# Can hourly-based annual daylighting simulations predict daylight availability in dynamic sky?

Jae Yong Suk

The University of Texas at San Antonio, San Antonio, Texas

ABSTRACT: For successful daylight harvesting in buildings, daylight availability should be accurately evaluated and predicted. Daylight availability can be evaluated by either point-intime computer simulations under a predetermined sky condition for a given site's geographical location or climate based daylighting simulations with standard meteorological datasets. However, predetermined sky condition or hourly climate data might not be able to predict drastic changes of dynamic sky. As daylight harvesting performance depends on daylight availability, it is important to check whether or not there is significant discrepancy between hourly-based daylighting simulations and real time measurements of luminous environment under dynamic sky conditions. Located in San Antonio, a closed office space with south facing windows was selected for both field measurements and computer-based daylighting simulations. Constant monitoring of indoor and outdoor luminous environments were compared to hourly-based daylighting simulation results in order to verify its effectiveness in predicting daylight availability in dynamic sky conditions. Vertical and horizontal illuminance levels were measured to document natural light distribution inside the office every minute for a 40 day period. Collected data shows how quickly and drastically indoor luminous environment has changed under the actual sky conditions, which would greatly impact electric lighting and interior blind controls.

KEYWORDS: Daylight Harvesting, Dynamic Sky, Weather Data, Daylight Availability, Daylighting Simulations

#### INTRODUCTION

Daylight harvesting has been a crucial strategy to save electric lighting energy consumptions and to promote occupant comfort in buildings. For successful daylight harvesting, daylight availability in buildings should be accurately evaluated and predicted. Daylight Availability is the ratio between the amount of natural light outside buildings and the amount of daylight inside a building (Kensek and Suk, 2011). Different from Daylight Factor which was developed to evaluate daylighting design performance under overcast sky condition, Daylight Availability was developed to evaluate daylighting design performance in dominantly clear sky conditions or dynamic sky conditions such as mostly cloudy or partly cloudy skies.

Daylighting performance evaluations have evolved and have become more sophisticated with the improved computer performance and sophisticated daylighting metrics. Also, climate data (weather data) is publicly available for researchers and practitioners to create a climatic condition close to what has happened for several decades. Daylight availability can be calculated by either point-in-time computer simulations under a predetermined sky model for a given site's geographical location or climate based daylighting simulations with standard meteorological datasets. These approaches seem promising as they not only consider actual sky condition history for a given location but also allow hourly-based simulations for an entire year. However, accurate prediction of daylighting performance has been still challenging for dynamic sky conditions. Predetermined sky model or hourly climate data might not be able to predict drastic changes of dynamic sky conditions such as San Antonio, Texas. As daylight harvesting's performance depends on daylight availability, it is important to check whether or not there is significant discrepancy between hourly-based daylighting simulations and real time measurements of luminous environment under dynamic sky conditions.

For this reason, it is critical to understand how much discrepancies can happen between simulated daylight levels and actual daylit conditions inside a building. Post occupancy evaluation study is one of the efforts to understand the gap between computer simulation and real world conditions. By performing and comparing field measurements in a completed project, more accurate and reliable daylighting performance predictions can be made (Nicol et al., 2016; Katzenstein, 2013; Hirning et al., 2013; Suk and Schiler, 2012; Suk et al., 2013; Konis, 2013). Even though many entities have made post occupancy evaluation studies, drastic changes of dynamic sky condition have not been addressed yet. This paper reveals the discrepancy between computer simulations and field measured daylight levels. In addition, it also explains potential issue of inaccurate estimations of energy saving benefit from daylight harvesting. Clear understanding of these issues can help achieving accurate evaluation of daylighting design performance.

#### 1.0. METHODOLOGY

A closed office space with south facing windows was chosen in San Antonio, Texas in order to document dynamic sky conditions (Figure 1). San Antonio, Texas is categorized in hot and humid climate (climate zone 2A) and is well known for hot summer season and dynamic weather conditions throughout a year (Baechler et. al., 2015). Collected weather data shows that July is one of the sunniest months in San Antonio with 74% sunshine percentage and 9 days of clear sky in a month (Weather Underground, 2017).

The selected office (3.65m x 4.26m x 2.74m) has (2) two ceiling recessed electric lighting fixtures with (3) three 32W T8 fluorescent lamps without dimming capability. Also, vertical interior Venetian blinds can be manually controlled. The selected office has been monitored for 40 consecutive days from sunrise to sunset. During the study period, the space was completely unoccupied and solely illuminated by natural light through the south facing window. Interior blinds were fully open in order to avoid any reflection or diffusion of incoming sunlight.

The field measurements were made from July 6th to August 15th, 2016. In order to fully track drastic changes of daylight levels inside the selected office space, Li-Cor photometric sensors and data logger were utilized. The photometric sensors were installed at six different locations throughout the space. Horizontal illuminance levels were measured at three different locations on top of the desk: 0.6m, 1.2m and 1.8m away from the south facing window. Another horizontal illuminance level was measured at the ceiling surface looking downwards at 1.2m away from the window. Two vertical illuminance levels were measured: one at the center of the window facing outwards and the other mounted at human eye position looking at the computer screen. The view direction of the sensor at human eye position is shown in Figures 1 and 2. These six different illuminance levels (four horizontal illuminance and two vertical illuminance) were recorded at 1 min. interval for a 40 day period. All six sensors were calibrated prior to the study.

The office space was virtually modelled in Rhinoceros software for daylighting simulations (Figure 2). And, daylighting simulations were performed for the same time period as the field measurements. Daylighting simulation plug in tool, Diva for Rhino with Radiance engine, was used for detailed simulations using climate data. A weather data file of the city of San Antonio was utilized for hourly-based annual daylighting simulations. Interior surface material properties have been defined in Diva for Rhino: 80% reflectance of the ceiling, 50% reflectance of the walls, 20% reflectance of the floor, and 71% visible transmittance of the double plane windows.

Figure 3 shows an example of simulated daylight illuminance levels (in lux) on task plane inside the office. Even though the entire space has been calculated in Diva-for-Rhino, illuminance values for the measurement locations (0.6m, 1.2m and 1.8m away from the window) were only collected and compared. In addition to these sensor points, two vertical sensor points at the windows and human eye position were calculated.



Figure 1. Fisheye image of the interior of the selected office space in San Antonio, TX.

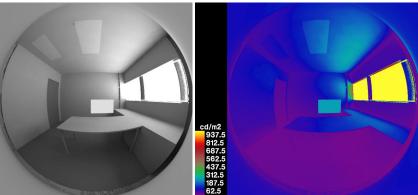


Figure 2. Angular fisheye rendering of the selected office on July 28 at 12:00PM (left) and false color image of the rendered view (right).

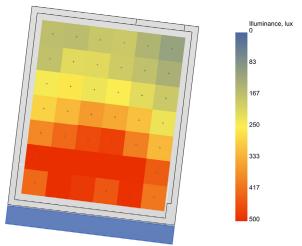
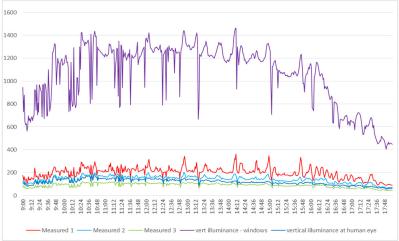


Figure 3. Simulated illuminance levels inside the office for July 21st 12:00PM.

# 2.0. ANALYSIS

Illuminance data collected for a 40 day period was first analyzed with the actual weather history of San Antonio for the study period. The collected weather history data shows that various sky conditions occurred during the study period: 71% clear sky, 15% partly cloudy sky, 8% mostly cloudy/overcast sky, and 5% rainy sky condition. Comparison between the weather history and the measured illuminance level patterns helped explain what actually happened under each of the sky conditions including clear sky, partly cloudy sky, and overcast sky. It also helped reveal any abnormal daylight pattern throughout a day.

Figure 4 shows an example of the measured horizontal and vertical illuminance data from 9:00AM to 6:00PM on July 7th. The fluctuation of the measured illuminance levels clearly represents how dynamic the sky condition is in San Antonio. Based on the weather history data of San Antonio, the sky condition of July 7th was categorized as a clear (sunny) sky. Vertical illuminance level collected at the windows (shown in a purple line in Figure 4) shows how much natural light was introduced through the windows and it fluctuates for the entire day. Constant daylight level is not quite observed from the measured data. The purple line is clearly higher than the other illuminance levels collected at task area, ceiling, and occupant eye position as illuminance level decreases while it travels throughout the indoor space. On this specific date, up to 750 lux fluctuation of incoming daylight at the windows is observed. The fluctuating illuminance levels clearly show that sky condition was not static. The peaks and valleys in the graph also show exactly when the sun was visible or hidden behind clouds.

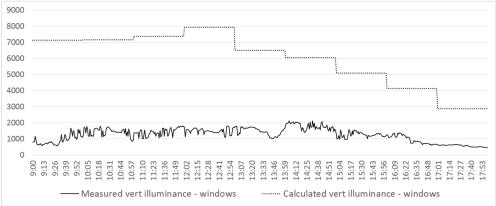


**Figure 4:** Measured illuminance levels inside the office for July 7th with clear sky condition in San Antonio (vertical axis: illuminance (lux) and horizontal axis: time of day (hour: minute)).

# 2.1. Comparison of incoming natural light

In the daylighting design practice, it is quite common to see discrepancy between daylighting simulations and actual measurements because of differences in between virtual and real environmental conditions and building material settings. In order to make a fair and accurate comparison of daylight levels between simulations and measurements, it is critical to calibrate computer simulation settings and results to real world conditions. Figure 5 compares the collected vertical illuminance values (incoming natural light in a solid line) to the simulated illuminance values at the windows (in a dashed line) under clear sky condition. It is quite surprising to see the huge discrepancy between the simulated and measured values especially when this specific day had a sunny (clear) sky condition. At noon, the calculated illuminance level is up to 8,000 lux while the measured illuminance level is around 1,700 lux. When a virtual model was built in Rhinoceros, 71% visible transmittance value was assigned to the window's material property for a typical double glazed window without additional tint or film. It was found that this assumption was too optimistic as there was no consideration of dust accumulations on the outer surface of the existing windows. To compensate the discrepancy between the

virtual model and real world building condition, additional 60% visible transmittance (VLT) reduction was applied to the window material property assumption which lowered its VLT to 42.6%. This additional VLT reduction was carefully calculated from the entire dataset collected for the 40 day period.



**Figure 5.** Measured and simulated illuminance levels at the windows for July 9th with clear sky condition in San Antonio (vertical axis: illuminance (lux) and horizontal axis: time of day (hour: minute)).

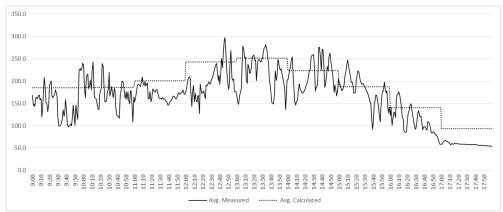
Measuring incoming daylight (available natural light in buildings) is critical to ensure the validity and accuracy of daylighting simulation results. Material settings in a virtual model can greatly affect simulation results and cause huge discrepancies between computer simulations and field measurements. Considering potential dirt accumulations on window surfaces in computer simulation would be appropriate for more accurate daylighting performance predictions in design phase. It is important to note that weather history data can accurately represent real world sky conditions and luminous environments only when validation procedure is conducted.

## 2.2. Horizontal illuminance levels at task plane

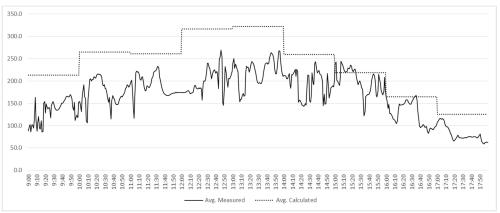
Computer simulations were performed again with the adjusted window material properties. And, the measured illuminance data was then compared to the calculation results. As lower visible transmittance of the windows was applied, this recalculation has reported lowered daylight levels inside the office. As both measured and simulated horizontal illuminance values were collected from three different sensor locations, average illuminance values were calculated for each day. Figures 6 through 8 compare average horizontal illuminance values between measurements and simulations for each of the three typical sky conditions: clear (sunny), partly cloudy, and mostly cloudy (overcast) sky. In all three figures, discrepancy between the calculated and measured illuminance values is quite obvious. In Figure 6, the solid line for the measured illuminance levels fluctuates for the entire day of July 30th. It is important to point out that the sky condition was clear and sunny based on hourly weather forecast data. On this specific date, fluctuation of illuminance levels greater than 50 lux has occurred more than 50 times from 9:00AM to 6:00PM. Illuminance level changes greater than 150 lux have occurred several times throughout the day. Different from the measured illuminance levels, computer simulation provided a stable illuminance value for every single hour as it is based on the hourly weather data collected at a weather station. An average measured illuminance level is 163.9 lux while an average calculated illuminance is 189.9 lux. The daily average measured illuminance is 13% lower than the simulation.

Figure 7 compares the measured and simulated daylight patterns in a partly cloudy sky condition on August 5th. For the entire day, the measured illuminance values are lower than the calculated values with the weather data file. Similar to the clear sky condition example shown in Figure 6, the measured illuminance values fluctuate up to 120 lux throughout the entire day. It is observed that more clouds in the sky makes daylight level fluctuations less severe than the clear sky condition. However, an average measured illuminance value is very

similar to the clear sky condition example which is 168.4 lux. An average calculated illuminance is 238.5 lux. The measured illuminance is 29% lower than the simulated illuminance.

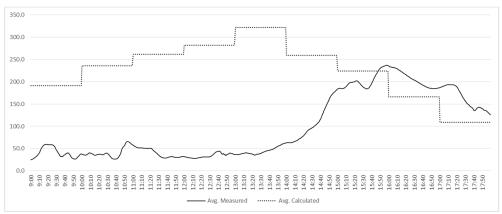


**Figure 6.** Clear sky condition on July 30th- avg. horizontal illuminance levels on top of the desk. Calculated values in dashed line and measure values in solid line.



**Figure 7.** Partly cloudy sky condition on August 5th- avg. horizontal illuminance levels on top of the desk. Calculated values in dashed line and measure values in solid line.

Figure 8 shows daylight patterns of August 13th under a mostly cloudy (overcast) sky condition. For the entire morning and early afternoon, the measured illuminance values are very low in a range of 25 lux to 60 lux. The calculated illuminance value pattern is very different from the measured values. The measured illuminance values became higher than the calculated values at 3:30PM and afterwards. It is possible to assume that this mostly cloudy day still allowed direct sunlight/solar radiation in the late afternoon. Different from the examples of clear sky and partly cloudy sky conditions, drastic illuminance fluctuation did not occur under mostly cloudy sky condition. An average measured value is 97.4 lux while an average calculated illuminance is 228.0 lux. This comparison shows that the changes of sky coverage cannot be accurately predicted or evaluated in computer simulations using a weather data file. It is also possible to assume that the discrepancy between daylighting simulations and real world measurements becomes larger as there are more clouds in the sky. The discrepancies observed between the calculated and measured illuminance values in Figures 6 through 8 were also found from the rest of the 40 day study period.



**Figure 8.** Mostly cloudy sky condition on August 13th- avg. horizontal illuminance levels on top of the desk. Calculated values in dashed line and measure values in solid line.

# 2.3. Daily average horizontal illuminance levels

Figure 9 compares daily average horizontal illuminance levels between the measurements and simulations for the 40 day study period. The figure shows that daylighting simulations predict higher daylight availability than the actual measurements even after calibrating the virtual model settings based on the amount of incoming natural light. A daily average measured horizontal illuminance level is 157 lux while a daily average simulated value is 184 lux. The daily average measured illuminance level is 27 lux lower than the calculated illuminance level. A computer based office task requires 150 lux horizontal illuminance level at task area and both simulations and measurements show that the selected office space has enough natural light for the task during the study period (DiLaura et. al., 2011). However, the amount of daylight is not sufficient for a paper based office task which requires 300 lux.

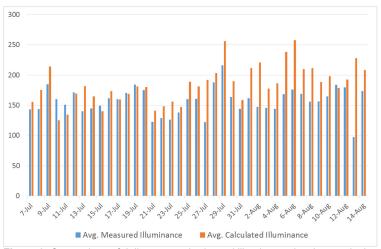


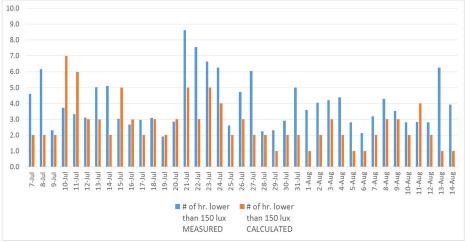
Figure 9. Comparison of daily average horizontal illuminance levels at task plane between measured and calculated.

## 2.4. Need for electric lighting

In order to estimate potential electric lighting energy saving benefits of daylight harvesting, the number of hours with horizontal illuminance levels below 150 lux thresholds were calculated for each day. Figure 10 compares numbers of hours with horizontal illuminance below 150 lux between computer simulations or field measurements. The blue bar represents the number of hours with the measured illuminance levels below 150 lux (Figure 10). Orange bar shows the number of hours with the calculated illuminance levels below 150 lux. The higher a bar is, the

more usage of electric light is required during the office hours. For example, one hour period with illuminance levels lower than 150 lux would require occupants to turn on electric lighting fixtures inside the room for one hour so that required light levels can be provided for computer based office tasks. On July 21st, the measurements show that electric lighting should be turned on for 8.6 hours while the simulations predicted 5.0 hour's operation of electric lighting. Average values for the entire study period are 4.0 hours per day from the measurements and 2.7 hours per day from the computer simulations. For the 40 day study period, a total of 104 hour of electric lighting operation was predicted by the computer simulations but electric lighting had to be turned on for 155.6 hours based on the actual daylit conditions. This clearly shows that the need of electric lighting can be underestimated by the computer simulations using a weather data file.

When considering wattage of the electric lighting fixtures inside the office, additional 249.6 watt-hour (0.25 kWh) should be consumed per day compared to what was predicted by the computer simulations. It becomes 69,888 watt-hour (69.8 kWh) energy consumption for an entire year when assuming the office will be occupied for five days a week (from 9:00AM to 6:00PM) and when assuming the same discrepancy happens for the rest of a year. This additional energy consumption might look insignificant but it is important to point out that this number is calculated only from one small office space (15.5 m² or 166.8 sf) of a large building. Inaccurate predictions of daylighting design performance in dynamic sky condition can result in inaccurate assessment of energy saving benefit in buildings.



**Figure 10.** Comparison of numbers of hours with horizontal illuminance levels below 150 lux at task plane between measured and calculated.

### CONCLUSION

The comparative analysis shows that hourly-based daylighting simulations using a weather data file or pre-determined sky model cannot make accurate predictions of daylight performance in dynamic sky conditions. Drastic changes of indoor illuminance levels were observed under dynamic sky conditions including both clear sky and partly cloudy skies. Hourly-based daylighting simulations cannot predict these drastic illuminance changes and its high frequency. Also, it was found that hourly-based simulations become less accurate as the sky is covered by more clouds. Inaccurate estimation of daylight availability can make energy saving benefit of daylight harvesting unreliable. More accurate daylight performance prediction particularly for dynamic sky is required.

Drastic changes of daylight availability inside a building can cause occupants visual discomfort and make them want to rely on electric lighting systems instead of natural light. Also, high frequency of drastic changes in luminous environment can force occupants to adjust shading

devices and electric lighting systems many times throughout a day. It would be very challenging to optimize lighting energy saving and occupant's visual comfort when hourly based daylighting calculations are performed for a project in dynamic sky conditions. Further study is required to investigate subjective response to drastic light level changes and high frequency of the changes in daylit spaces.

The findings from this study can help daylighting design professionals to be aware of potential issues of daylighting simulations under dynamic sky conditions. It is important to note that the study was performed only for 40 day period and further investigation is required for a longer period of time to ensure consistency of the findings in the study.

## **ACKNOWLEDGEMENTS**

This project was funded by the University of Texas at San Antonio, Office of the Vice President for Research, Economic Development, and Knowledge Enterprise.

#### REFERENCES

- Baechler, Michael, Theresa L. Gilbride, Pam C. Cole, Marye G. Hefty, and Kathi Ruiz. 2015. High-Performance Home Technologies: Guide to Determining Climate Regions by County. U.S. Department of Energy
- https://www.energy.gov/sites/prod/files/2015/10/f27/ba\_climate\_region\_guide\_7.3.pdf
- DiLaura L. David, Kevin W. Houser, Richard G. Mistrick, and Gary R. Steffy. 2011. The Lighting Handbook 10th edition. Illuminating Engineering Society. ISBN-13: 978-0-87995-241-9
- Hirning, Michael, Gillian Isoardi, Coyne S, Ian Cowling, and Veronica Garcia-Hansen. 2013. Post occupancy evaluation relating to discomfort glare: A study of green buildings in Brisbane. Building and Environment 59: 349-357
- Katzenstein, Erick. 2013. Occupancy Comfort Sensors. LMN Architects, September 9, 2013. https://lmnarchitects.com/tech-studio/interaction/lmn-post-occupancy-comfort-sensors/ (accessed August 25, 2017).
- Kensek, Kensek. and Jae Yong Suk. 2011. Difference between Daylight Factor (overcast sky) and Daylight Availability (clear sky) in Computer-based Daylighting Simulations, Journal of Creative Sustainable Architecture & Built Environment (CSABE), Volume1
- Konis, Kyle. 2013. Evaluating daylighting effectiveness and occupant visual comfort in a sidelit open-plan office buildings in San Francisco, California. Building and Environment 59: 662-677
- Nicol, Mark, Jerrod Kennard, and Mario D Goncalves. 2016. Analysis, sensors, and performance- closing the loop with post-occupancy data analysis. Proceeding of Façade Tectonics World Congress, Los Angeles, CA
- Suk, Jae Yong and Marc Schiler. 2012. Investigation of Evalglare Software, Daylight Glare Probability and High Dynamic Range Imaging for Daylight Glare Analysis. Lighting Research and Technology
- Suk, Jae Yong, Marc Schiler, and Karen Kensek. 2013. Development of new daylight glare analysis methodology using absolute glare factor and relative glare factor. Energy and Buildings 64: 113-122
- Weather Underground, 2017.
- https://www.wunderground.com/history/airport/KSAT/2016/7/7/DailyHistory.html?req\_city=&req\_state=&req\_state=ar