a taxonomy of existing atrium roofs can be rapidly established, enabling designers to make fast and informed decisions on which roof type is best for their needs based upon case study buildings.

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