The Effect of Daylight on Visual Comfort
The Case of the Dome as a Classical Architectural Element

تأثير ضوء النهار على الراحة البصرية
حالة القبة كعنصر معماري كلاسيكي

by

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Abstract

Visual comfort is a subjective response to the amount and light quality within the workplace at a certain time. The idea behind visual comfort revolves around person’s capability to regulate the light levels surrounding him. Having very small or excessively high amount of light can lead to visual discomfort.

This paper investigated and assessed to which extent the use of geometric configurations in the classical architectural elements can fulfill the need for adequate lighting required for acceptable visual comfort. Domes as a classical architectural element function as a main daylight source and at the same time aesthetically pleasing and give the feeling that the room is bigger in size. The dome was chosen as the classical element to be tested in this paper, choosing a building at the University of Sharjah to be the case study. The research used simulation tools including Revit with Insight Plugin and IES with Radiance Plugin Software which will be used to get the glare evaluation and visual comfort index using Daylight Glare Probability metric (DGP), Glare Threshold Differential (GTD), illuminance, Spatial Daylight Autonomy ($sDA_{300/50\%}$) and Annual Sunlight Exposure ($ASE_{1000/250}$) for different simulated scenarios. The scenarios included cases where the dome was modified and its geometrical configuration were changed in order to enhance the dome capabilities, which included changes in dome’s diameter, drum’s height, and glazing area to drum area percentage.

Results showed that, comparing modification done in each variable, highest effect is the glazing percentage =100%, followed by glazing percentage=25%, then drum height =4m, glazing percentage=15% and drum height=3m are almost the same, followed by diameter of 18m and last diameter of 14m. If the dome is already constructed and needed enhancement its preferable to increase the amount of glazing within the dome since it makes the highest impact compared to other variables, with taking into consideration the values of sDA and ASE by testing them in simulations since increasing the glazing percentage increases the possibility of glare to occur. If the architect/designer wants better, uniform and equal daylight distribution bigger diameter can provide it although it doesn’t increase the illuminance levels that much, but if he is looking for higher illuminance level and ensure the glare won’t occur the designer should go with higher height. Equations were concluded showing the relationship of the glazing area with sDA and ASE values. Suggested recommendations for preferred combination of height, diameter and glazing percentage for dome's design and indicated the best orientation per date and time in order to prevent disturbing/intolerable glare.

ملخص البحث

الراحة البصرية هي استجابة ذاتية للمقدار والجودة الخفيفة في مكان العمل في وقت معين. تدور الفكرة وراء الراحة البصرية حول قدرة الشخص على تنظيم المستويات الخفيفة المحيطة به. يمكن أن يؤدي وجود كمية صغيرة جدًا أو عالية جدًا من الضوء إلى عدم الراحة البصرية.

بحثت هذه الورقة وقيّمت إلى أي مدى يمكن أن يؤدي استخدام التكوينات الهندسية في العناصر المعمارية الكلاسيكية إلى تلبية الحاجة إلى الإضاءة الكافية المطلوبة للراحة البصرية المقبولة. تعمل القباب كعنصر معماري كلاسيكي كمصدر رئيسي لضوء النهار وفي نفس الوقت ممتعة جماليا وتعطي الشعور بأن الغرفة أكبر في الحجم. تم اختيار القبة كعنصر كلاسيكي يتم اختباره في هذه الورقة ، باختيار مبنى في جامعة الشارقة ليكون مجال الدراسة. استخدم البحث أدوات المحاكاة بما في ذلك Revit مع Insight Pluginو IES مع Radiance Plugin والتي سيتم استخدامها للحصول على تقييم التوهج ومؤشر الراحة المرئية باستخدام مقياس احتمالية التوهج النهاري (DGP) ، التباين الفائق للوهج (GTD) ، الإضاءة ، الاستقلالية المكانية لضوء النهار ($sDA_{300/50\%}$)والتعرض السنوي لأشعة الشمس ($ASE_{1000/250}$) لسيناريوهات محاكاة مختلفة. تضمنت السيناريوهات حالات تم فيها تعديل القبة وتغير تكوينها الهندسي من أجل تعزيز قدرات القبة ، والتي تضمنت تغييرات في قطر القبة وارتفاع الاسطوانة ومنطقة التزجيج إلى نسبة مساحة الأسطوانة.

أظهرت النتائج أنه بمقارنة التعديل الذي أجري في كل متغير ، فإن أعلى تأثير هو نسبة التزجيج = 100٪ ، تليها نسبة التزجيج = 25٪ ، ثم ارتفاع الأسطوانة = 4 متر ، ونسبة التزجيج = 15٪ ، وارتفاع الأسطوانة = 3 متر تقريبًا ، ويليه قطر 18 م وآخر قطر 14 م. إذا تم بناء القبة بالفعل وتحتاج إلى تحسينات ، فمن الأفضل زيادة كمية التزجيج داخل القبة لأنها تحقق أعلى تأثير مقارنة بالمتغيرات الأخرى ، مع مراعاة قيم sDA و ASE من خلال اختبارها في المحاكاة منذ زيادة التزجيج تزيد النسبة المئوية من احتمال حدوث وهج. إذا كان المهندس المعماري / المصمم يريد أفضل ، فإن التوزيع الأكبر لضوء النهار يمكن أن يوفره على الرغم من أنه لا يزيد من مستويات الإضاءة كثيرًا ، ولكن إذا كان يبحث عن مستوى إضاءة أعلى ويضمن عدم حدوث الوهج ، يجب على المصمم تذهب مع ارتفاع أعلى. تم الانتهاء من المعادلات التي تبين علاقة منطقة التزجيج بقيم sDA و .ASE توصيات مقترحة للجمع المفضل للارتفاع والقطر ونسبة التزجيج لتصميم القبة وتشير إلى أفضل اتجاه لكل تاريخ ووقت لمنع الوهج المزعج / الذي لا يطاق .

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Table of Contents

List of Figures

List of Tables

CHAPTER 1: INTRODUCON

CHAPTER 1: INTRODUCTION

1.1. Research Background

Daylight was considered as the essential wellspring of light in 1940s, yet after the creation of artificial light it supplanted the natural daylight choice. During that short period of 20 years, electric lighting had changed the work environment by accomplishing what the occupants need to get their lighting needs. Nowadays, energy and environmental issues have aware of importance of day lighting as a part of daylight configuration, and also inquiries regarding the effect of artificial light on individuals' well-being, have driven researchers, architects and designers to reconsider the advantages of natural daylight and the innovative ideas of visual comfort that can be implemented.

Visual comfort is known as a subjective response to the amount and light quality within the workplace at a certain time. The idea behind visual comfort revolves around person's capability to regulate the levels of light surrounding him. Having very small or excessively high amount of light can lead to visual discomfort. Another thing to be aware of the adjustments in levels of light or the intense contrast that could lead to stress and fatigue when exposed to for long time because of the fact that the human eyes continuously adjust to light levels.

From the excessive research on the topic, it seems that there are no research papers that targeted the visual impact of having a dome as an element for daylight. Most of the research related to domes either tested the acoustical impact or some daylighting analysis targeting only illuminance level (lux) and none discussed nor searched on the glare, the Spatial Daylight Autonomy or Annual Sunlight Exposure.

Though this research will be focusing on glare, illuminance to evaluate visual discomfort on educational space (University of Sharjah) to be a benchmark and recommendations for educational and other building types to follow.

This research is focusing on assessing the visual environment by evaluating and measuring several light aspects which are glare (using Daylight Glare Probability metric (DGP), Glare Threshold Differential (GTD)), illuminance, Annual Sunlight Exposure (ASE) and Spatial Daylight Autonomy (sDA) for different simulated scenarios, targeting the visual comfort.

For ages, daylight was the only effective and obtained light source that's why designing buildings that provide maximum amount of daylight throughout the day was essential for architects and designers, and though the architectural design for daylight was controlled by the desire of having spaces with large spans and making openings sufficiently big to disseminate sunlight to as much possible of the internal space. (Phillips 2004)

In the end of 19th century, daylight was replaced by artificial lighting, thought of having adequate daylight techniques was a primary concern. The famous architect "Le Corbusier" highlighted the importance and significance of daylight in architecture with some statements saying that a part of architecture is to be skillful, redress and capable to play with geometries to provide daylight, and that architecture history is a history of struggling for light. Within the middle of twentieth century, artificial lighting replaced daylighting in buildings totally, but luckily, by the late twentieth century and beginning of twenty-first century, designers and architects went back to designing considering daylight and making it essential factor of design after all the issues that came from the extensive use of artificial lighting. (Fuller M. 1991)

All through the architectural historical periods, planners and architects created classical architectural components to adjust depending on the requirement of light and the functionality of the space. For example, ancient Egyptian utilized clerestories openings and little windows to avoid glare and blinding daylight. Romans utilized the barrel vault, arch and dome to make it possible to make bigger openings to permit more daylight for limited and small passages and corridors as well as and deep spaces.

The research will be highlighting to which extend the classical architectural elements can be reshaped or adjusted in order to fulfill the need for adequate lighting needed for acceptable visual comfort. The dome was chosen as the classical element to be tested in a building at the University of to be the study field. simulation tools will be used including Revit, IES, Insight and Radiance Software will be used to get the glare, illuminance, Annual Sunlight Exposure (ASE) and Spatial Daylight Autonomy (sDA) for different simulated scenarios. The scenarios include cases where the dome is modified and others where other modern elements are used to enhance the dome capabilities.

1.2. Problem Statement

Visual comfort in buildings is critical for the health and efficiency of people. The challenge is to think and redesign buildings from an environmental perspective by considering day lighting as a main parameter.

On the other hands educational institutes/buildings have tested glare, illuminance, Spatial Daylight Autonomy or Annual Sunlight Exposure but none tested any classical architectural elements (domes, oculus, vaults, flying buttresses,…) impact on educational, public or office spaces. In fact, not only religious institutes (mosques and churches) are the only buildings using domes for daylight purpose, they are many other types of buildings using this technique to enhance daylighting in space such as:

- Educational : University of Oxford, Massachusetts institute of technology, University of Notre Dame, University of Sharjah, American University in Sharjah, The Maharaja Sayajirao University
- Offices: The Dome of the US Capitol , Cleveland Trust Company Building
- Museums: Dali Theatre and Museum, Kuppel des Bode-Museum
- Hotel : Threadneedles Hotel , West Baden Springs Hotel

The research will conduct a study on the natural light efficiency on the dome of one of University of Sharjah buildings to determine if it provides adequate and sufficient daylight suitable for students using the building. In educational buildings it's essential to have sufficient lighting and illumination. The goal is to achieve better lighting efficiency and visual comfort in educational buildings using Simulation tools. Research can help make the building get more daylight, use it more efficiently and reduce the use of artificial light which leads to less energy consumption. The research will test the amount of daylight coming into the room and whether adjusting the dome geometrical properties will enhance the visual comfort within the space or not. Later on, all this data will be evaluated against standard luminance levels and visual comfort zones.

1.3. Research Questions

The main aim of the research is to get an answer for the following questions:

1) Do classical architectural elements such as domes have the ability to actually affect amount of sufficient daylight necessary for adequate visual comfort?

2) What are the correct techniques or methods that should be considered whenever a symbolic or classical element is presented to avoid visual discomfort and glare?

3) Within working hours, is the amount of daylight provided in the space is sufficient or artificial light should be presented to enhance the space visual comfort quality?

4) What are the best locations to be considered for furniture distribution to avoid glare during the day?

5) What are the optimal dimensions of the dome?

6) What is the best occupants’ orientation?

1.4. Aim of the Study

The main aim behind this research is:

1) Investigate how some parameters could affect daylight and how to achieve sufficient visual comfort levels.

2) Presenting an overview of the different design possibilities that can be used in UAE buildings while maintaining the iconic and unique architectural features and characteristics of gulf region.

3) Giving suggestions and recommendations to efficiently use the local architecture and design elements

3) Identify the best areas and orientation for furniture (tables and seating areas) to avoid glare and discomfort light.

1.5. Significance and Motivation of the study

Daylight is considered as the one that supplies much better light than the energy efficient electrical. Especially in educational buildings, it's essential to have sufficient lighting and illumination in order to achieve comfort environment.

The history of daylighting in architecture went through many developments, and one of them is discovering new structural elements that made it possible to create larger openings and though better daylight accessibility. Most of the universities and public facilities around the world especially in Europe and Middle East are designed using classical architectural elements, including domes, flying buttresses, barrel vaults, rose windows and many more.

The research investigates the functionality of the design of architectural elements form and space in serving daylight. In fact, there is no or limited studies that investigated the daylight relationship with the architectural design, this search can focus the attention to this neglected topic. The findings of this study can be used by architects and designers in order to design better, healthier, more visually comfort spaces and less energy consuming, also people who are concerned about the preservation of historical building or current buildings with classical design can learn how to enhance the functionality of the architectural light elements.

Section 2.6.2. "The gap which this research paper will be focusing to fill" will give more details on the study significance and the gap that it covers.

1.6. Limitation of the study

There were some limitations within the study. Those limitations must be resolve and taken into consideration to enhance the results and to make future researchers who investigate about similar topics more aware:

1. The research area is vast and many scenarios can be given and discussed. What was chosen were some scenarios to get a general idea of how to make the building get more daylight, use it more efficiently.

2. Software can do many analyses and generate variety of results. Software errors in analysis can happen and software might have an inaccuracy percentage. Also the use of one software may have assumptions that are not compatible with real life.

3. Dome diameter is only increased up to 18.0m since the building dimensions won't be changing during simulation process and though so roof size is limited and increasing even more the dome diameter will be exceeding the roof boundaries and the lobby limits.

4. Limitations of surface reflections (Assumption of Wall Paint Varnish =50%, Floor Tile Porcelain Ceramic = 20%, Ceiling tile 600x600 =80%).

5. Time and date of the year chosen for Simulations was limited to 21 June, 21 Sep, 21 Dec at 8:00am, 12:00pm and 4:00pm for illumination results and glare

6. The simulations were done with considering clear sky and no presence of furniture.

1.7. Research Outline

This research is divided into five Chapters as following:

Chapter 1: Introduction

It discusses background information and overview about visual discomfort and how domes were used/investigated in that matter as well as investigating several daylight parameters to evaluate the dome parameters. Section 1.1 Research Background and 1.2. Problem Statement explain the "research background" and 1.5. Significance and Motivation of the study explains "rationale behind carrying this research".

Chapter 2: Literature review

2.1. Daylighting importance for Sustainable Lighting

This section is to understand the importance of daylight and why I should be investigated and searched it focuses on the value and benefit of introducing daylight and the sustainability aspect.

2.2 Visual Discomfort

This section is very important since it explains each metric I will be using in evaluating daylight and defines what are the aspects/factors to be considered/evaluated when studying visual discomfort. It also states the glare metrics (which is a factor in causing discomfort) and explains each glare metric to highlight for the reader why I have chosen GTD and DGP as my glare metrics rather than the others.

2.3. Classical Architectural Elements of Light

This section was essential to decide the field of the study. This was the starting point, as stated in chapter 1 in the latest centuries the use of artificial light increased and replaced the daylight and per section 2.1. in the literature this increase the physiological , psychological , health issues and comfort of occupants and from an architectural perspective the space lost its attraction and value. Because of that an investigation should have been done (2.3.1. How Classic Buildings Used Daylighting) to understand how the previous centuries have introduced light within space using daylight as the main source (since artificial light wasn't invented yet) and there I have found that domes were one of the techniques used in many centuries and eras and it was available here in UAE to be investigated. Also it was important to understand why daylight was replaced in the first place" what was the issue with daylight only" that's why the section (2.3.2. Development of Architecture elements of light through Eras) was added, highlighting the development and when the artificial light was introduced and for what reasons, this also helped in highlighting the objectives of my study since one of the reasons or replacing adding artificial light was because of the GLARE which later become one of my research objectives to understand what causes it.

2.4. Variables affecting daylighting

This section was to check previous research about variables which affect daylight to know what to target in my investigation and to see what previous researchers have stated (for example doubling the height of the window will double amount of daylight coming in through it) to either agree/disagree with those statements with evidence from my analysis.

2.5. Previous research papers on domes and their relationship with daylight.

After section 2.3. I decided to use the dome as my investigation field, I had to check what was the previous research papers that investigated the domes and in which matter. In this section I concluded the gap that I have to fill, since most of the research related to domes either tested the acoustical impact or some daylighting analysis targeting only illuminance level (lux) and none discussed nor searched on the glare, the Spatial Daylight Autonomy or Annual Sunlight Exposure.

2.6. Literature Review summary and outcomes

This section is to summarize and critically review the outcomes of the literature as recommended by my supervisor. (Section 2.6.1. Lessons learnt from literature) highlights the important statements concluded from the literature in which I will agree/disagree with in my conclusion. Then section (2.6.2.The gap which this research paper will be focusing to fill) stated how the literature helped me in getting the objectives of my study and the GAP that I should be investigating since it hasn't been done/investigated yet

Chapter 3: Research Methodology

It includes the previously used methodologies used to study visual discomfort in educational spaces and also the several metrics used to do so and justification of choosing simulation approaches. Followed by clarifying the chosen building to be investigated and displays details of building, model set up should displayed and project boundaries. In addition to software exploration, how each would be used, which metric will be measured by each, evaluation, and selection. Ending with variables tested and the simulation scenarios (cases) to evaluate them based on metrics.

Chapter 4: Results Analysis and Discussion

In this section, I will be testing three variables drum height, dome diameter , and percentage of glazing in the mentioned timings targeting several properties of daylight (illuminance, glare, sDA, ASE ,..) and to do that I have conducted more than 1084 analysis that were listed in the Appendix and there were others during the testing process, all this (more than 1084 analysis) were done for precisely testing three variables.The section was divided into three main cases (scenarios):

Case 1: Annual Variables $sDA_{300/50}$ and $ASE_{1000/250}$, will be calculated from 8:00 am till 6:00 pm from 1st January till 31st December which is around 3650 hours. The term $sDA_{300/50}$ (>300 lux, >50% of year) is presenting the floor area percentage getting over 300 lux for 50% of 3650 annual hours (LEED recommend values between 55%-75% of area). $ASE_{1000/250}$ is presenting the floor area percentage getting over 1000 lux for more than 250/3650 annual hours. The following table13 demonstrates the results for sDA and ASE simulations, they will be discussed and analyzed shortly. The results can be found in Appendix D - Annual Variables Results (SDA and ASE).

Case 2: Light Properties This case measures the illuminance level (lux) in different dates and timing around the year. The simulation will be done on 21 June – 21 Sep – 21 Dec at timings 8:00am – 12:00pm – 4:00pm. Table15,16,17 are case of D=7.0m H=2m and S=10,15,25,100% cases on 21 June – 21 Sep – 21 Dec, the simulation results can be found in Appendix A – Illumination Results. It was simplified into the following sub-sections:

- Comparing brightness between months
- Trends within results
- Effect of increasing diameter
- Effect of increasing drum’s height
- Effect of increasing glazing percentage
- Maximum and minimum illuminance levels
- Impact of independent variables “D, H, S” on dependent variable “illuminance level”

Case 3: Glare. Glare will be investigated using two metrics which are daylight glare probability (DGP) and Glare Threshold Differential (GTD). DGP considers contrast and vertical illuminance as contributors to visual discomfort, GTD gives a value of glare discomfort by differentiating the maximum luminance that the viewer is looking at with the threshold of the view. Glare is a function of the location of the viewer and the observation direction. Therefore, simulations will be taking in several locations. The simulation will be running on two days 21 June and 21 December at 8:00am, 12:00pm and 4:00pm testing 15 points each point looking horizontally in 4 directions. The case that would be tested is the case with diameter = 14m, drum height = 4.0 m and drum fully glazed. The first part will be showing DGP and GTD simulation results on plan view for each day and time, the second part will be line charts for DGP and GTD results individually comparing the 15 points four directions values per each date and time. For further details please refer to *Case3: Glare* in section (3.4.3.Simulation Scenarios). The simulation results can be found in Appendix B – DGP simulation results and Appendix C – Glare threshold simulation results for GTD calculations.

Chapter 5: Conclusion and Recommendation

This chapter was divided into two sections to accurately highlight the findings:

5.1. Conclusion from simulation results

Where everything concluded from the analysis and simulations in chapter 4 was stated and organized based on case (Case1: Annual Variables , Case2: Light Properties , Case3: Glare)

5.2 Recommendations

In this section I had stated all the research questions and answered them based on what I have concluded from my simulations and supported it with statements from literature (as shown in the sample screenshots below). And last added some recommended Future Studies. I have stated a list of the other variables that other researchers could investigate to follow up with my search.

CHAPTER 2: LITERATURE REVIEW

CHAPTER 2: LITERATURE REVIEW

Several research papers and journals have been investigated and studied in the following sections. In the end of the chapter, there will be a summary of the outcome and lessons leant from literature review (section 2.6.1.). Plus, the gap that this research will cover (section 2.6.2.).

2.1. Daylighting importance for Sustainable Lighting

2.1.1. Value of daylight.

The importance of daylighting has increased in the recent time since it was approved that daylight is related to human health and wellbeing and the productivity levels of people either living, using or working in buildings. No artificial light can coordinate or correspond the colour variety of sunlight. The human eyes have the ability of effectively adjust and recognize things and objects better when sunlight is provided, and it enhanced with using windows since it gives people a sense of contact and interaction with the outside (US Office of vitality, 2012). Human brain cells get important information and energy from the illuminated surroundings which play a major role in regulating the mood, how people react, and mental health. (Dogan and Park 2018).

Another value of daylight is the physiological and psychological effects on human body. Daylight has this impact of making a person feels more comfortable, satisfied, and healthier and creates a productive environment. As known, sunlight is the major source for vitamin D which is responsible for production and creation of teeth and bones. To stay healthy and get the necessary amount of Vitamin D needed by the body, a person should be exposed to the sun for at least 15 minutes per day. (Menzies and Wherrett 2005).

A study conducted by Nicklas and Bailey on school students examining relation between students' exposure to sun and their health. The results showed that students were healthier and attended school regularly in the cases that were exposed to full light spectrum having an absence rate of 3.0 to 3.8

days per year only, compared to students who attend schools with no to minimal exposure to sunlight. They found out as well that students exposed to sunlight had better mood and satisfactory feelings compared to the ones who don't. The additional exposure to daylight increasing the vitamin D level has also resulted that those students were less infected with dental decay by 9 times than those students studying in a none daylight school (Plympton and Conway 2000).

A study done by Thayer, B. (2005) testing also students productivity and its relation to their exposure to daylight. He figured out that students with optimal daylight have higher productivity levels compared to the regular illuminated schools. Students with optimal daylight had made a progress in one year by solving mathematical questions 20% quicker and solving reading tests 26% faster comparing to students who used to study in less day lighted classes. Students became more mindful and showed lower rates of hyperactivity (Thayer 2005).

A privilege that daylighting has on artificial lighting is that it's in continuous variance and unpredictable. The amount and levels of daylight reaching a surface or entering a room varies due to movement of clouds and though variation in the exposure to the sun. Many researches stated that the variance in daylighting gives a relaxing effect for the eyes. (Sze-Hui 2000)

Leather et al. (1998), conducted an experiment on 100 people in office buildings from different careers to test their satisfaction levels with different daylight exposure levels. He found out that employees who work in environments that penetrates more direct sunlight than other had higher satisfactory levels, better health and the lower chances of quitting their jobs. In his experiment, he also highlighted that when comparing classroom with windows with the windowless ones, students who studied in classrooms with windows had significantly positive feedbacks in their relaxation levels and focus. (Edwards and Torcellini 2005).

The Wang and Boubekri (2012) research reached contradictory results. They have stated that people will not always preform or produce more if their sitting space was exposed directly to sunlight or near windows. They stated that to verify this statement the room environment should be evaluated as whole to get correct results for the daylight effect and external views. They also highlighted that control and privacy have effect on occupants' performance evaluation. In their study, they have evaluated some office employees' performance using previous mentioned variables, they found out that having better outside views were related to having better performance, but on the other hand being exposed to glare had reduced their performance. (Wang and Boubekri 2012)

Daylight is considered to have better "light quality" compared to artificial lighting. The term "light quality" refers to variables that make the environment generally acceptable by people using the room. The quality of daylight includes light distribution, color radiation, absence of flicker. When daylight is present, colors look brighter and closer to their real tone compared to artificial light since artificial light produce a spectrum that differs from place to another being strong in some spaces and weaker in others. In contradiction, daylight has continues light spectrum which gives an excellent color rendition. From experiments and previous studies, flicker is a cause of many health issues and problems such as headaches, eyestrain and attention deficit problems. Daylight doesn't flicker but artificial light has noticeable flicker. Some artificial light like fluorescent lamps has electric ballast which is used to reduce the flicker issues, but to ensure and guarantee that 100% no flicker would occur then a person should count on daylight. (Plympton and Conway 2000).

Daylight also effects the person's location and seating preferences since it is effecting directly their mood. In Aries research (2005) most of the participants in his survey mentioned that they preferred sitting next to the window since it's the place exposed to most of the daylight. Farley and Veitch (2001) found a slightly different conclusion from their study on literature which is that most occupants would prefer windows areas because of the views rather than daylight. A questionnaire done by Bodart and Deneyer’s study (2004) testing people’s aspects of windows, the results showed highest vote for daylight followed by connection with outdoors and as the most preferred spot for work compared to areas with artificial light. After collecting the questionnaire, the results showed that most of people preferred as seating options in working place to be near windows or have outdoor views, so in another words introducing daylight and having outdoor views are more preferable and attracting to people when choosing where to sit. (Wang and Boubekri 2011).

2.1.2. Benefits of natural daylighting.

One essential benefit of daylight that it grants visual exchange channels to the outside; it provides the views for building's occupants. In many of the research of windowless spaces, many people occupying those areas mentioned they would prefer to have contact with the exterior world. Although the desire for a view looks important, but it also relays on whether this view is providing enough daylight and whether a certain view is necessary. In one large survey by Markus, he assessed the view preferences of around 400 English office employees from Bristol, ranking their office views. Approximately 73% of the workplace employees voted their view as good, and 23% voted for the view to be an adequate view. The majority (88%) desired a view of a far-off landscape or a clear view of the sky since this allowed daylight comes inside directly without any restrictions like adjacent buildings. Only about 12% preferred a view of the city or the view of surrounding buildings. Many of people interviewed who sat away from windows stated that they would prefer to have closer seats to the windows. He noticed that most of the people sitting near windows were in better psychological when doing the survey. Markus also stated that the need for view and even the need for daylight could goes into the favor of ideal environmental elements if windows and openings have been designed properly. He mentioned that introducing variety of windows could be used to supply maximum adequate daylight. Vertical glazing provide a view of the sky (an upward view), the town or landscape (a horizontal view) and the ground (a downward view); some of these views can be design in a way to allow for sunlight at different hours, such as angled wall or roof apertures or horizontal roof glazing for illumination to be coming in varieties and though enhance the psychological statement of the occupants. (Mohamed 2017).

In a survey via “Cooper et al.” on English workplace workers, only 40% felt that desirable view was the most necessary function of a first-class workplace environment. A majority indicated that larger windows were preferable because it provide bigger portion of views and allow more daylight in. In addition, he indicated that the higher floors of workplace and the age of occupants play important role because the offices which are significantly above the ground have better views, and provide good quantities of light to perform the visible tasks since there would be less probability of facing buildings blocking daylight. As the human eye grows in age, the infections start to harm the eye having a noticeable effect on vision capabilities. And because of that bigger size of glazing would be preferable in offices that have a high percentage of elderlies. (Cooper and Codonhito 2009)

Roche et al. (2000) had also conducted similar survey, results showed that people prefer having windows in their working place, most of the survey participants (74%) voted to having windows to introduce daylight in their work to be “essential”, while only around 5% preferred to have sufficient artificial light to be more important than daylight. Another survey conducted by Veitch and Gifford (1996) on universities and college students showed that around half of participants preferred to be studying in a classroom lighted up by daylight since they believe it help them to focus, concentrate and produce their best work.

It’s true that having artificial light within the room would make workspace have better visibility but introducing daylight would make it appear even better and attractive. Although electric powered spaces can make a workspace very well visible, the addition of daylight can make a room appear greater and increase its attraction. Another researcher, Collin (1976) stated that daylight can control our daily life activities, daylight amount varies and comes in different ranges during day which is something the artificial light cannot do. A lot of people prefer and select certain timings within the day that have adequate daylight to their important physical activities and tasks since they believe that daytime supports better fitness (Galasiu and Veitch, 2006).

2.1.3. Advanced technology and those developed in the last decade.

Nowadays, with all this technology and new innovative daylight systems, human was able to control daylight by either redirecting it or focusing it in areas to be placed in the locations which has to be immoderate luminance and glare are required. Those modern structures utilize optical technologies which create reflections, refractions, and make it possible to utilize the skylight and daylight internal reflectance completely. Those new technologies could be customized and modified to passively monitor both direct daylight and skylight. In 1995, architects and designers started to use those systems as a part of new design elements. (Ozgun 2007)

1) Louvers Systems.

Fixed and mirrored louvers were created originally to control direct sunlight. High altitude solar and skylight mirrored off louvers enhance internal daytime levels. This could help with sky that has daylight access from low latitude to become less and this is when daylight access from angles 10°-40°above horizon. Another type of louvers could be fixed, it also called in some regions as the “Oka solar” in which they have mirrors used for controlling glare but this type of louvers reduces daylight significantly. (Ozgun 2007)

The standard thought of indoors louvers for solar protection has currently been more advantageous with many sparkling ideas. While exterior louvers typically are higher in decreasing the direct solar warmth impact, interior structures don't appeal dirt. Because of this, they can two be made with excessive gloss surface, which grantees very superb redirection properties (Ozgun 2007)

- *Prismatic Acrylic Louvers*

For the daylight expert, prismatic panel is not a new system or technology. The new technique that was added recently is turning the prismatic panels' concept and principle into stackable louver. This system has to accurately follow the solar height to ensure good sun protection. (Ozgun 2007)

- *Curved Metallic Louvers*

This type or louvre use horizontal louvre instead of the traditional vertical ones and replace the normal surface with a high glossy surface. This help to redirect sunlight in the simplest and easiest ways. (Ozgun 2007)

- *Folded Metallic louvers*

This type of louver comes in many designs and more flexibility compared to the previous. It redirects the low angles sunlight and in the same time reflect high angles unwanted direct light. (Ozgun 2007)

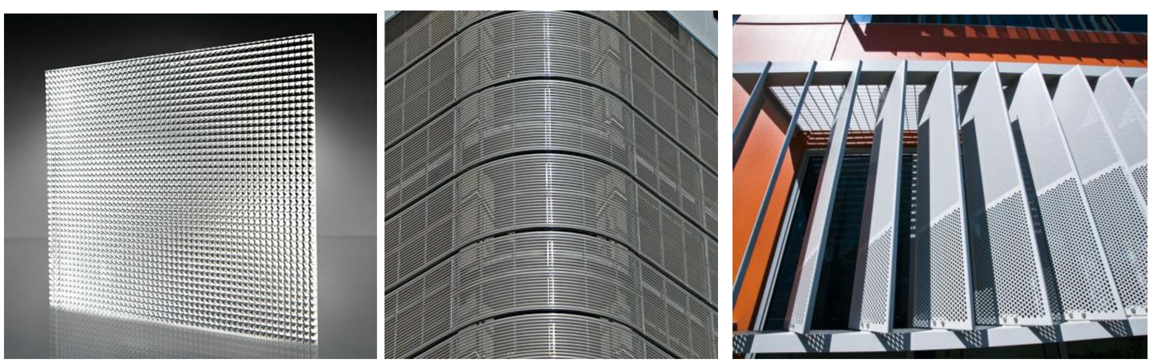


Figure 1: a) Prismatic Acrylic Louvers b) Curved Metallic Louvers c) Folded Metallic louvers (Ozgun 2007)

2) *Light Shelves*

A light shelf could be defined as a horizontal or tilted aircraft piece placed on windows in order to divide it efficiently for redirecting daylight purposes especially in deep plans conditions. The shelf itself has two layers materials, the top one an opaque reflective material and bottom is a white surface to diffuse light . The location of the shelf regarding the window should be measured accurately and to keep enough space of windows above the shelf to make it possible for adequate and desired daylight to be reflected towards ceiling and then hit the targeted space. A useful addition to this system are “light cabinets” which are cabinets with reflectors placed externally that create virtual sky from the reflected daylight whenever there is an overcast sky or even with cases that have buildings facing them. Another example of the use of this science is shown at Ash Creek Intermediate School in Monmouth, Oregon. This was based on a study conducted to evaluate the lighting properties at the school. The lights in the classrooms was once barely uneven, this includes the luminance from all sources (daylight and electric) in a south-facing classroom. While the electric powered lights are the greatest single source of illumination, the daylighting, on a sunny day, without problems that match the energy of the electric lights. The study examined the viability of daylight hours to provide sufficient and even lighting fixtures using a number of new applied sciences such as external light shelves. (Ozgun 2007)

Figure 2: Light Shelves ("Light shelf - Designing Buildings Wiki" 2019)

3) *Optical Shutter.*

This technology first started with French architect Jean Nouvel 1998, when he tried to create dynamic elevation using high optical technology inspired from camera movement in a mashrabiya pattern. The high technology used in creating such structure is one of a kind and support the concept of daylight controlling but it kind of lost the beauty and uniqueness of the beautiful Arabian patterns and mashrabiya design. Institut du Monde Arabe France use metal sunscreen in figure 3 integration with the curtain wall creating a type of active daylight screening. (Rayaz and Rubab 2013)

Figure 3: Institut du Monde Arabe France by John Nouvel (Rayaz and Rubab 2013)

4) *Angular Skylight*

This type of system is customized using laser cut panels to shape glazing and make it into certain shapes that efficiently introduce daylight into the space, relying on the angle of the incidence, selectively reject or admit light. For that purpose, two glazing types were created, first for skylights and second for conventional windows. The initial idea behind the angular skylight started as a way to enhance the atriums and regular skylight performance. Basically, skylights admit a great deal daylight near midday in summer considering that sun is at high elevation, leading to overheating inside buildings. On the other hand, at winter season having low solar elevation in beginning of the morning and late at afternoon the skylight stops direct daylight to pass and allow only for minimal. This scenario can be rectified by means of the use of laser reduce panels in a pyramid or triangular form over the skylight aperture. At this point, excessive elevation light is deflected again upwards to the sky and low elevation light is deflected down via the skylight aperture. The angular selective skylight is marketed in a size vary from 0.8m2 to 2.4m2 (Rayaz and Rubab 2013)

Figure 4: Angular Skylight ("angular skylight" 2019)

5) <u>Light Pipes</u>

The light pipe is basically a tube with reflective material covering the interior of the tube with interior opening having a transparent acrylic dome with aluminum reflective sheet and the roof opening with a semi-opaque diffuser. This technique implemented on roof in order to collect more daylight and increase the amount of light coming inside even when having low illuminance levels, additionally allows for indirect accessibility of daylight. The concept of light pipes is beneficial and more desired in spaces such as basements, underground floors, rooms without windows or places with low access of daylighting and requires high illuminance levels. For a room 3.5x2.0m is illuminated by way of four 330mm diameter vertical light pipe with clear exterior dome and diffusers in lower aperture measurements showed that with outdoor illuminance degree of 16Klux the common inside illuminance used to be 177lux and large Daylight aspect (DF) of 1.1%. DF ranges from 1-5. (Rayaz and Rubab 2013)

Figure 5: Light Pipes interior and at roof top (Rayaz and Rubab 2013)

6) Super Windows

These are double or triple-paned home windows filled with argon or krypton fuel and containing almost invisible low-emissive coating. They are the most dramatic improvement in window technology. They offer R-values of 4.5 to nearly 12. Super windows additionally block noise and defend interior finishes from ultraviolet damage. Though they value greater (15% - 50%) they save massive amounts of heating and cooling energy, ensuing in immediate paybacks through allowing for the downsizing of air conditioning and heating structures in buildings. Heat Mirror TM is an example of a top-notch window (Rayaz and Rubab 2013)

Figure 6: Super Window ("Charlotte Vinyl Window" 2019)

7) Exterior Reflectors

A large area of the exterior reflectors is exposed to sky. This gives this system the privilege of reflecting more light inside through the windows compared to other systems following different principles. (Rayaz and Rubab 2013)

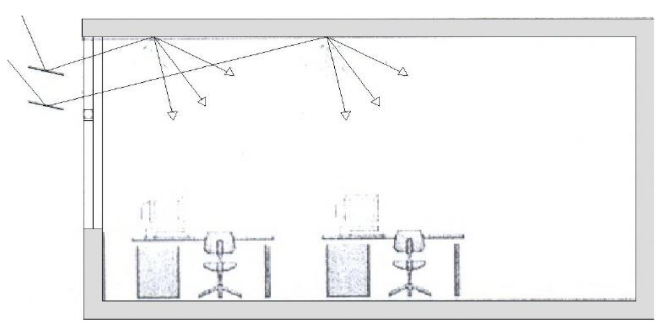


Figure 7: Exterior Reflectors (Rayaz and Rubab 2013)

8) Anodolic mirrors

The amount of daylight reflectance from reflectors in this system is appreciably superior because of this system special curved mirrors. These curves are customized and specifically design to light up certain places within spaces, so it should be calculated and designed carefully. (Rayaz and Rubab 2013)

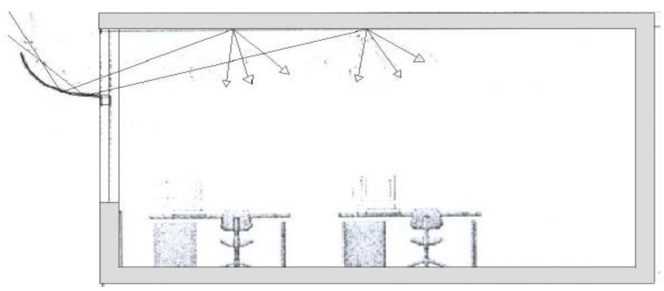


Figure 8: Anadolic Mirrors (Rayaz and Rubab 2013)

9) Prism Panels

Those panels are specially utilized as solar shields, due to the fact they shield in opposition to low angles of incident daylight. Some of those panels are placed in asymmetric way in order to redirect daylight in certain hours of the day. The panels normal vector should always be adjusted and modified in direction following the solar altitude. (Rayaz and Rubab 2013)

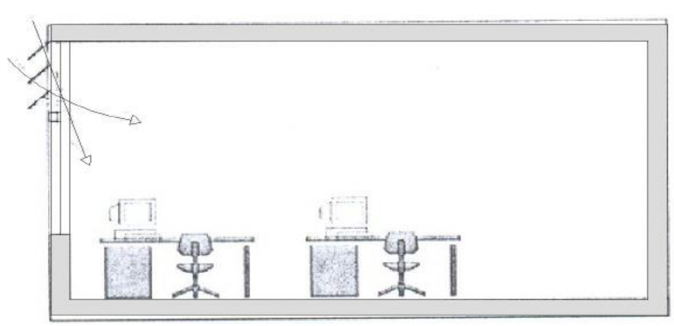


Figure 9: Prism Panels (Rayaz and Rubab 2013)

2.2 Visual Discomfort

Visual discomfort is the situation or condition in which the person is experiencing discomfort or reduce in his ability to observe objects or details within the illuminated space which is a result of not properly design the space for sufficient light access or lighting distribution and/or having unsuitable range of luminance values. (CIE 2017)

In another words, visual discomfort means any distress or pain regarding the eyes. Other symptoms that usually follow up the overall generic optic discomfort are watering eyes, itchy eyes and red eyes. The preceding conditions are always as result of poor lighting settings acting as an involuntary trigger to such effects. Lighting settings associated with visual discomfort include but are not limited to shadows, veiling reflections, glare and flicker related to the activity. (Boyce and Wilkins 2018)

2.2.1. Illuminance

The most common reason for visual discomfort is having poor visibility which can be a result of having low illuminance level. There has been a well-developed evaluation method for visual discomfort based on illuminance levels but this method is rarely used by researchers. Some countries have added illuminance as criteria or standard whenever a new building needs to be submitted to municipalities or government approval, targeting to get an illuminance level that satisfies effective visibility. (Society of Light and Lighting 2012)

The first use of illuminance as criteria for building evaluation was in UK 1936 named as IES codes. Nearly all countries have their own illuminance regulations and rules and they vary depending on how each country calculates the illuminance level and method use to verify it. But in all cases, none of the standards nor codes have specified a value for the maximum illuminance level. Some studies and experiments have indicated that illuminance can cause visual discomfort if it was above 1000 lux and others mentioned 2500 lux. Winterbottom and Wilkins have conducted a test on the adequate or preferred illuminance level by occupants. To do that they tested the satisfaction of people in a semi-blinded and fully open window and distributed a survey to evaluate it. The results showed that most people were satisfied with having windows semi-blinded having the illuminance levels more than 1000 lux in 40% of classes and for 17% of classes' area the illuminance levels were more than 2000lux. (Winterbottom M, Wilkins AJ. 2009)

Luminance is considered the only basic lighting parameter which is perceived by the eye. It relays mainly on two aspects which are the brightness of the source as well as the surface properties which means the degree of reflectance (color and surface) plays a major rule in luminance level that the eye could receive. ("IES lighting handbook" 1974)

Luminance is known as the amount of luminous energy received in a specific area; it demonstrates the amount of luminance energy arrives towards the eyes seeing the surface from a specific vantage point, with an SI unit of candela per meter square (cd/m^2). Human body has the ability to follow up with the luminance variation through physical adjustments and mental adaptation to suit the person's preferences. The eyes go through three complicated steps in order to adapt the changes within luminance level received by the eye, the first step is when the pupil become narrower and reduce in size (physical adjustment), followed by the retina inside the eye try to adapt the luminance level and be less sensitive to it (mental adapting), and last is when pigments within the eye start to breakdown as a respond to the change in light levels. (Boyce 2006)

Figure10 highlights the relation between luminance levels and eyes adaptation showing the acceptable luminance range as an area between two log curves.

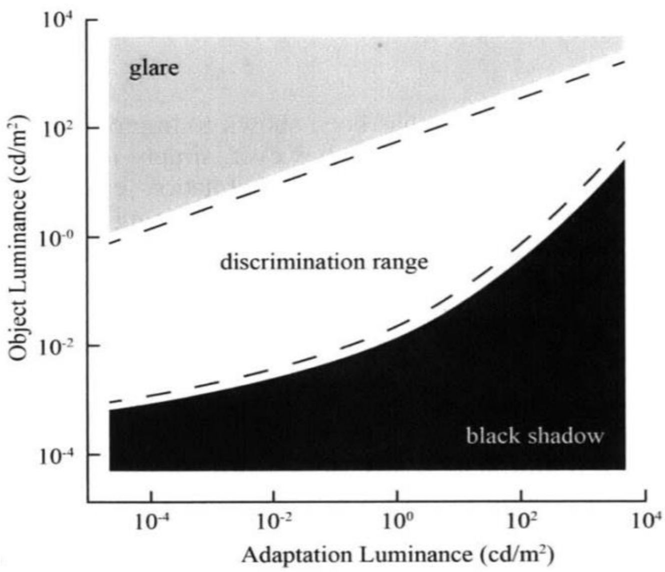


Figure 10: Relationship between luminance and adaptation and the acceptable luminance range (Boyce 2006)

The figure indicates that in order to be able to sense an object luminance it should be within the adaptation luminance acceptable range. For instance, when lighting up a lamp (object luminance) during the day, the luminance coming from it won't be effective nor noticeable as if it was used in a dark night (adaptation luminance), in the two condition the lamp is giving the same luminance level but the perception is different. (Boyce 2006)

2.2.2. Illuminance Uniformity

What is recommended for illuminance if effectively coordinated to the necessities of the tasks in action, it should ensure great perceivability but doing it solely won't be sufficient to stop visual discomfort from happening. Also ensuring that the illuminance is distributed equally is essential. In order to achieve that a uniformity ratio (UR) needs to be implemented, it can be calculated by knowing the average and minimum illuminance levels in the work place (min/avg). A few experiments have demonstrated that for workplaces a UR of 0.7 or more prominent is alluring. But considering having a big room with large windows, a table which is closer to that window would have higher illuminance level compared to another table deep inside. The UR for the table far from window will be substantially less than 0.7, but during the experiments not much complains were heard except for cases where interior deterrence was presented. (Slater, Perry and Carter 2008)

This could be because of the fact that illuminance rate change gradually with the distance but this gradual variation won't affect the visual comfort if there is enough illuminance giving acceptable visibility. Visual discomfort can only happen when dramatic illuminance no uniformity is evident. An example of that is when shadows are casting over the workplace or even if highly illuminated areas are next to the workplace. Tests conducted on people to record their reaction to multiple forms of daylighting on workspaces shown that most people preferred the space with a uniform and shadow free illuminance over the workplace and with low illuminance values surrounding the space (Eklund and Boyce 2006). The latest European Standard had indicated several rules and recommended values for illumination levels in several workspaces and tasks and how to reduce the surrounding distractions. (British Standards Institution. 2018)

2.2.3. Shadows

The shadows are created when light moving in a certain direction is stopped or interrupted by a solid surface. The magnitude and nature of shadows generated with a lighting source relays on the size, how many light sources are there and light reflectance nature in room. The shadow is strongest when one-point source is lighting up a totally black room. The shadow gets weaker when the room has many light sources and large in size plus the reflectance rate is high. If the building considerably large, for instance a deep plan office tower with occupants, the shadows cast will decrease illuminance levels on wide areas and though decreases the ability to see details and visibility. Keep working with such minimal amount of light without any assistance from outdoor light (opening windows or removing curtains) or artificial light visual discomfort will happen. Shadow can also lead into confusion and problems in understanding details in small scale scenarios. A simple case is when a person tries to work in a very small and tight room with a small light bulb where light coming from the light bulb creating overcast shadow in the area. (Mangum 2003)

It's true that shadows can produce visual discomfort, but it is also helpful to highlight the shapes of 3D objects and texture. When it comes to display objects, it relays on the lighting display techniques which is a combination of proper shadow, highlights and light that controls the received characteristics of the object to the receiver (human). Though, shadow can be used differently depending on what a person desire and should be treated carefully, it could make the object appearance become better and highlighted or it can cause visual discomfort. (Boyce 2008)

2.2.4. Glare

IESNA Definition of glare states that it's a sensation happening due to a certain luminance in the visual field which is considerably higher than usual illuminance level that the eye can adapt, which leads either to discomfort, reduction in visibility and performance or even annoyance. The sensation value or amount of glare relays on several aspects which are the luminance source, size and position, number of sources and the amount of the luminance that reaches eyes and been adapted. To correctly identify the four most common glare types, it's helpful to categorize them either as direct or indirect glare and by the effect they have on the observer creating either disability or discomforting glare. Direct glare happens due to having bright areas from windows, luminaries or ceiling being in the view field and lighting up the space directly. Indirect glare happens due to the reflection in the task area (working surface) towards the eye within the view field. Disability glare causes reduction in visual performance and visibility. Discomfort glare causes physical discomfort. A person can experience discomfort with no disability or verse versa but usually accompanies with each other.

In cases where a high luminance exists, they usual reaction is either to look away or cover the eyes. If such behavior occurs, it means that glare exists. Vos from his research and experiments on glare had listed 8 forms of it, the most known and common one is the “indoors discomfort glare”. His experiments and search was done for a whole 60 years where he investigated many sources of glare including daylight and luminaires. Nowadays, his outcomes with glare research were used in many of today’s many national systems for indicating the discomfort glare degree generated by several light situations. (Vos 2006)

Tuaycharoen and Tregenza studied how the viewpoint from windows could influence discomfort glare levels and proved how having same luminance but different position, orientation or view angle could result with different perceptions of discomfort glare; having better view will lead to less discomfort glare levels. Although they suggested that glare should be studied and investigated further. (Tuaycharoen and Tregenza 2015)

Glare generally is calculated by measuring the glare sources size ratio, location and difference between luminance in the view field and average luminance. The following equation expresses this relation:

$$Glare = \sum_{i=1}^{n} \frac{L_{s,i}^{exp} \omega_{s,i}}{L_b^{exp} P_i^{exp}}$$

Whereby ɢϽ is the source Solid Angle size, Ls is the “Source Luminance”, Lb is background luminance and P is the Position Index. It can be noticed that having high luminance (very bright source of light) or large source will increase the possibility for glare to occur, while having a brighter background luminance, a high position index or the glare source is distance from the visual field center then the possibility of glare to occur would be less. The position index value becomes higher when the source comes closer to the view field. (Jakubiec, J., Reinhart, C. 2012)

The diagram created to indicate the position index of a source was create by Guth, its considered an accurate way to indicate the strength and degree of glare depending on viewer location. The index can be seen in figure11, but it's quite hard to demonstrate the exact value if data about the room properties compared to the other variables in the equations (Ꞷ, Ls,Lb) which are easier to get. The glare equation mentioned previously is the basic for many other derived metrics that other searchers have created by either adding of specifying variables on the original equation. Following sections explains some of those derived metrics. Though, the data collected for each metric can differ due to the conditions when it was collected, recording the test conditions is essential in evaluating if the metric is applicable to a given situation. (Luckiesh and Guth 1949)

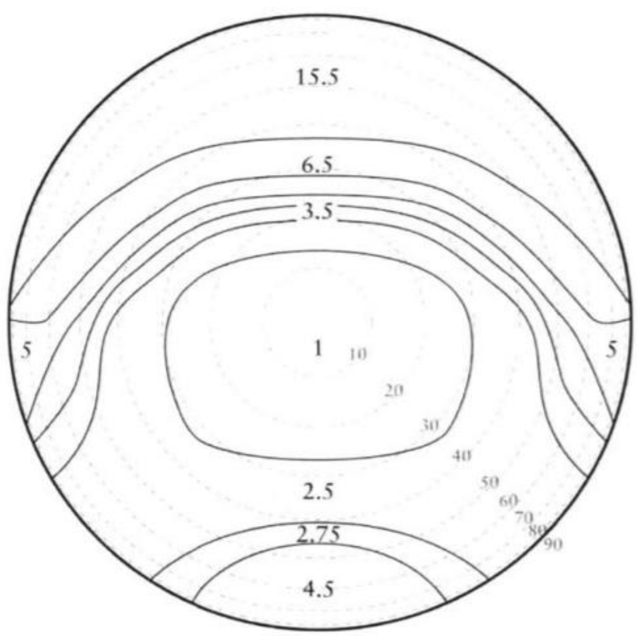


Figure 11: Position Index drawn from top (above 180°) viewpoint as created by Guth (Luckiesh and Guth 1949)

2.2.4.1. Daylight Glare Index (DGI)

DGI measures the possibility of glare to happen because of daylight coming directly through windows from large sources like sky. This metric was derived by Hopkinson in 1972 after many tests on human preferences in a room with big diffuser screen lighting it up with fluorescents lamps. In his research, he tested several locations for light source and several sizes of source and recorded the glare which occurred in each situation. There are some restrictions when using DGI metric since it's only applicable to for specific conditions which don't include direct light or excessive shiny reflections within the viewpoint. That's because when Hopkinson was conducting his experiments for DGI metric he only considered diffused light source. (Hopkinson 1972). DGI tests the relation between the luminance source, view field position and its size to the luminance background. The metric evaluates the glare as any value more than 31 to be intolerable and values less than 18 to be 'barely perceptible'. After more tests, Hopkinson stated that adding other variables into his metric is important and necessary to get a more precise and subjective results from the metric. Also he mentioned the viewer position and angle also the interior space specifications (reflection factors) to be the two of essential missing variables in his metric. (Jakubiec and Reinhart 2011)

2.2.4.2. CIE Glare Index (CGI)

The CGI metric was developed by Eeinhorn that was trying to create a metric that covers all variables tested by previous researches about glare into one unified metric and to be used as a standard glare indicator for the "Commission International de Eclairage" (CIE). It was into consideration for all measured source solid angles (Ꮗ) to be summed to one number to make it mathematically easier to understand. Glare Adaptation was indicated as the ratios of illuminance component vertically that is multiplied by the rest of equation as a sum of multiple tests results. Einhorn added two fixed variables to the equation called scaling factors which are Cl= 8 and C2= 2. The metrics stated that values more than 28 are intolerable and values less than 13 are imperceptible. No studies from the user perspective were done while developing CGI metric, but correlation investigations on user's preferences and position were studied in the other glare metrics. (Einhorn 1979)

2.2.4.3. Visual Comfort Probability (VCP)

VCP indicates the possibility that a person doesn't experience any discomfort while having a light under specific situations. This metric is simpler than other metrics, the VCP metric measures the glare as a function of the size and source luminance to its location within the workplace and the illuminance average for a viewing solid angle of 5 steradain. This metric can only be used for artificial lighting with specific sized, ceiling-mounted, and uniform luminance source, as it was concluded and discovered under these conditions. It is not usable for daylighting sources evaluation or even to compact artificial lights like halogens which means it only used for specific range of illuminance and not suitable for little or massive glare sources. This metric evaluates glare as percentage range between 0-100, the resulted value indicates the percentage of occupants feeling satisfied (comfortable) when being within the specified light conditions. (Harrold 2003)

2.2.4.4. Daylight Glare Probability (DGP)

This metric is considering most aspects and factors participating in causing visual discomfort compared to other metrics. It can predict the presence of discomfort glare in the space even without having significant visual contrast. It solved several issues that Hokinson had when he was creating the DGI metric by adding several variables within the equation which included adding other sources to glare rather than only direct light from sky, which is something that wasn't done by any previous metrics. DGP recognizes the glare coming from the direct daylight falling on work place and the reflections from surfaces as well. Like VCP metric, the DGP value scale is instinctive; it measures the occupants' satisfaction and comfort with the applied light conditions. Intuitively, a value of 45% indicates intolerable glare while a value of 35% indicates imperceptible glare. (Wienold and Christoffersen 2006)

2.3. Classical Architectural Elements of Light

Daylighting has been a critical part in architectural design for ages and through eras. From old buildings in Persia planned to let decomposable products cool using huge glazing windows to Roman and Greek churches oculus and clerestory windows, daylight had always been a part of buildings architecture and design.

2.3.1. How Classic Historical Buildings Used Daylighting

In the pre-electrical period:

In numerous aspects, ancient architecture was much mindful with significance of sunlight compared to nowadays buildings. As artificial lights could be generally modern innovation, numerous of the famous churches and other imperative buildings of past times gave more intention and importance on daylight compared to designs of the twentieth century. Lack in technology and electrical knowledge in old buildings frequently driven to interesting and special designs and arrangements to the lighting issue. During that era, where lighting was cheap and endless energy was available, significant number of old religious buildings focused mainly on providing daylighting more than homes and office buildings. A lot of buildings used special design mirrors to enlarge utilized space and reflect limited natural daylight sources all through their insides, lighting up corridors and passage ways only, in another words it was only use for accessibility and a decorative parts in churches. Sunlight characterized design in numerous projects and religious buildings, with huge marketplaces by utilizing of skylights and big windows to increase accessible daylight through the short day-time hours. (Henley 2019)

Through the Industrial Revolution:

As manufacture grew to be significant and valuable along with technology supporting fabrication methods development, daylighting function become different than what used to. In previous eras, daylight only function was to provide a sense of accessibility in churches and mosques and have been treated as decorative elements in religious places, but when the industrial revolution started in the early twentieth century and more attention was going to office buildings and industries as places for work, daylight was necessary for another function which is lighting up the working place in order to enhance the productivity of occupants. The design of windows, openings and skylight still existed in that period because they were providing huge amount of necessary daylight. And since daylight was the only source of light back then, the floor plans were designed to be significantly small in order to allow of daylight coming from windows to lighting up the full floor. All through the twentieth century, daylight kept on playing essential part within the design of numerous modern architecture designs. Many buildings in that period were designed for commercial and administrative purposes, utilizing windows and atriums in a modernized way and gave more intention to the industrial and commercial buildings because those buildings become places that people spend time in for long hours per day to work. Larkin Company Building, a building by Frank Loyd Wright which its main concept revolved on maximizing daylight presence to make a comfort, beneficial and create a productivity working place. (Brain 2015)

The "International Style" and beginning of artificial light:

The style of small floor plans and to count only on daylight for lighting up the floor that was used in the industrial revolution period at the beginning of twentieth century become less popular and started to vanish because of the rise of "international style" which focused on having wider floor plans and massive buildings, the relaying on only daylight was not enough and other solutions needed to be done. And as a result of that, gigantic increases in artificial light were utilized this was what happened in twentieth century. Architects and designers for the most part agreed on depending on artificial light for lighting up spaces, and due that over-illumination issues popped out, and proceeded until daylighting became again a major attention in architectural design in 1995. (Team 2018)

The comeback of daylight and energy efficiency:

In the last two centuries, daylight was again the center of attention, focus and importance in architectural design. The artificial light working environments of the 20th century have generally been cleared out, by focusing on efficiently design buildings with energy conservation methodologies instead of the artificial lighting that characterized the previous era of late 20th century. (Team 2018)

2.3.2. Development of Architecture elements of light through Eras

PREINDUSTRIAL ARCHITECTURE:

Along this period, sunlight was an essential source of light and illumination was an image of cleanliness, purification, knowledge and paradise supported by combustion fills such as candles. The building's design was affected and influenced by the provision of sunlight to the internal building spaces. (Florence N. 2015)

Ancient Egypt

This era practiced great amounts of sunlight where buildings were designed to avoid glare and blinding daylight with minimal sizes of openings in walls and roof. Their Strategies for daylighting were by having restricted opening sizes because of having short spans capability of stone with most of them being square headed and secured with gigantic lintels. Clerestories, which permitted for deep plans also enhanced the daylight in the internal spaces. Thick walls functioned to reduce and diffuse the sunlight through numerous reflectors. Other openings to allow daylight in were roof openings, little windows and entrance doors. (Fuller M. 1991)

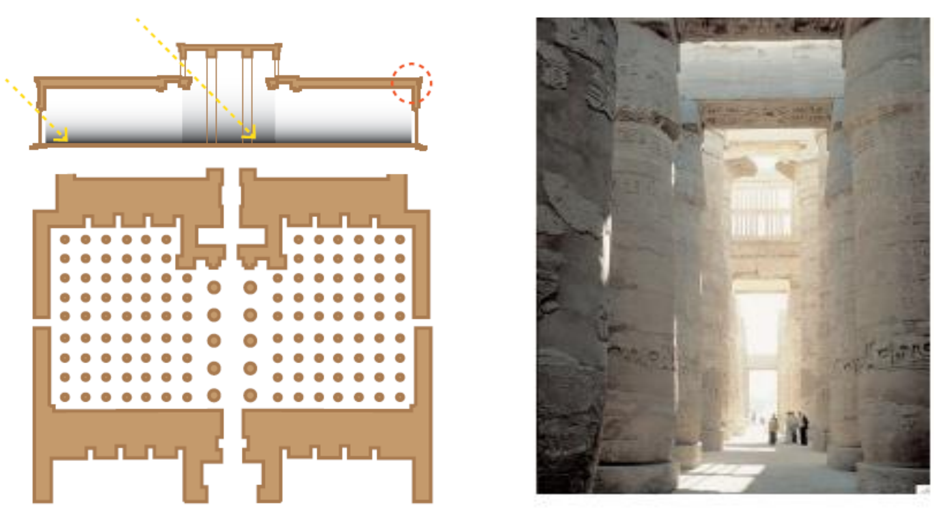


Figure 12: The Great Temple of Ammon showing clerestories and roof openings (Florence N. 2015)

Ancient Greece

Most activities were carried outside and buildings subsequently got to be objects planned to be seen instead of occupied. Colonnades and porticoes made shade and spatial layers. For their Strategies for daylighting, openings were of minimal significance except to illuminate the statues and express ornamentation. The strong direct and reflected daylight enunciated the ornamentation on the exterior with gold leaf and colored stone. Temples were arranged to be oriented towards the East to light up the gods statues through corridors and huge roof openings at dawn. Restriction of spans caused in having little limited openings and the light was subsequently introduced and presented from small tiny shafts of light. In residential zones, the orthogonal ancient Greek Town plan gave sunlight accessibility inside homes to get adequate lighting and heat up. (Fuller M. 1991)

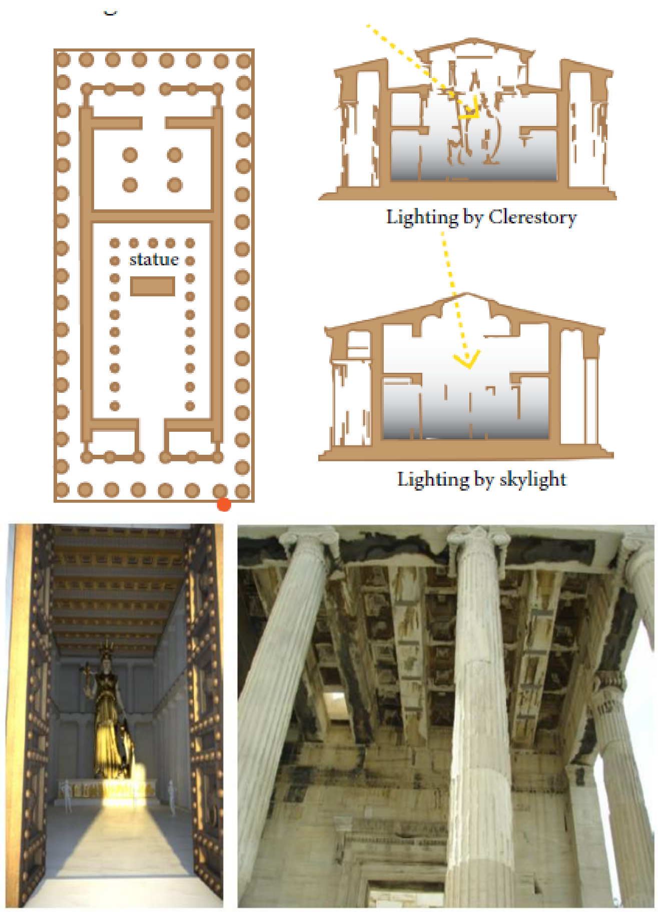
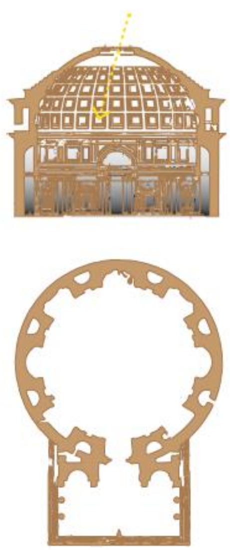


Figure 13: Sanctuary of Olympia (Florence N. 2015)

Ancient Rome:

Development in innovation in Roman Architecture of the circular arch, the barrel vault and the dome made it possible to design bigger openings that may concede large sheets of light opposite to the limit shafts seen with the Greeks' daylighting techniques and permitting bigger spans inside the buildings. Their strategies for daylighting were because the progressions within the openings were central square-headed or circular rounded and the primary application permitted daylight in whereas blocking cold winds and rain. Skylights and clerestories were bigger and conceded more light into deep internal spaces. The rectilinear buildings that were design longitudinal along the East and West given more prominent exposure to the South which was Vital at winter season. (Fuller Moore 1991)



ıtheon in Rome (Florence N. 2015)

Early Christian (A.D. 313 - 800) :

The building designed as Basilica typology was before utilized as a law court or as commercial use was taken and developed with small differences to be functioned as religious buildings. Timber trusses were replacing the Roman vaults strategy and this created the inclined rooftops that decreased wall space obtainable for clerestory windows. Strategies for daylighting, Clerestories sizes are smaller and various decreasing in the internal lighting. This functioned to improve the mystical of religious buildings. The plan was encouraging the linear perspective as well fortified a straight point of view joining to the apse which had the altar encompassed by tall longitudinal windows. This enhanced more prominent emphasis to the space. (Fletcher and Palmes 1977)

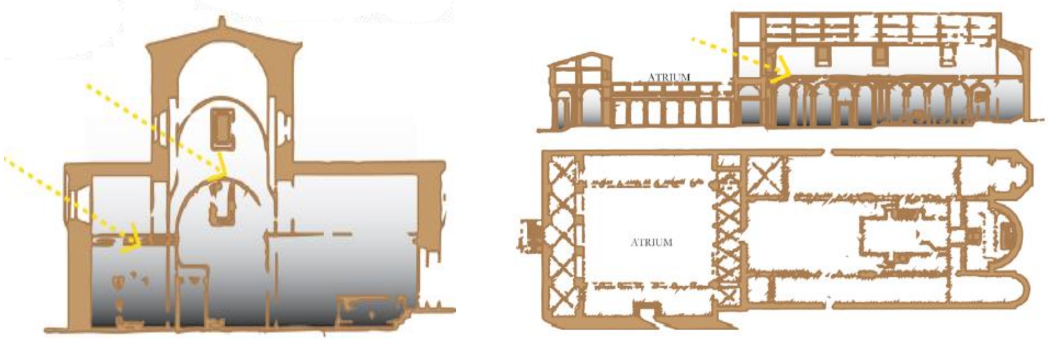


Figure 15:St. Clemente Rome (Florence N. 2015)

<u>BYZANTINE (A.D. 330 - 1453):</u>

The particular characters of this era were to utilize the dome upheld at foul corners to cover a rectangular base or floor plan as contradicted to the permanent bolstered dome of the Roman era. The Byzantines arrangement was centralized around a main dome encompassed by secondary spaces with half domes crossing underneath the primary dome. Their Strategies for daylighting were that light was conceded through numerous little stained-glass windows assembled together puncturing the base of the dome. Parcels of the windows are filled with thin slabs of translucent marble which gave an impact of the stained-glass. This made an illusion that the dome is floating over the fixed structure. Openings became half circle headed with either horseshoe or angled openings. (Fletcher and Palmes 1977)

Figure 16: St. Sophia in Constantinople (Florence N. 2015)

INDUSTRIAL ARCHITECTURE

During the industrial revolution

Industrial revolution advertised implies to free buildings from the limitations on essentially and radically changing the perspective of architectural design. The improvement of the structural frame and the accessibility to temperate, highly strong steel members permitted the building to be backed just by columns. The external walls were presently backed by the frame at each floor and its part was diminished to that of a skin to avoid wind and water, and its thickness and mass were decreased to the minimal to reduce its weight on the columns. Strategies for daylighting were bigger openings were filled by massive windows, use of bigger glass sizes since it was available at that time in markets which increased the amount of sunlight all the way through the edge of the building. But, this came with the probability of increasing glare, winter solar loss, and summer heat gain. (Florence 2015)

The modern movement (1900s)

Famous architects held numerous of the historical standards of location, orientation, natural ventilation and sunlight illumination as well as joining the modern innovation, some of them are:

Frank Lloyd Wright, Louis Kahn, Alvar Aalto and Le Corbusier

Economy in structural material, spatial limitation, decoration, laboring and development costs didn't expand to energy. Implementing those modern techniques like artificial lights, structural framing, lightweight facade materials using mainly aluminum, expansive glass, waterproofing materials, lifts, sounds systems and communication equipments, led to increase in the energy demand. Although those discoveries freed architectural design from the climatic and site limitations and allowed for unlimited design options. This modern path for architectural design evolved quickly but was so complicated since it needed from a single person to be aware and know different backgrounds including mechanics, MEP and structure engineering. This decreased the involvements of architects in design phases since specialist from other disciplines were required in order to achieve the modern building requirements and their feedback was affecting the overall conceptual design which means architects weren’t able to work independently as before. (Florence 2015)

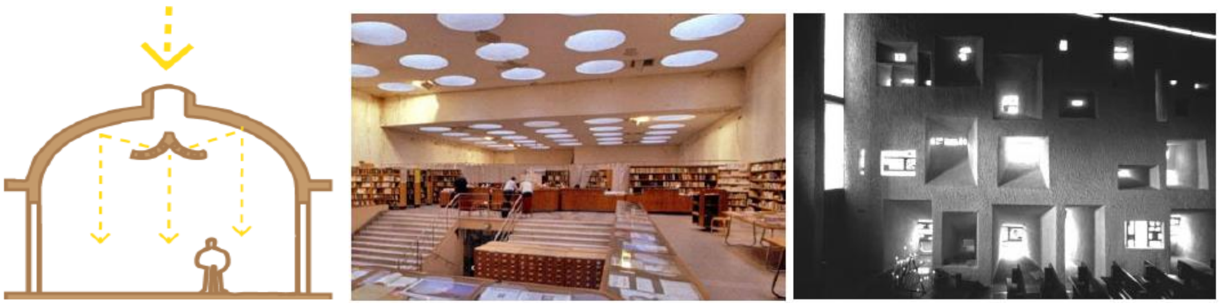


Figure 17: a) Louis Khan's Kimbell Art Museum b) Alvar Aalto's Vipuuri Library c) Le Corbusier's Chapel (Florence N. 2015)

<u>POSTINDUSTRIAL ARCHITECTURE</u>

After the arousing of architects to the fact that of environmental awareness, daylighting became again an important and essential point in architectural design. The artificial lighting that was excessively use in the beginning of 20th century was replaced gradually by a more efficient, environmental-friendly and economic solutions and designs as well as providing more daylighting. Using daylighting not only had its benefits in energy savings perspective but also as health benefits which was tested and investigated by scientific researches and experiments on lighting. This has driven towards shared architectural knowledge of daylighting standards. (Florence N. 2015)

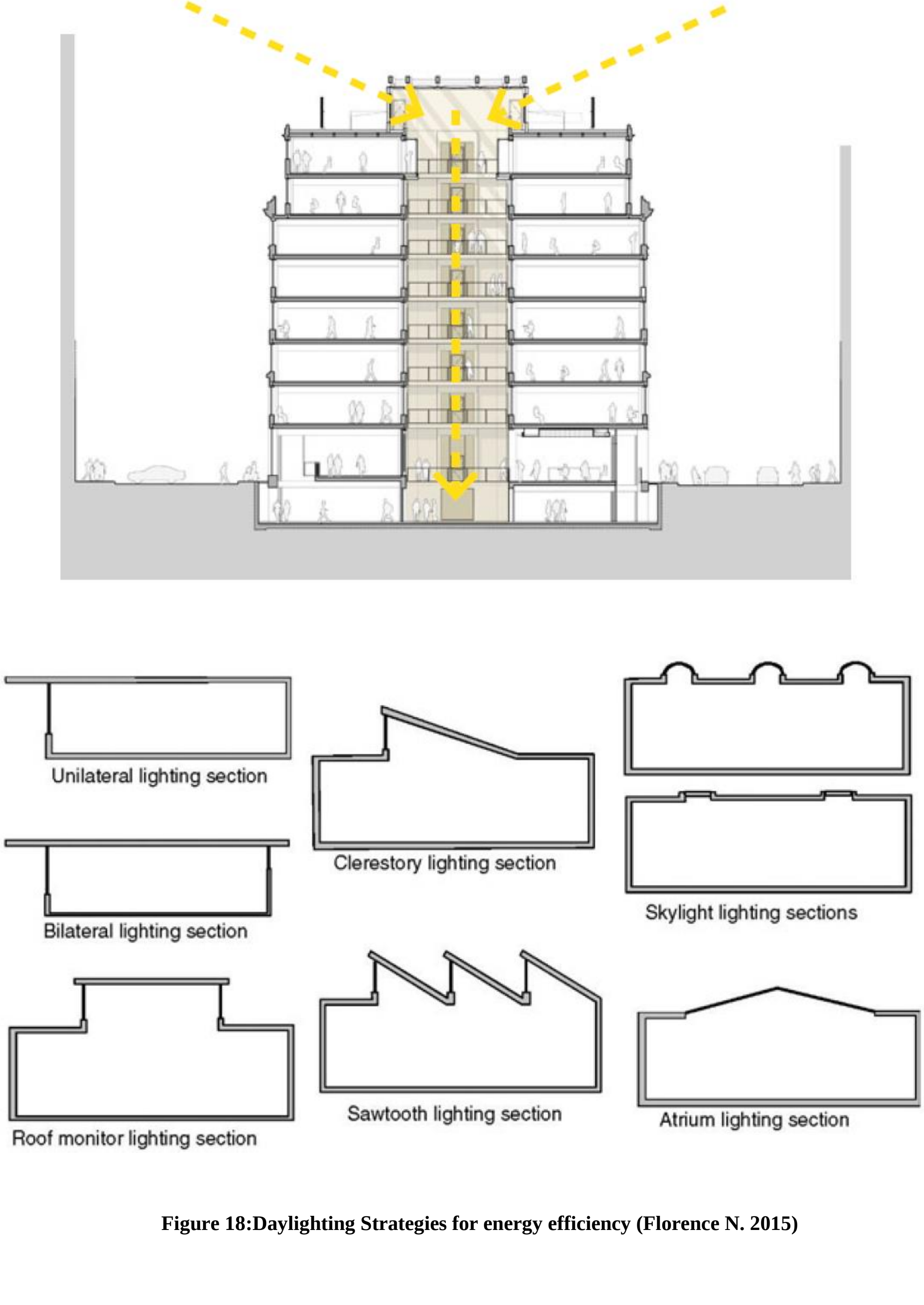


Figure 18:Daylighting Strategies for energy efficiency (Florence N. 2015)

2.4. Variables affecting daylighting

2.4.1. Window size

Many researches were using scaled maquettes in order to understand and prove their theories regarding the relationship between sizing of the window and visual discomfort. One of these researches is Hopkinson and Neman study in 1970 regarding the most suitable window size in office buildings. They tested a scaled maquette as well as an actual mockup office room. Their outcome included that window size doesn't depend on daylight accessibility but it depends on the targeted view. Another outcome was that if we want to highlight an object located close from the observer's view this would need bigger windows to grab the attention of the observer. For far away objects, a small window would be more efficient since the object apparently small in size and it would be hard to see it in detail. Regarding the preferred width of window, they stated that its depending on the distance of the object from windows. They have conducted several tests and experiments on occupant's preferences on windows size as a percentage of wall area, they tested the participants with different windows widths (from 1.2m up to 3.35m) and asked them about their preference, the average of answers were that 2.4m (which is 23% of wall area) was the most preferred one, although the researchers thought the participants would go for the biggest window width which is 3.35m (which is 32% of wall area) but only 16% of participants found it suitable. Another study conducted by Keighley (1973), with a 1to12 scaled maquette, showed same results as Hopkinson's study. They found out that the most preferred range is an area of window ranges between 25to30% of total area of the wall. They also stated when area of window to wall area was higher than 35% or lower than 25% the participants weren't feel comfortable with amount of daylight coming in (lower than requirement for good visibility or too high causing discomfort). (Hellinga 2013).

Other researchers Butler and Stuerwald (1992) used as well a maquette of 1to12 scale in their study. They stated that best window size is not related to an exact glazing percentage to wall area but its dependent on space characteristics, size and view nature. But in their results, they figured out that the best window size for a small space would be 30% of wall area as founded in previous researchers. In their tests on bigger rooms that percentage became lower (around 23-25%)(Veitch,2001). The outcomes of those researches showed that a space should have minimal percentage of 20-25% glazing to wall area, preferably to be up to 30%. Although they got similar results but other aspects and variables should be studied like the possibility to have windows in more than one façade, or different depth and width rooms.

2.4.2. Window shape and position

Going through literature reviews and papers, many recommendations and tests where done to figure out the best window form and position. A paper written by Markus (1967) stated that the people are attracted to sit or to work in certain area inside a room impacted by glazing shape and location. That statement was tested by Kieghley's study (1973), the results showed multiple glazing dimensions had been desired depending on tasks and distinctive views. Kieghley study outcomes showed that having high window heights and vertical displacement from floor to floor (fully glazed) is less preferable by people than just having smaller upper windows, it might be because of the glare and heat caused by the fully glazed façade or privacy issues. However, because Keighley didn't move forward with his research on the impact of daylight on the topics, there was no ensured conclusions to his findings. What we can conclude is that size and position effect daylighting entering the space as well as the person's preferences but no research have been yet conducted about the best or more preferable window configurations in presence of daylight. (Hellinga 2013).

In a study done by Markues (1967) he stated that the most preferred window shape is to be small and vertical in order to give a good view in all three dimensions. He as well assumed having multiple smaller vertical windows distributed along the wall will enhance window's dynamic features. He believed that by having multiple small series of windows this will make it possible for the observer to experience several views instead of one big window looking at one view. Disagreeing with his statements, Keighley (1973) in his study on windows shape preference, participants didn't like the idea of having multiple windows shape, in fact he founded that participants satisfactory and comfort reduced when they were in a room with a long horizontal window divided into smaller ones, they felt that this configuration is disturbing and interrupting the continuity of the view. Most of the participants preferred regular shape large horizontal windows. For views with higher view angle, the preferred head top was to be higher tha1.9m in order to have a view towards sky and less direct daylight in. When the view was completely blocked by other elements in the exterior and less daylight (mostly diffused daylight was coming in), researchers had greater difficulties to distinguish and agree on which is the most appropriate or preferred window configurations.

2.4.3. Materials Reflectivity

Another important aspect that effect daylight and identify if the space has adequate daylight or not is the internal material reflectance. Materials including wall finishing, floor tiles, type of furniture and ceiling tiles can impact the daylight performance. Rooms contain high reflectivity surfaces makes the room appear brighter, and in contradictory ark surfaces will make the room look dull by absorbing daylight. Experiments have shown that changing a material reflectivity from 0.4-0.6 will enhance the illuminance level within the room upto 50%, and from 0.4- 0.7 up to almost 100%. (Ahmad, Sh Ahmad and Talib 2012)

A study by Sament and Sharples (2004) investigated the impact of several wall reflectivity for atrium with multiple distribution patterns on average DF values for atrium model that was modelled inside a virtual sky that resembled the CIE overcast sky. In this experiment, atrium walls were painted with two colors white and black in strips, and the width of the strips change in order to check the illuminance changes with the increase or decrease of white and black. The experiment was ranged from being fully black (reflectivity =0) to being fully white (reflectivity = 100%). Results indicated that the percentage of floor reflectivity underneath the atrium was impacted by the reflectivity levels from the atrium walls. Having wide strips were the ones who showed big differences and variations in reflectance distribution, the narrow small strips showed less variations and didn't affect the floor reflectance that much. This experiment has shown the significance and effect of walls material reflectance on amount of daylight reaching the floors when using an atrium. (Samant and Sharples 2004)

2.4.4. Glazing Type

An experiment by Dubois, M. and Pineault, N. (2010) was done to investigate the effectiveness of multiple windows with several glazing types on daylight quality. The experiment tested five windows in a small fully furnished living room with a scale of (1:6) looking towards a clear sky oriented towards south east. Around thirty participants were in the experiment and had to fill up a survey covering 7 factors effecting daylight quality where are: lighting level, naturalism, glare (comfort), aesthetics, accuracy, light allocation and shade. The outcome indicated although the glass type had numerically noticeable impact on the lightlevel concentration, naturalness, aesthetic and precision but it didn't have any impact on lighting allocation and shading. The glazing visual transmittance showed positive and direct relationship with light level, glare (comfort), naturalness, aesthetics, and accuracy. The study also showed that using two directions for color deformation and distribution is more preferable and positively affect people compare to one directional color. (Dubois and Pineault 2010)

Lee, J., Jung, H., Park, J (2013) made a study testing the different application of several windows glazing types that has variations in properties to investigate the annual lighting energy within the experiment building. The properties that were investigated Uvalue, Solar HeatGain Coefficient

(SHGC), and visible transmit by using single, double and triple glazing and evaluated using computer simulation software, from hot to cold areas. The simulation outcomes showed that triple glazing reduced thermal conductivity and heating energy compared to double and single glazing and provided the best amount of light in terms of LUX and glare (comfort). (Lee et al. 2013)

Krarti M. (2005) made an investigation testing the effect of different window sizes and glazing type on the daylight performance inside buildings in 4 different locations in U.S. The research objective was to prove that window size and parameter and glazing use transmittance (which he called daylight aperture) actually affect the daylight performance, improve indoor lighting and decrease lighting energy consumption. His investigation results showed that increasing the windows perimeter or glazing transmittance has actually enhanced the daylighting performance. He stated that having daylight aperture higher that 0.3 will enhance the energy savings within the building. But he also pointed out from his tests on commercial building that having glazing transmittance or window to floor ratio above than 0.5 won't add that much or give any significant differences in lighting energy savings. In another words, he concluded that daylight aperture should be between 0.3 and 0.5 in order to enhance daylight performance. (Krarti, Erickson and Hillman 2005)

2.4.5. Orientation

Kareem S. Galal (2019) studied classroom orientation in Lebanon Coast area in order to identify the impact of the different daylight parameters the preferred orientation in order to get the desirable (preferred) daylighting amount. In his study he conducted a simulation on an existing school and tried several orientation alternatives to indicate best orientation. To do that he used Design Builder software with Climate Consultant plugin, this software analyze multiple daylighting metrics getting annual values. Then, he planned to compare the simulation outcomes with the recommended values in the Lebanon Coast Area. His study investigated three metrics (as requested by the Illumination

Engineering Society (I.E.S.) which are Spatial Daylight Autonomy (sDA), Annual Sunlight Exposure (ASE) and Useful Daylight Illuminance (UDI). (Galal 2019)

The case study of the research was Evangelical School in Tripoli city (Koura district) and classrooms were uniformly spread within the two facing elevations (North East and South West). The classroom was 8.0m deep from window, 6.45 m wide, and 3.80m high. Windows were allocated on long façade side, having a sill height of 0.90m and a 2.95 m for lintel. (Galal 2019)

Figure 19: The Evangelical School satellite image(Galal 2019)

The tested classroom in the case study had two types of sun breaker horizontally and vertically having a thickness of 0.25m and depth of 1.0m. The simulation was conducted on two classroom models, model (A) is done on the existing classroom condition with sunbreakers, and model (B) also with the same classroom configuration but with no sunbreakers. In the software, the windows type that was used is double glazing having the inner layer as a 6mm thickness of bluish green glazing and outer layer is an 8mm thickness of clear glass having a 10mm air gap in between them. The two cases AandB were investigated with simulations for eight orientations: North, North East, East, South East, South, South West, West and North West.

The sDA evaluation to the two models were over the minimum values (300Lux) for the 50%of class area. Both models exceeded preferred values of sDA (which is more than 75%) for the south orientations (South, South West, and South East), as well as East and West for model B (the classroom with no sunbreaker). The rest of the orientations for the two models were in the acceptable range (55% and 75%), but only some couldn't pass like the North orientation in model A that was lower than the accepted range (less than 55%) as can be seen in table1.

Table 1: The simulation results for sDA (exceed 300lux), ASE (exceed 1000 lux per 250h) and UDI as a percentage of the tested area (Galal 2019)

	sDA % in Range%		ASE % in range		UDI Area in Range (%)	
	Case (A)	Case (B)	Case (A)	Case (B)	Case (A)	Case (B)
NE	61.19	70.80	99.80	86.90	100.00	100.00
N	52.90	62.24	100.00	100.00	100.00	100.00
NW	56.29	65.56	97.00	82.90	100.00	100.00
W	65.73	75.52	60.00	51.60	100.00	93.88
SW	83.92	98.78	59.60	54.40	96.62	86.36
S	97.10	100.00	73.90	64.70	96.86	86.19
SE	89.51	99.30	59.40	54.90	99.03	86.89
E	72.73	86.71	69.80	60.70	100.00	94.76

The ASE evaluation for both models A and B values for most of the orientations were below the required values for it to pass (less than 10% of the yearly1000 lux per 250 hours), that indicated a high possibility of discomfort glare to occur, and as noticed from results the sun-breaker presence had reduced it. The North orientation passed the ASE evaluation for both models, but only passed for model B for other North orientations (North East and North West). The worst orientation for model A was the South East and for model B was West.

From (Table1), the UDI value accomplished a value of 100% for both models North orientations, and also West and East orientations but for only model A. The worst orientations were the South for model B and South West for model A.

The main goal in LEED V4 regulations is to decrease the usage of artificial lighting by increasing the use of natural daylighting within space, and the requirements to get the LEED V4 points include to have an $sDA_{300/50\%}$ value for 55% of the area, the result showed that the North orientations basically achieved the acceptable values of the metrics (North East and North West for model A and North for model B)

As an overall, the South orientation had the highest sDA values for both models but couldn't pass the ASE requirements, which means that an adequate amount of daylight is coming into the space but glare has occurred. The same results were recorded also for East and West orientations in model B.

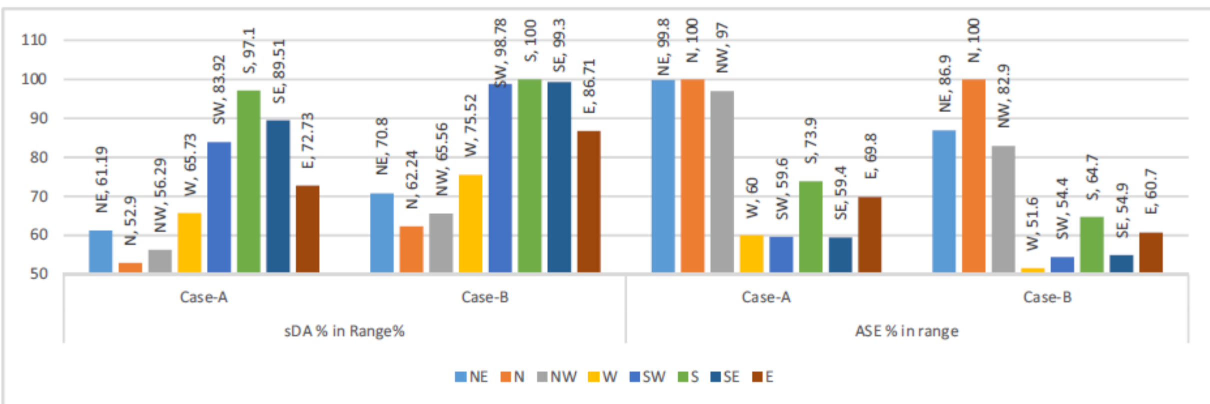


Figure 20: Annual sDA values which are more than 300 lux (in percentage), Annual ASE values that exceed 100lux per 250 hours annually (in percentage) (Galal 2019)

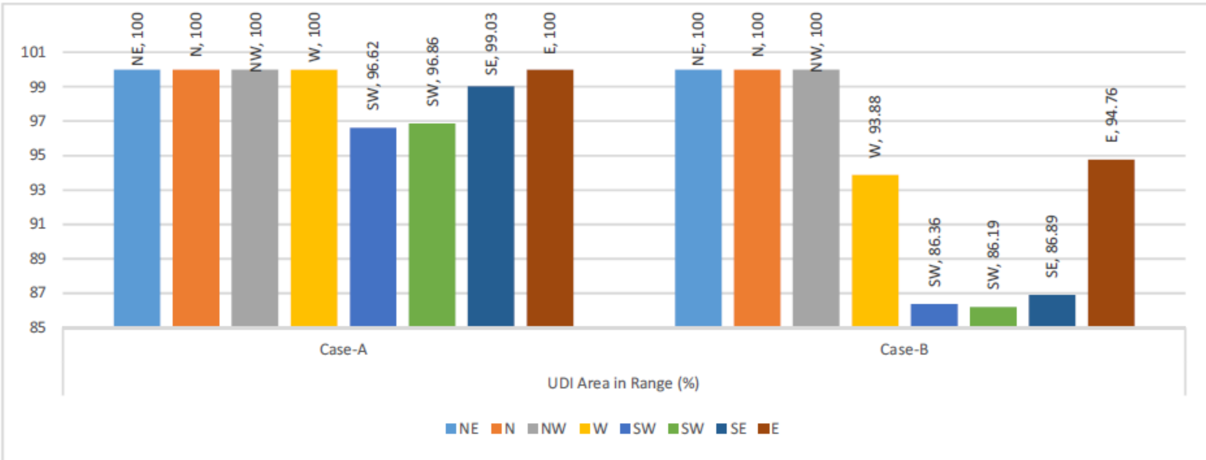


Figure 21: The casestudies annual UDI factors per area within range of 300to1000 lux (in percentage) (Galal 2019)

What was concluded is that the sDA metric is the most important metric when it comes to evaluating the preferred orientation in order to achieve the required lighting levels (300 lux). In the Lebanese climatic zone, almost all the models and orientations tested have reached the minimum requirements of sDA metric except for model A North orientation. The recommended orientations were South orientations (South, SouthWest, SouthEast), West and East.

Also to mention, most orientations couldn't reach acceptable requirements for ASE, except for model A north orientations (North, NorthWest, NorthEast) and only North for model B. When compared to sDA results, the recommended orientations are the NorthEast and NorthWest for model A and the North for model B.

When it comes to choosing the best orientation, the UDI metric is the most important when it comes to the light performance. It approved the outcomes concerning the North orientations and proved that West and East orientation are more preferred for better lighting performance for model B.

2.4.6. Architectural Design information

Khaled A. Al-Sallal studied and analyzed several important architectural design issues in his journal studying daylight and visual performance by evaluating the problems founded in the design of UAE schools' classes. He was testing the credibility of the architectural design proportions assigned in the schools since most of schools in UAE are following some pre-designed prototypes. He wanted to understand the relation between architectural design proportions on visual comfort which included room dimensions, depth to height ratio, glazing allocation (on which façade), daylight view point and tables positions. He simulated several scenarios at specified timings and different angles using Desktop Radiance to indicate any possible visual discomfort. (Al-Sallal K. 2010)

The main goal was to find out any possible visual issues, from the selected tables positions, and comparing it to accepted levels of luminance ratios in the viewfield. The simulations were done on several orientations in multiple dates and hours. Classrooms for seven typical school prototypes were tested and modeled in Radiance with their exact design information following their architectural drawings provided by authorities. (As shown in Table 2). (Al-Sallal K. 2010)

Table 2: The collected design data for the seven casestudy schools (Al-Sallal K. 2010)

Case study	Depth	Length	Height	Floor area	Wall area	Glass area
School 1	4.80	10.64	3.60	51.05	38.29	8.93
School 2	6.00	6.57	3.60	39.44	23.66	5.52
School 3	6.00	9.71	3.60	58.28	34.97	8.16
School 4	6.00	4.40	3.60	26.40	15.84	3.70
School 5	5.25	9.72	3.60	51.02	34.99	8.16
School 6	5.50	9.28	3.60	51.04	33.41	7.80
School 7	6.00	8.51	3.60	51.04	30.62	7.15

Table 3 showed a comparison between the chosen case studies and the recommended values as per UAE government guidelines and rules of thumb. As per recommendations, the class should be 4.6m deep, Height:Depth ratio as 1:2, glazing to wall percentage around 20%, glazing to floor percentage

20%, and the orientation to be towards North and the sun lighting to be coming from left side. (Al-Sallal K. 2010)

Table 3: Checklist whether the classrooms design is follwoing rules of thumb. (Al-Sallal K. 2010)

Case study	Depth 4.60	D/H[a] 1:2 Max	G/W[b] 20%	G/F[c] 20%	Orientation North	DL Dir. Left
School 1	4.80	1:1.3	23%	18%	Diverse	Diverse
School 2	6.00	1:1.7	23%	14%	Diverse	Diverse
School 3	6.00	1:1.7	23%	14%	North	Left
School 4	6.00	1:1.7	23%	14%	Diverse	Diverse
School 5	5.25	1:1.5	23%	16%	Diverse	Diverse
School 6	5.50	1:1.5	23%	15%	Diverse	Diverse
School 7	6.00	1:1.7	23%	14%	Diverse	Diverse

To decide the position and vision direction for simulation, the author decided to choose the worst-case scenario positions within the class, choosing the one with lowest and critical values. He found out that more visual issues appeared in the area located on left side of the class due to the severe contrast in illuminance levels occurred between the board and sidewall. He found out that the worst-case scenarios were the corner points which are indicated as A,BandC in figure22, those points had the worst evaluation of illuminance levels compared to the rest points and indicated the critical view among all of them looking towards the board. (Al-Sallal K. 2010)

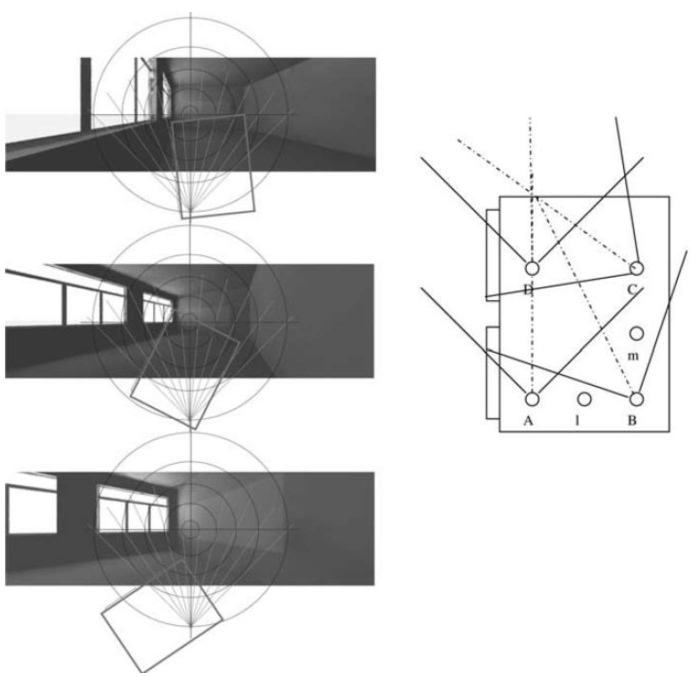
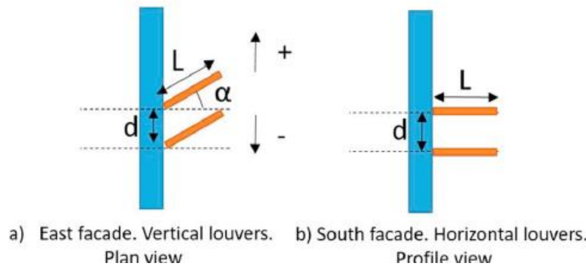


Figure 22: The three positions (A, B, C) from the desk, right: from plan view, left: from camera simulation view (Al-Sallal K. 2010)

Simulations were done testing different angles to study the luminance levels in the targeted view fields on 21 March 10am with angles of 0, 5,15, 25, 35 and 45. Point B founded to be more problematic than the rest of the points and was chosen for the rest of the analysis which included to identify the critical times and luminance ratios analysis. The classrooms in UAE following the typical prototypes design information have shown several problems when it comes to having adequate daylighting for classrooms and good visual comfort. Some of the classrooms had a depth exceeding 4.50m, glazing to floor area were low (less than 20%) and the orientation of most of them were not towards north which considered the best orientation fir this region. The outcomes from simulation indicated three essential issues causing visual discomfort which were the contrast illuminance between the board and sidewalls, high brightness through windows and unequal daylight distribution in classes. (Al-Sallal K. 2010)

2.4.7. Shading Devices

Francisco, Jose and Simon investigated impact of louvers as shading devices on the visual comfort in an office building in Málaga, Spain. Their research studied if using shading device appropriately would be assessing the visual comfort for an office building which has glazing on south and east facades. That's why computer software were needed to simulate the shading devices effectiveness in dynamic conditions. Simulations were done using Daysim as the simulation tools for daylight analysis. The grids for illuminance sensors were placed on a height of 0.85 from floor (desk height). For south façade, he implemented a horizontal louver fixing it to an angle 0º. And east façade will have vertical louvers having several angles for analysis. (Hernández et al. 2017)



Orientation	L (m)	d (m)	α (º)				
Vertical	1	0.5	VL_0	VL_30	VL_60	VL_-30	VL_-60
			0	30	60	-30	-60
Horizontal	1	0.5	VH				
			0				

Figure 23: Summary of shading control strategies followed in simulations (Hernández et al. 2017)

The daylight analysis was testing several visual comfort parameters including the Illuminance levels (lux), Daylighting Autonomy (DA) and Useful Daylighting Index (UDI). Figure 24 showing a comparison for the different simulated cases having the average values for daylight metrics (DA,UDI) and lighting exposure annually having the base case as the case where the building is without shadings. (Hernández et al. 2017)

Figure 24: comparison of the simulated shading cases for the tested visual comfort metrics and annually light exposure. (Hernández et al. 2017)

The results of the simulation indicated that angles of 30 and -30 are the best condition to satisfy and create acceptable equilibrium with cooling needs, visual comfort and artificial light consumption. The values of DA indicated that angles of 60 and -60 were cases that blocked daylight the maximum compared to others. This is because these two angles have high inclination which blocked more solar radiation and enhanced the shading effectiveness. The UDI results confirmed that angles of 30 and -30 for shading devices were the best when it comes to reducing glare possibilities. (Hernández et al. 2017)

2.5. Previous research papers on domes and their relationship with daylight.

A paper done by I.Alturki, Schiler and Boyajian investigating methods to enhance daylighting in mosques using domes, they studied the possibilities for enhancing daylight in mosques by testing several dome sizes for "Guzelce Hasan Bey Mosque in Hayrabolu" to investigate how the dome size would affect the illuminance levels. Three configurations of the dome were simulated which are case1: a dome with no opening (current dome situation), case2: dome with central opening and case3: dome with openings in drum. The illuminance level for the three cases were simulated and recorded. The simulations outcomes showed that the best case was having glazing on drum since it gave an equal and uniform distribution of daylight all around the prayer area in the peak hours (12:00pm and 3:00 pm) plus it enhanced the quality and quantity of daylight throughout the day compare to the other two cases. (Alturki, Schiler and Boyajian 2000)

A research investigating daylighting being a design strategy at the Ottoman era done by A.Belakehal, K.Aoul and F.Abdallah studied several mosques from Ottoman times in Algeria and Tunisia. The objective behind the research is to enhance and strengthen the idea of preserving the historic and heritage monuments in the country, along with clarifying and supporting the idea behind the functionality of daylighting architectural devices in introducing daylight into space and use it as an idea for contemporary environmentally friendly sustainable architecture element. Around 9 mosques in Tunisia and 14 in Algeria built in Ottoman period were investigated. The research was divided into two parts, first one investigated daylight architecture elements then classified them by the strategy used, and the second part investigated the effects of those architectural elements in terms of luminous environment. For the first part, the research covered several elements in courtyard, open-to-sky inner space, and prayer hall envelope like the openings found in doors (low windows), high windows, domes, and cupolas. They were classified by how much they allow daylight in either as direct penetration, redirect it (through reflection), or control its access (filter it, changing the illuminous flux capacity or blocking daylight infiltration). The classification can be seen in figure 25. (Belakehal, Tabet Aoul and Farhi 2015)

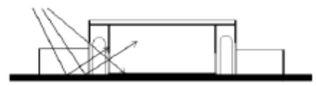
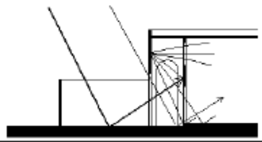
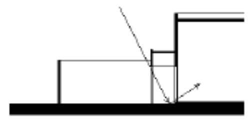
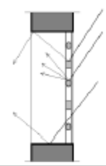
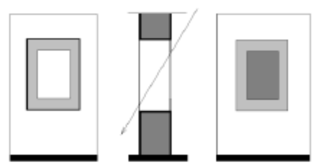
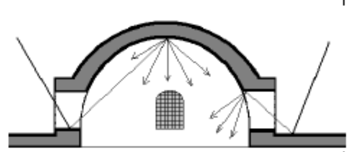
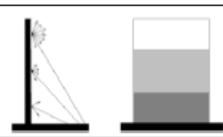
N°	Device	Explanatory scheme	Strategy
1	Courtyard		Allowing natural light direct penetration + Redirecting sunlight by reflection
2	Gallery		Controlling (Stopping sunlight direct penetration) + Redirecting it by reflection
3	Porch		Controlling (Stopping sunlight direct penetration) + Redirecting it by reflection
4	High windows		Controlling (Filtering sunlight admission)
5	Low window		Controlling (Varying the luminous flux)
6	Dome		Controlling (Filtering sunlight admission) + Diffusing it by multiple reflections
7	Cupola		Redirecting it by reflection + Diffusing it by multiple reflections
8	Internal wall covering		Diffusing it by multiple reflections

Figure 25: architectural elements in terms of luminous environment (Belakehal, Tabet Aoul and Farhi 2015)

Several Correspondences Analysis were chosen as a convenient statistic approach to analyze the interaction between those many various components. It helped in creating several models to what would be a "more preferable" design for mosques. The following graph shows a sample of this analysis; the marked dots on the graph represent what was preferred from literature and from field investigation to previous mentioned mosques as a good architectural element providing sufficient daylighting.

A sample of the Correspondences Analysis can be seen in figure 26. (Belakehal, Tabet Aoul and Farhi 2015)

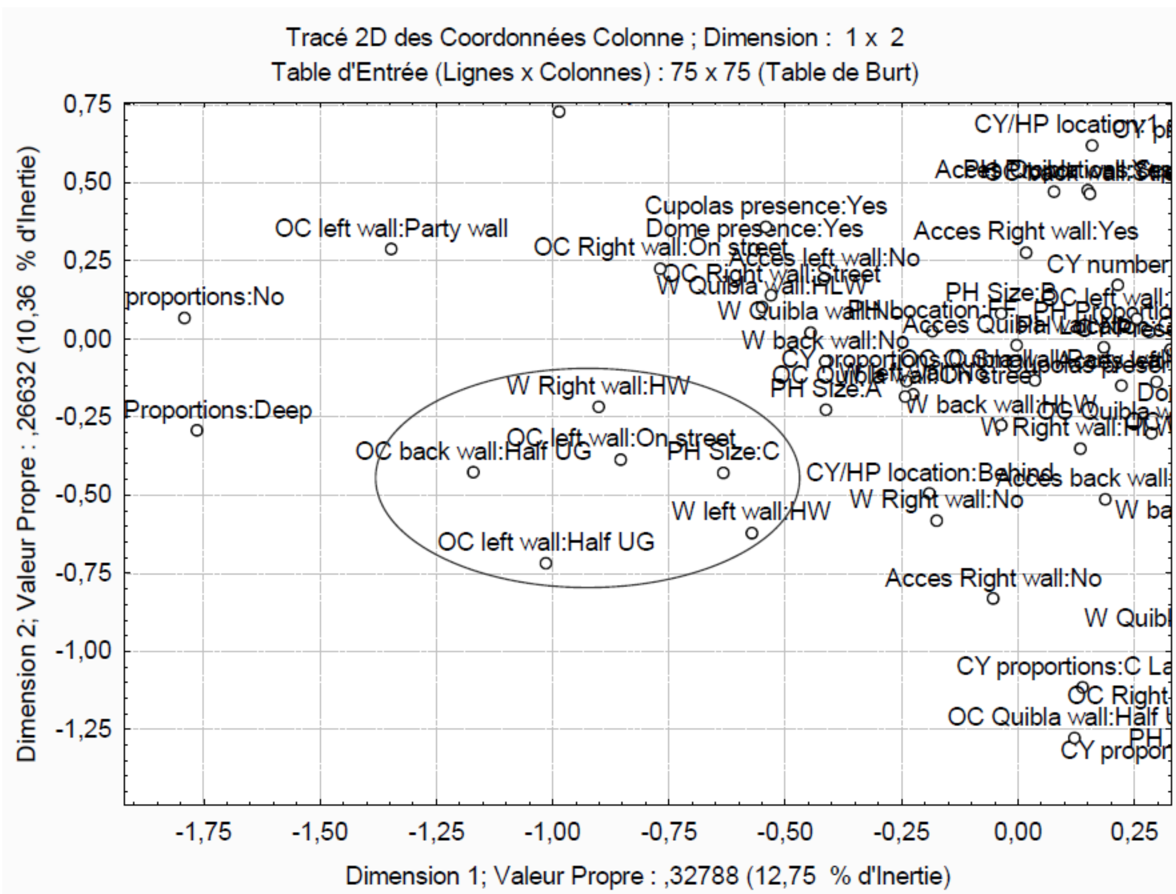


Figure 26: A sample of the results of several Correspondences Analysis to clarify relation between multiple morphologic characters founded in tested ottoman mosques corpus in Algeria and Tunisia (Belakehal, Tabet Aoul and Farhi 2015)

The researchers suggested several models including having a (Case A) presents a mosque consisting of prayerhall with daylight elements (Dome and cupolas) including two windows rows in the drum and without a courtyard for small prayer hall proposal. (Case B) will consists of a large square prayer hall connected to a courtyard without any top lighting devices but walls should have high double row of windows. This can conclude to us that dome is more preferable when having small or medium size space and it will cover all requirements of daylight within space without needing any other opening or side windows on walls. Domes can replace a courtyard if it was measured and calculated accurately, this will help not only aesthetically and functionally but it will also help to use the lower space as shaded air-conditioned space instead of an open plan (courtyard). (Belakehal, Tabet Aoul and Farhi 2015)

The research concluded that using daylight elements (refereeing to domes and cupolas) are efficient in improving internal illuminance level in room in cases where no courtyard is provided or when the courtyard doesn't give enough daylight, the central dome within the mosques helped in providing adequate illuminance levels and distributing the daylight uniformly and equally throughout the prayer area. The research suggested some guidelines for new mosques or restoration daylighting design strategies including having domes with vertical arrangement of windows, the windows located at low position within the building should be bigger, transparent and fine internal faces treatment. Researchers suggest going further in the research by having a quantitative analysis using simulation to test the luminous nature inside mosques to enhance daylight performance in upcoming designs for mosques. (Belakehal, Tabet Aoul and Farhi 2015)

I.Fitoz and G.Berkin research based on literature talking about "The Use of Daylighting in Churches and Mosques" stated that in mosques the dome not only functions for daylight and aesthetics but also has a spiritual purpose symbolizing the heaven lights. It also was used to minimize darkness at mosques which explains its importance in the Arabic and Islamic culture as an architectural element, as well as daylighting has the ability to enhance penetration of the whole room by establishing luminous and spacious environment. It stated as well that domes where also used in other cultures like Roman, Byzantine and Renaissance to introduce daylighting through high angles coming from windows at drums of domes. Domes are an architectural representation to the span size in the inner spaces. In the beginning domes were used to highlight the central areas when the concept of centrality started in architecture history, later on the addition of windows and glazing made it serve another function which is lighting up the space. Those windows on dome were considered as another type of roof windows and being one of the best light distributor configurations. Modern studies on daylight proved that getting daylight from high levels gives a better and uniformly distribution of daylight, and domes is one of those high level structures that help to equally and clearly distribute daylight instead of creating mystic ambiance. (Fitoz and Berkin 2014)

A paper by E. Aljofi highlighting the issue of daylight in deep spaces especially those that don't have penetrated light access on the external walls such as mosques. He investigated the efficiency of the dome as light distribution devices that's usually used in mosques by having a survey study and experimental process. He believed that Due to mosque dimensions, side windows may not be efficient for satisfactory light, therefore, domes, have been used since old times to introduce daylight no matter what is the size of the mosque. The research targeted the optimization of using the dome with different openings' configuration and tests their effect on daylight. A field investigation of daylight performance using light meter was done on Alarfaj mosque in Alkhobar Saudi Arabia which has a dome with two vertical openings of (1.2 m 6.65m) each on both ends.

The readings were taken at three sections of the prayer hall (A-A, B-B, C-C) at an interval of 1m as shown in the section figure 28. Section A-A was in the front of the prayer hall where light introduced in this area coming both ends with vertical windows of facing North West. Section B-B in the middle area directly under the dome where most of daylighting is coming through large glazing panels through both ends. Section C -C was in the back area where there is no side light contribution. (Aljofi 2018)

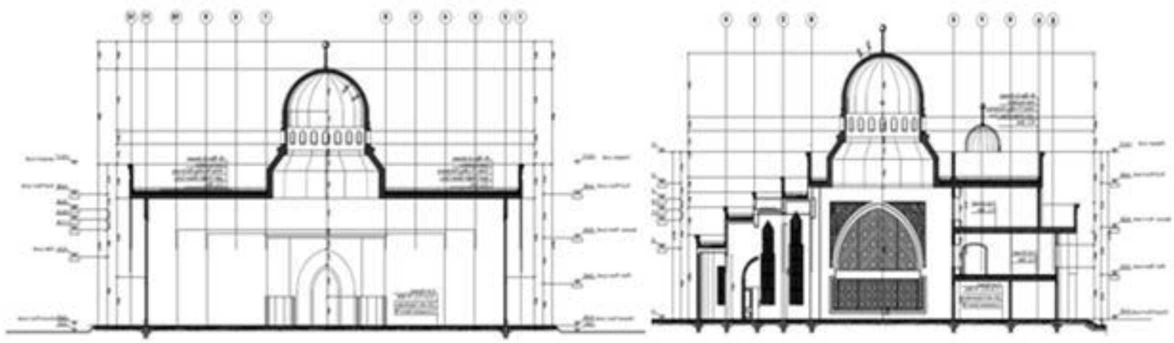


Figure 27:Setions of Alarfaj mosque in Alkhobar Saudi Arabia (Aljofi 2018)

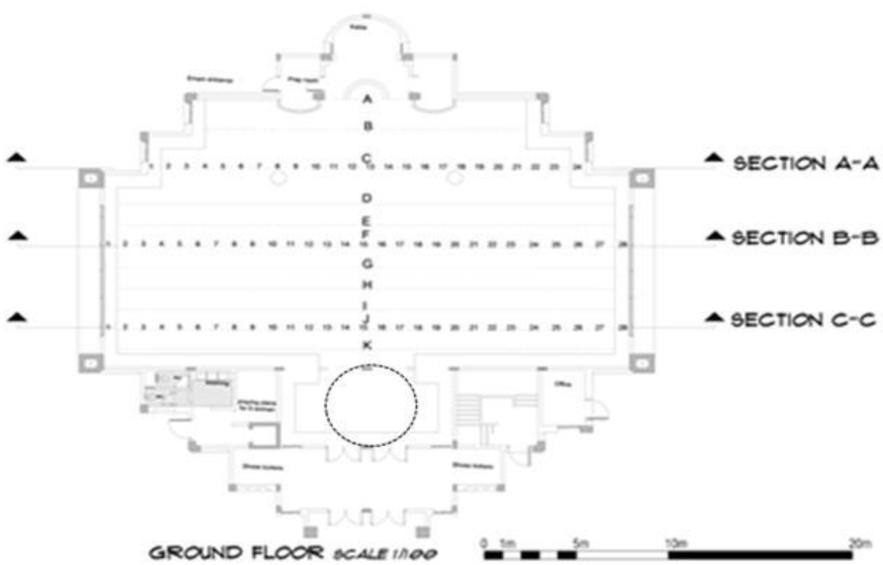


Figure 28: Ground floor plan of Alarfaj mosque in Alkhobar Saudi Arabia (Aljofi 2018)

An experimental investigation using a physical model of the same mosque was done keeping into the consideration the orientation of the mosque in real life, the experiment tested several side openings with different glazing area of 25, 50, 75, and 100% using Megatron light meter. The following figure represents the model scenarios tested in this experiment. (Aljofi 2018)

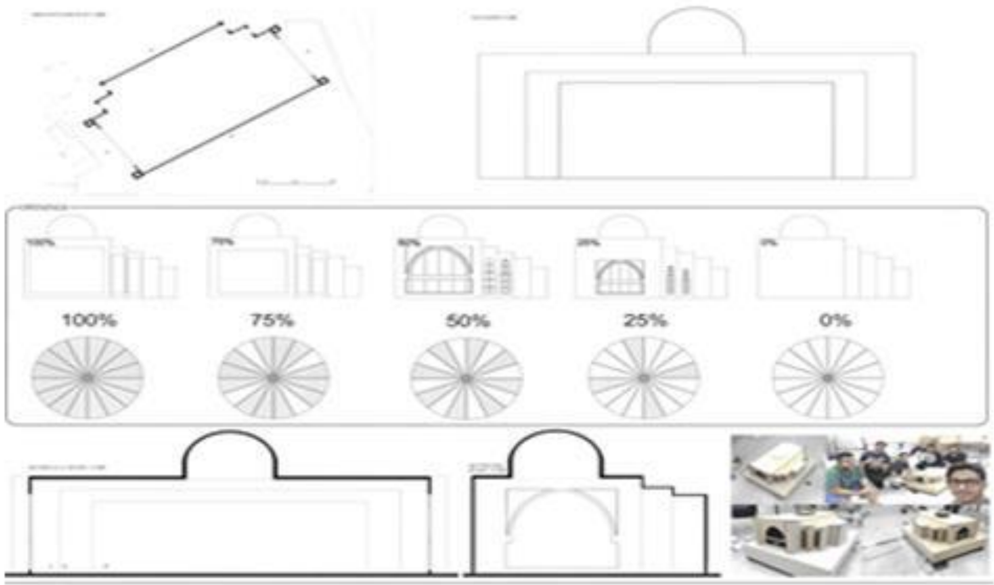


Figure 29: The physical model used and its different tested scenarios (Aljofi 2018)

The results of the field experiment showed high light level contribution through the side opening, whatever the area of the glazed panel is limited to the adjacent zone to these opening of up to 8M. Section AA had very low light level of less than 160 Lux. Section BB maximum light under the dome on both ends was recorded as 480 lux while it was much reduced under the dome of up to a maximum of 180 – 200 lux. Section CC The light level contributed at this zone is very low (100 -250 Lux) through all the section. This means the light contributed through the dome with side opening is still inefficient. This may be due to the limited glazed area within the dome. (Aljofi 2018)

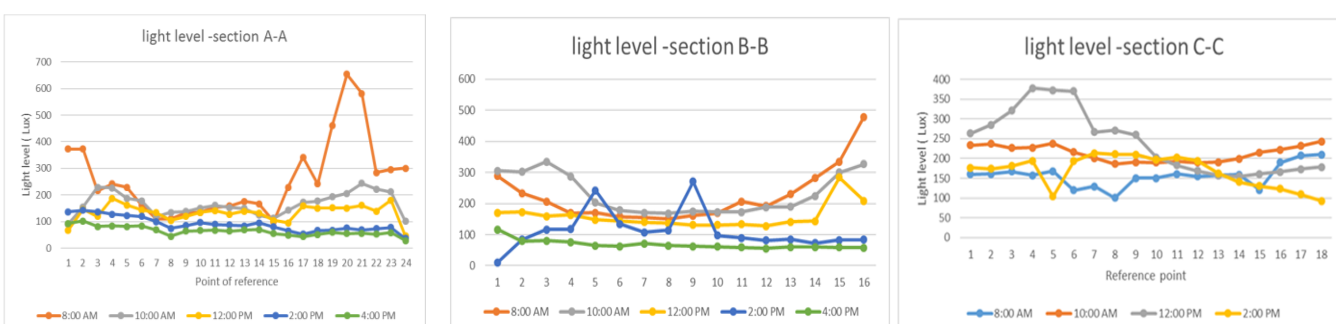


Figure 30: Light level results for field investigation

For the experimental investigation, the light penetrated through the dome was lower than the standard level for reading purposes (500 lux) in all types of tested domes through the day. In order to get benefit from the dome as light concerned, further treatments could be investigated such as changing the domes parameters or to increase the reflectivity of the roof area around the external part of the dome to reflect the light beam at the inner ceiling of the dome of a reflective material. (Aljofi 2018)

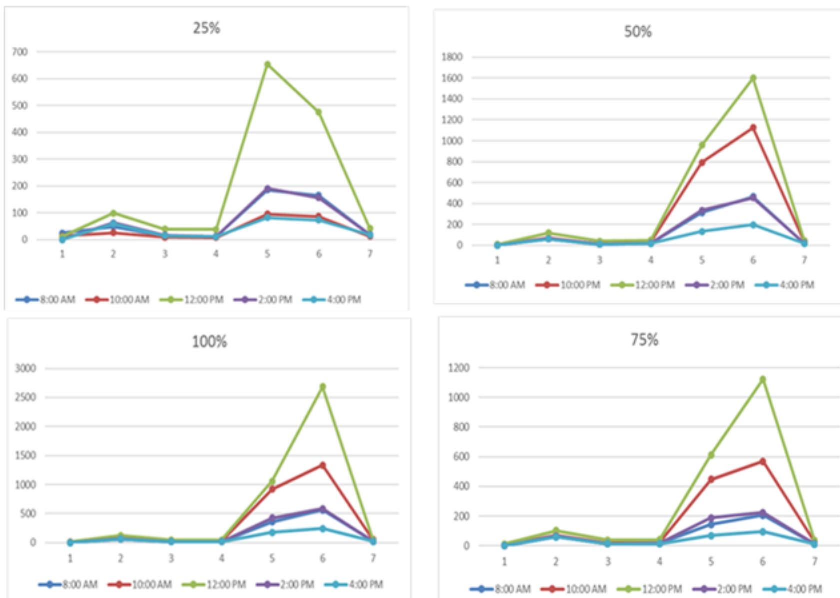


Figure 31: light level results for the physical model with different areas of openings (Aljofi 2018)

Another research done by Arab, Y. and Hassan, A. (2013) investigated wither domes are capable to provide efficient indoor daylighting. To do that they studied two domes in two different mosques the Firuzaga Mosque and Orhan Gazi Mosque compared the illuminance level of the two domes with the illuminance level table conducted by Krochmann (1989) and also comparing the outcomes of the two domes with each other. To do that researchers used 3DStudio Max which uses EnergyPlus 2010 weather data file (*.EPW). The simulations were conducted in summer Solstice each hour ranging 6:00am to 6:00pm on 21st June 2010. Simulations were taken on a height allocated on a height of 0.45m similar to human level when sitting on the mosque’s floor, simulations were taken in five points in both of mosques, Point1: Access door; Point2: mid of prayerhall; Point3:mihrab ; Point4: eastern area and Point5: western area. (Arab and Hassan 2013)

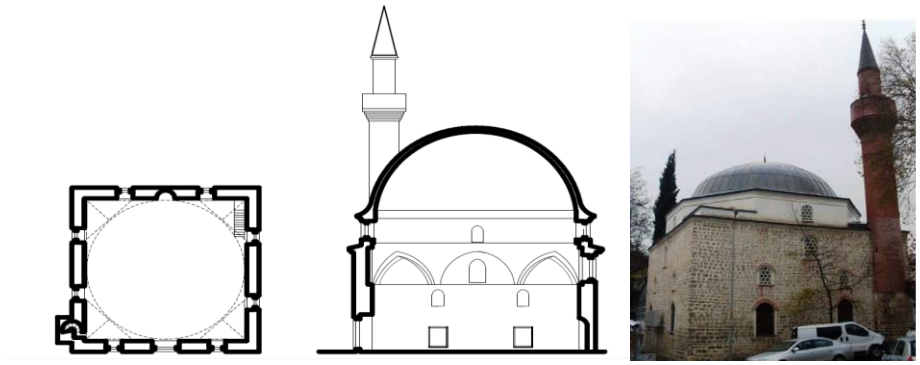


Figure 32: Orhan Gazi Mosque(Arab and Hassan 2013)

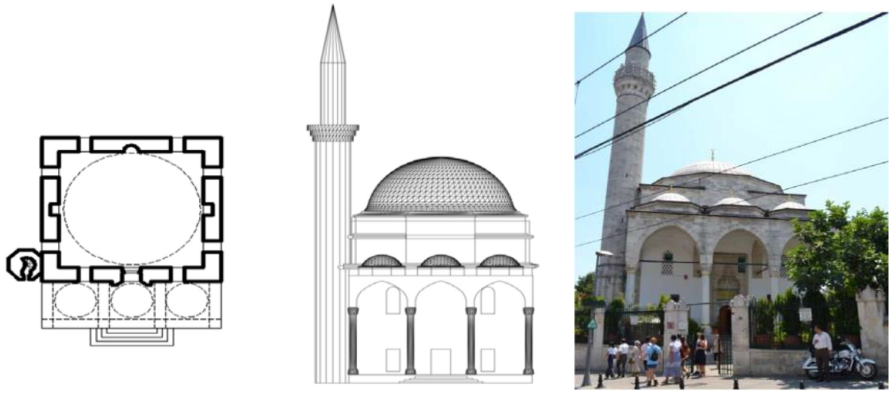


Figure 33: Firuzaga Mosque(Arab and Hassan 2013)

Table 4:Scale for illuminance level evaluation(Arab and Hassan 2013)

Scale	Illuminance (lux)	Level
1	0 - 20	Total darkness to dark
2	20 - 49	Do not demand a high visibility of the task (public areas)
3	50 - 99	Do not demand a high visibility of the task (orientation during short stop)
4	100 - 199	Do not demand a high visibility of the task (rooms not in permanent use and hallway brightness)
5	200 - 499	Details easy to see at normal brightness for reading or office area
6	500 - 999	Details difficult to see like intricate work for brightness
7	1000 - 1999	Tasklighting for highly demanding work - extremely fine details like microelectronic assembly
8	2000 - 10000	Tasklighting for highly demanding work - extremely fine details like special tasks in surgery (10000 lux is maximum brightness from sunlight to indoor area)
9	10001 - 100000	Outdoor area brightness (100000 lux is the maximum measurement)

The study concluded that domes enhance the mosque indoor lighting quality and provide an excellent illuminance level distribution all over the floor area which is the reason why Ottomans preferred using domes more frequently than other architectural elements. Adding an upper row of glazing (windows) on drums surround the OrhanGazi Mosque dome provided extra daylighting access specially in center space of prayerhall; on the other hand, having few windows applied in the Firuzaga Mosque resulted with very low and minimal illuminance levels coming into the central of prayer hall. Also having high drum/dome to the plan ratio helped in enhancing illuminance levels in the Firuzaga Mosque although it didn't have a top row of glazing (windows). In another words, having a dome made illuminance level distributed evenly and uniformly towards all points and areas inside the mosque that improved illuminance level. (Arab and Hassan 2013)

Hassan and Arab few years later did another investigation analyzing daylight coming through domes in a mosque in Kuala Lumpur, Malaysia not only to make sure that their design is giving adequate daylight but also check the accuracy of 3dSMax software which uses weather data base from Energy Plus weather files (*.EPW) for analyzing illuminance distribution is reliable. The researchers compared field results Lux Meter (Tecpel DLM-531) with computer simulations. The mosque had a central dome along with three $^{1}/_{2}$ domes built on west, south and north sides. The analysis was conducted on 21st December 2013 each hour ranging 6:00am till 6:00pm. The lux meter was allocated on a height of 0.45m similar to human level when sitting on the mosque's floor. The measurements for both field investigation and computer simulations were taking in five points as shown in the figure below. (Hassan and Arab 2014)

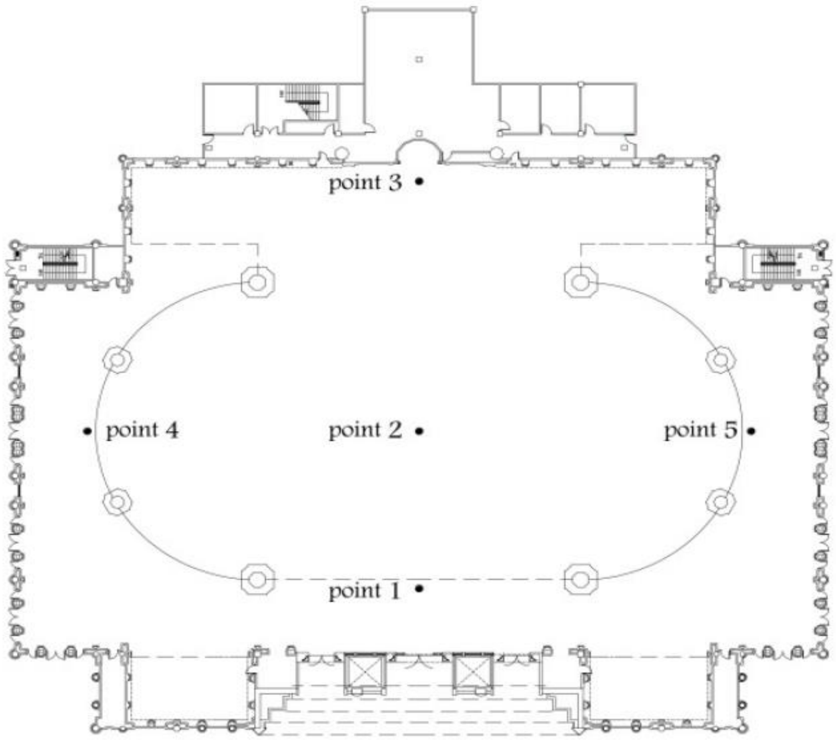


Figure 34: Location of the five points that measurements were taking at (Hassan and Arab 2014)

The field outcomes proved that weather data base in Energy Plus weather file (*.EPW) is very reliable. The search found out similarity in the values outcomes from field measurements and simulations for points 1 to 5 with minimal overall difference that ranges between (0.7 to 7.4 lux). The results shown that points (1,2,3) had a sufficient illuminance levels throughout the tested timings but point(4,5) had illuminance levels lower than minimum requirements. The mosque architectural design proven to be providing sufficient illuminance levels during the day (from 9:00am to 4:00pm) in point(1,2,3) which are appropriate for tasks that doesn’t require high visibility to be done like reading activities. This confirms that using software analysis will help architects and designers to generate the daylight level before construction to ensure no issues would occur related to daylight design. (Hassan and Arab 2014)

2.6. Literature Review summary and outcomes

2.6.1. Lessons learnt from literature

Daylighting importance for Sustainable Lighting:

Daylight is related to human health and wellbeing and the productivity levels of people living, using or working in buildings. Another value of daylight is the physiological and psychological effects on human body. Daylight considered having better “light quality” compared to artificial lighting. Daylight also effects the person’s location and sitting preferences since its affecting directly their mood.

Benefits of daylight would include that it grants visual exchange with the outside. Another benefit that it provides good quantities of light to perform the visible tasks. Although electrical lighting can enhance visibility in workspace, but adding daylighting would let the room appear more refreshing, well-lit and much attractive. A lot of people select certain timings within the day which have certain levels of daylight to do their important physical activities and task since they believe that daytime supports better fitness.

With all this technologies and new innovative daylight systems, human was able to control daylight by either redirecting it or focusing it in areas to be placed in the locations which has to be immoderate luminance and glare are required. Those modern structures utilize optical technologies which creates reflections, refractions, and make it possible to utilize the skylight and daylight internal reflectance completely. Those new technologies could be customized and modified to passively monitor both direct daylight and skylight.

Visual Discomfort:

The most common reason for visual discomfort is having poor visibility which can be a result of having low illuminance level. Some countries have added illuminance as criteria or standard whenever a new building needs to be submitted to municipalities or government approval, targeting to get an illuminance level that satisfies effective visibility.

Luminance is considered the only lighting variable that is received by the eye. It relays mainly on two aspects which are the brightness of the source as well as the surface properties which means the degree of reflectance (color and surface) plays a major rule in luminance level that the eye could receive.

Studies on peoples' reactions to multiple types of daylighting on workspaces shown that most people preferred the space with a uniform, shadow free illuminance on workplace and with low illuminances values surrounding the space.

It's true that shadows can produce visual discomfort, but it also helpful to highlight the shapes of 3D objects and texture. When it comes to display objects, it relays on the lighting display techniques which is a combination of proper shadow, highlights and light

Glare as per IRENA definition is a sensation happening due to a certain illuminance in the visual field which is considerably higher that illuminance level that the eye can adapt, which leads either to discomfort, reduction in visibility and performance or even annoyance.

The most common categorization for glare include four types either by their direction into direct or indirect glare and by the effect they have on the observer creating either disability or discomforting glare.

Direct glare happens due to having bright areas from windows, luminaries or ceiling being in the view field and lighting up the space directly. Indirect glare happens due to the reflection in the task area (working surface) towards the eye within the view field.

Disability glare causes reduction in visual performance and visibility. Discomfort glare causes physical discomfort.

Daylight Glare Index (DGI) indicates the probability of glare to occur due to large sources such as sky being visible directly to a window. It predicts the lowest likelihood of discomfort. DGI isn’t considerably reliable when direct light or specular reflection are existing in a view field. DGI tests the relation between the luminance source, view field position and its size to the luminance background. The metric evaluates the glare as any value more than 31 to be intolerable and values less than 18 to be 'barely perceptible'.

CIE Glare Index (CGI) predicts the highest likelihood of discomfort. Its Calculations require both direct and diffuse illuminance. It’s only for luminaire sources of glare. Values >28 are intolerable while those <13 are imperceptible.

Visual Comfort Probability(VCP) indicates the possibility that a person doesn’t experience any discomfort while having a light within specific circumstances. It evaluates glare as a function of the size and source illuminance to its location within workplace and the illuminance average for a viewing solid angle of 5steradian in a range from 0-100. It is not usable for daylighting sources evaluation nor to compact luminaires.

The Daylight Glare Probability (DGP) index is known as one of the most reliable metrics when it comes to light analysis because the process of driving it came from experiments with actual human subjects. DGP is newest and recently metric used for evaluation of glare due daylighting, it recognizes the glare coming from the direct daylight falling on work place and the reflections from surfaces as well. This metric is considering most aspects and factors participating in causing visual discomfort compared to other metrics. It can predict the presence of discomfort glare in the space even without having significant visual contrast.

DGP of 45% indicates an intolerable glare, while a value of 35% indicates imperceptible glare.

DGP solved several issues that Hokinson had when he was creating the DGI metric by adding several variables within the equation which included adding other sources to glare rather than only direct light from sky, which is something that wasn't done by any previous metric.

Classical Architectural Elements of Light:

The lack of technology and electrical knowledge in old buildings has frequently driven to interesting and special designs and arrangements to the lighting issue.

All through the 20th century, daylighting kept on playing an imperative part within the design of numerous modern buildings. As the 'international style' of architecture started to spread worldwide, with expansive floor plans and large square feet architects depended on artificial lighting but later on due that over-illumination issues popped out, and proceeded until daylighting again got to be a major attention in architectural design in 1995.

In the last two decades, daylighting was again the center of attention, focus and importance in architectural design by focusing on efficiently design buildings with energy conservation methodologies.

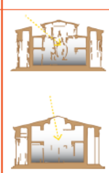
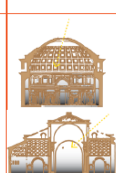
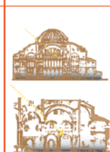
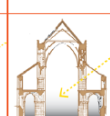
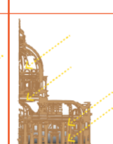
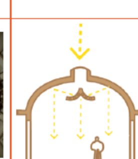
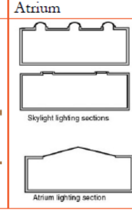
In ancient eras, sunlight was an essential source of light and illumination was an image of cleanliness, purification, knowledge and paradise. Ancient Egyptian having restricted opening sizes because of having short spans capability, Clerestories enhanced the daylight in the internal spaces, and Thick walls functioned to reduce and diffuse the sunlight. Ancient Greek only use direct daylight to light up statues but for the rest of the room strong direct and reflected daylight used on the exterior with gold leaf and colored stone to enhance daylight.

Roman Architecture of the circular arch, the barrel vault and the dome made it possible to design bigger openings that may concede large sheets of light. Early Christian used Timber trusses replacing vaults to create the inclined rooftops that decreased wall space obtainable for clerestory windows. Byzantines arranged was centralized around a main dome encompassed by secondary spaces with half domes crossing underneath the primary dome.

From literature through eras, domes were used in different shapes and sizes as the main and most efficient daylight source and in the same time its aesthetically pleasing and gives a feeling that the room is bigger in size.

Table 5 is a summary for all the classical architectural elements used throughout the different eras. This shows that daylight had always been a part of buildings architecture and design.

Table 5: Daylighting has been a critical part in architectural design for ages and through eras (Florence N. 2015)

PREINDUSTRIAL PERIOD									INDUSTRIAL PERIOD & POST-INDUSTRIAL PERIOD	
ANCIENT EGYPT	ANCIENT GREECE	ANCIENT ROME	EARLY CHRISTIAN	BYZANTINE	ROMANESQUE	GOTHIC	RENAISSANCE	BAROQUE	MODERN MOVEMENT	BUILDING SCIENCE & CLIMATE RESPONSIVE ARCHITECTURE
50th C B.C. - 1st C B.C.	8th C B.C. - 2nd C A.D.	2nd C B.C. - 4th C A.D.	A.D. 313 - 800	A.D. 330-1453	A.D. 800-1100	A.D. 1100 - 1600	A.D. 1400- 1830	A.D. 1575 - 1770	A.D. 1900 - onwards	1972 - onwards
Clerestories Roof slits Small windows Doors	Clerestories Skylights Small windows Doorways	Clerestories Skylights Glazing	Clerestories Linear Perspective High level windows	Stained Glass Windows Play of perspective Semicircular headed openings	Clear glazing Rose windows Recessed openings Southern facing openings	Stained glass Southern facing openings	Vertical grouping of windows Semicircular or square-headed recessed openings	Play of light Play of perspective Recessed openings	Deeper floor plans Unique styles by architects experi-menting Use of walls and roof to light the building	Return to historic principles of daylighting design Sky lights Roof Monitors Roof Clerestories Lateral Lighting Bi-Lateral Lighting Atrium
										

Variables affecting daylighting:

From several research papers, the best window size from the outcomes showed that a space should have minimal percentage of 20-25% glazing to wall area, preferably to be up to 30%. They stated that best window size is not related to an exact glazing percentage to wall area but its dependent on space characteristics, size and view nature.

For views with higher view angle, the preferred head top was to be higher tha1.9m in order to have a view towards sky and less direct daylight in.

In some researches people comfort reduced when they were in a room with a long horizontal window divided into smaller ones, they felt that this configuration is disturbing and interrupting the continuity of the view, they preferred regular shape large horizontal windows. Others indicated having multiple small series of windows this will make it possible for the observer to experience several views instead of one big window looking at one view. The size and position effect the evaluation of daylighting entering the space as well as the person's preferences but no research have been yet conducted about the best or more preferable window configurations in presence of daylight.

Rooms contain high reflectivity surfaces makes the room appear brighter, and in contradictory ark surfaces will make the room look dull by absorbing daylight. Experiments have shown that changing a material reflectivity from 0.4- 0.6 will enhance illuminance levels within the room upto 50%, and from 0.4 to 0.7 up to almost 100%.

Although the glass type had numerically noticeable impact on the light level concentration, naturalness, aesthetic and precision but it didn't have any impact on lighting allocation and shading.

The glazing visual transmittance showed positive and direct relationship with light level, glare (comfort), naturalness, aesthetics, and accuracy.

The sDA metric is the most important metric when it comes to evaluating the preferred orientation in order to reach the minimum requirements of light levels (300 lux).

In the tropic of Cancer area, the recommended orientations are the South orientations (S, Southeast and Southwest) orientations. Most of orientations failed to achieve requirements for ASE, except North orientations (North, North-West, North-East). The South orientation had the highest sDA values for both models but couldn't pass the ASE requirements, which means that an adequate amount of daylight is coming into the space but glare has occurred.

Important issues were indicated causing visual discomfort which was the contrast illuminance between the board (task field view) and sidewalls, high brightness through windows and unequal daylight distribution in classes.

For shading devices, angles of 30 and -30 are the best condition to satisfy and create acceptable equilibrium with cooling needs, visual comfort and artificial light consumption.

The values of Daylighting Autonomy (DA) indicated that angles of 60 and -60 were cases that blocked daylight the maximum compared to others. This is because these two angles have high inclination which blocked more solar radiation and made the shading more effective.

Previous research papers on domes and their relationship with daylight

Domes explain their importance in the Arabic and Islamic culture as an architectural element, as well as a method to enhance daylight presence in the spaces uniformly by establishing luminous and spacious environment.

Domes are more preferable when having small or medium size space and it will cover all requirements of daylight within space without needing any other opening or side windows on walls. Domes can replace a courtyard if it was measured and calculated accurately, this will help not only aesthetically and functionally but it will also help to use the lower space as shaded air-conditioned space instead of an open plan (courtyard).

Using software analysis will help architects and designers to generate the daylight level before construction to ensure no issues would occur related to daylight design. Weather data base from Energy Plus weather file is very reliable.

In order to get benefit from the dome as light concerned, further treatments could be investigated such as changing the domes parameters or to increase the reflectivity of the roof area around the external part of the dome to reflect the light beam at the inner ceiling of the dome of a reflective material.

Adding an upper row of glazing (windows) on drums surrounding the dome provided extra daylight access specially in the central space of prayerhall and having few windows resulted with very low and minimal illuminance levels coming into the central of prayer hall. Also having high drum/dome to the plan ratio helped in enhancing illuminance levels although it didn't have a top row of glazing (windows). In another words, having a dome made illuminance level distributed evenly and uniformly towards all points and areas inside the mosque that improved illuminance level.

Domes can be classified by how much they allow daylight in either as direct penetration, redirect it (through reflection), or control its access (filter it, changing the illuminous flux capacity or blocking daylight infiltration).

Several researches used a Measurable scale of indoor lighting performance which evaluate and highlight recommended ranges of minimal illuminance levels. What is recommended is around 200-500lux to have enough brightness for visibility to tasks like reading or using computer and around 2000 lux for highly demanding work and tasks that demand high visibility like drawing small details, this parameter will be used in the research to evaluate illuminance level.

2.6.2.The gap this research paper attempts to fill.

From the excessive research on the topic, it seems that there are no research papers that targeted the visual impact of having a dome as an element for daylight. Most of the research related to domes either tested the acoustical impact or some daylighting analysis targeting only illuminance level (lux) and none discussed nor searched on the glare, the Spatial Daylight Autonomy or Annual Sunlight Exposure.

On the other hands educational institutes/buildings have tested glare, illuminance, Spatial Daylight Autonomy or Annual Sunlight Exposure but none tested any classical architectural elements (domes, oculus, vaults, flying buttresses,…) impact on educational, public or office spaces. In fact, not only religious institutes (mosques and churches) are the only buildings using domes for daylight purpose, they are many other types of buildings using this technique to enhance daylighting in space such as:

- Educational : University of Oxford, Massachusetts institute of technology, University of Notre Dame, University of Sharjah, American University in Sharjah, The Maharaja Sayajirao University
- Offices: The Dome of the US Capitol , Cleveland Trust Company Building
- Museums: Dali Theatre and Museum, Kuppel des Bode-Museum
- Hotel : Threadneedles Hotel , West Baden Springs Hotel

Though this research will be focusing on glare, illuminance to evaluate visual discomfort on educational space (University of Sharjah) to be a benchmark and recommendations for educational and other building types to follow.

Figure 35: ("University of Notre Dame – Global Grad Show" 2020) ("The Massachusetts Institute of Technology (MIT)" 2020)

Figure 36: ("University of Sharjah" 2020)

Figure 37: ("University of Oxford" 2020) **("The Maharaja Sayajirao University Baroda" 2020)**


Figure 38: The Dome of the US Capitol ("Capitol Dome" 2020) ("Cleveland Historical" 2020)


Figure 39: ("Dali Theatre and Museum" 2020) ("Kuppel des Bode-Museum" 2020)


Figure 40: ("Threadneedles Hotel | 5-Star Hotels in London City" 2020) ("West Baden Springs Hotel" 2020)

CHAPTER 3: RESEARCH METHODOLOGY

CHAPTER 3: RESEARCH METHODOLOGY

3.1. Review of Previous Methods

Several research papers were selected and analyzed based on methodology type. As will be discussed shortly, simulations methodologies were used in many research papers discussing the relationship of light and architecture.

Most of the research papers concerning daylight prefer more the simulation method to evaluate illuminance and lux levels. A research paper done by Johnsen, Dubois and Grau investigated daylighting characteristics in three rooms with three window types: a regular size vertical window, a dormer window, and a ceiling window through computer simulation analysis. Simulations in this research were done using Radiance software after exporting the architectural drawings from AutoCAD program after modelling it as per shop drawings (actual dimensions). Radiance software has the ability to analyze the daylight and lighting design and create illustrations of the building massing, sun paths and results for many daylight metrics for real-life situations. Different majors use Radiance in their work, architects and engineers use it to get an idea of the illuminance levels, lighting accessibility and quality and test some of the new innovative designs, also researchers used it to evaluate and test the new daylight concepts and lighting technologies. To do the simulation accurately, some data should be identified such as building massing, materials used, luminaires type, timing, dates and sky conditions (for daylighting calculation). In the research they were trying to test daylight by doing a comparison for three rooms within different sky conditions (overcast sky, sunny sky) at two timings (12:00 and 15:00) having the same room area, floor to ceiling height and oriented towards South. (Johnsen, Dubois and Grau 2003).

Another research investigated and tested daylight in an office building with several atrium types options, proportions and design shape. The main goal was to optimize and enhance atrium designs and preferred dimensions to enhance buildings' energy efficiency for with atriums. The research tested several daylight metrics on different types of atriums which includes attached, central and semi-closed atriums. To test these different types, the researchers relied on computer simulations. DIVA software which is a plugin for Rhino software was used to access daylighting performance as illuminance levels, daylight factor. It also targeted to validate the use of daylight analysis software (such as DIVA) as a prior step before construction to evaluate the building design and that's by a comparison of daylighting outcomes using simulations with the exact scaled mockup. (Mohsenin and Hu 2015).

Another research was done to an educational building in Brazil to test the validity of EnergyPlus software for daylight analysis as well as comparing it with other softwares known in the market and evaluate them. The simulation analysis conducted on three rooms: square (5m×5m×3m), shallow rectangular (10m×5m×3m) and one deep rectangular (5m×10m×3 m). The first part was a comparison of some daylight metrics which are Useful Daylight Illuminance (UDI) and the daylight factor (DF) resulted from EnergyPlus with simulation results of another two softwares Daysim+Radiance and TropLux. Also, the validity of EnergyPlus was investigated with field measurements by testing the external horizontal illuminance results from software with the one measured, this test was conducted for Florianópolis, Santa Catarina State, Brazil between 2003-2005. (Ramos and Ghisi 2010).

From literature through eras, domes were used in different shapes and sizes as the main most efficient daylight source and in the same time its aesthetically pleasing and gives a feeling that the room is bigger in size. This paper conducts a study on the natural light coming through the dome in the Architectural Engineering Department at University of Sharjah. It discusses the problems concerning visual comfort. It analyzes the efficiency of the dome in bringing in adequate amount of daylight in corridors and main halls needed for students to work on their drafting work and designing process. Therefore, this research will be a presentation of solutions for getting better lighting efficiency in educational buildings and comfort using several softwares.

Software will be used to get the glare, illuminance, sDA and ASE. The scenario will be modeled in REVIT and IES , Revit with INSIGHT plugin to get illuminance (LUX) to measure luminous flux per unit area, also to measure Spatial Daylight Autonomy (sDA) to indicate how much of the room gets adequate daylighting annually, it gives the floor area percentage which receives at least 300 lux for 50% of annually utilized hours and another metric which is Annual Sunlight Exposure (ASE) indicating how much of the room gets extensive direct daylight that can lead to visual discomfort (glare), it shows the floor area percentage which gets at least 1000lux for 250 occupied hours in a year. IES with Radiance plugin will be used to get the daylight glare probability (DGP) to check the visual discomfort percentage in space and Glare Threshold Differential (GTD) calculations. Further details and explanation can be found in section 3.4. Simulations will be done on 21 June, 21 Sep, 21 Dec at 8:00am, 12:00pm and 4:00pm, these timings of the year are the most appropriate to test in different sun altitude, 21 June (Summer Solstice) is when the sun is at the highest point in sky and being longest day of the year, 21 December (Winter solstice) where the solar altitude will be at its minimum and having shortest day of the year and 21 September (equinox) day and night of equal length so it's in between 2ljune and 21 December and the timings chosen are the sunrise with low sun angle on east at 8:00 am, mid of day when sun is at its highest 12:00 pm, and before sunset with low sun angle on west at 4:00pm. Another reason to choose these timings is that these are times when students are using the building. 8:00 am is the arrival timing, 12:00 pm is the design studio timings and training, 4:00 pm is the end of design classes and start of brainstorming sessions in the lobby area.

3.1.1. List of Variables

From literature review, there are plenty of variables that can affect the visual comfort within a space, in this research it will be limited into the following:

Table 6: List of research Variables

Controlled	Fixed	Measured / Calculated
Dome Diameter	Room Size “ width , length , height”	Illuminance (LUX)
Drum’s height	Walls and floors Materials	Annual Sun Exposure (ASE1000/250)
Glazing ratio (Area Windows /Area Drum)	Dome position within the space	Spatial Daylight Autonomy (sDA300/50%)
	Material reflectance	Glare (GDP)
	Day and Time of simulation (21 June at, 8am 12:00 pm 4:00pm) (21 Sep at 8am 12:00 pm 4:00pm) (21 Dec at 8am 12:00 pm 4:00pm)	

The controlled variables will be the dome’s diameter, drum’s height and $S_{windows}$ (W_{area}/D_{area}). The simulation will be done for 3 different diameters each with 3 different heights and 4 different glazing percentages. This will be 36 models to be simulated in different timings depending on the measured variable tested. Further explanation can be found in section 3.4.3.controlled variables and section 3.4.3.Simulation scenarios (Measured variables).

3.1.2. List of Assumptions

1. Windows are directly under the dome and not affected by dome shade, so the results won't be affected by any shades from the dome.
2. Glazing type is uncoated double glazed.
3. First floor will not be modeled in the analysis because the simulations will be testing the effect on ground floor.
4. No furniture in the hall to avoid any reflection from furniture material.
5. Orientation of building is fixed because orientation won't be tested as a variable effecting visual comfort.
6. No external/internal reflectors are affecting the dome function
7. Shading of adjacent buildings is neglected, since shadow won't be tested as a variable effecting visual comfort.
8. Reflection factor, Wall = 20%, floor = 50% , Ceiling =80%
9. The dome had double sets of windows at different heights. The upper sets of windows are not included in simulations, only the lower set of windows is included.

3.2. Sharjah weather data

UAE is relatively small country, that has a hot and humid climate. All Emirates, expect Al Ain, are located on the coast. Therefore, it is noticeable that the climate in Abu Dhabi, in Dubai, or in the Northern Emirates is the same.

Sharjah city is on the west coast of UAE. It is connected to both sides, the Arabian Sea and the Indian Ocean. The geographical coordinates of it are 25°17′18.84 "N and 55°28′36.12" E and using the universal transverse Mercator are 346632.34 m E and 2797635.36 m N.

The maximum temperatures can occur on June and August. The temperature during summer can never go below 30 ° C; it can also go up to 55 degrees.

In summer, humidity is high. It can reach 90% and saturate the air with salt water coming of the sea. The humid southeastern wind made the coastal region unpleasant. It provoked people to stay in the airconditioned areas. The latitude and high insolation levels of the UAE lead to the high intensity of solar radiation which requires a serious attention towards finding effective strategies to control Daylighting and achieve both visual and thermal comfort.

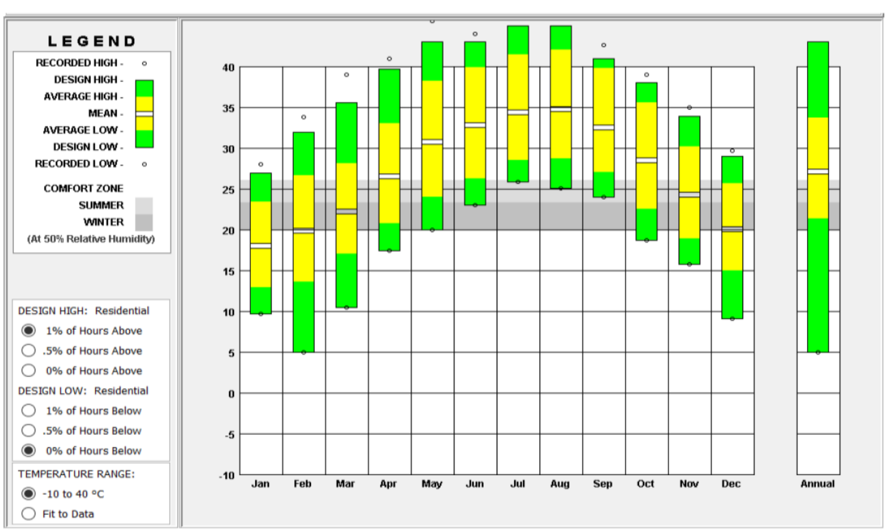


Figure 41: Temperature Range in Sharjah, UAE

Wettest month (with highest rainfall) is **February** (35.7mm). Driest month (with lowest rainfall) is **June** (0mm).

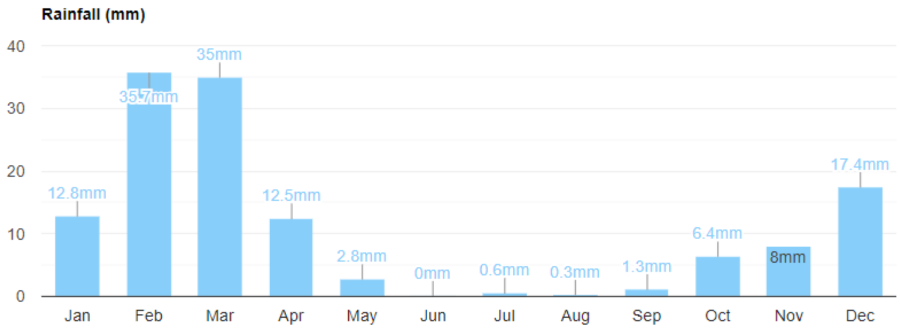


Figure 42: Rainfall Percentage per month in Sharjah UAE

The soalr irradiance (radiant exposure) is at its highest between May and August and reaches its peak in June with around 1155 Wh/m^2 per hour.

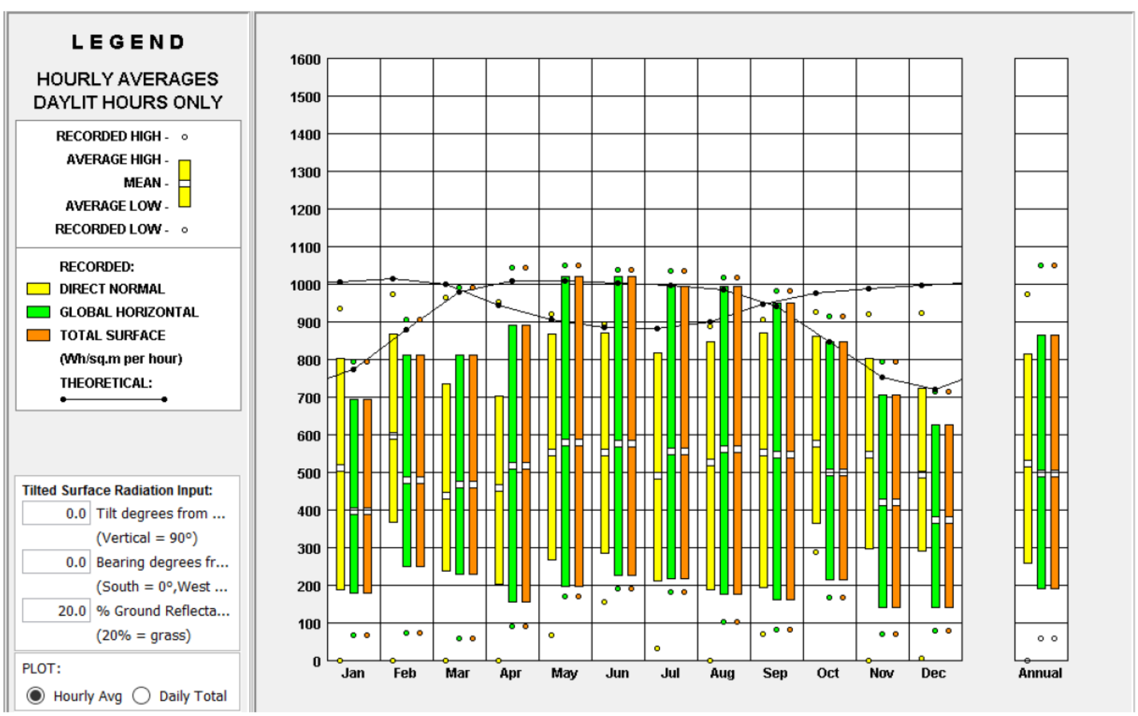


Figure 43: Solar Irradiance at Sharjah City UAE

The following figure represents the sun path which indicates sun locations at sunrise, specified time and sunset. The building is site oriented not sun oriented. The main façade is oriented towards Northeast providing a cool environment and less solar radiation, the right façade is completely blocked by the nearby building (fully shaded), the left façade facing the main entrance road and the green space in front, and the back elevation has the back entrance that leads to the parking lots and it has shaded waiting area with seats. Any type of shading happening due to nearby buildings will be ignored in simulations.

The back and left façades receive the highest amount of noises since they are directly facing roads and cars parking. Summer winds hit the two exposed facades, while the winter winds affect mainly the left and front elevations.

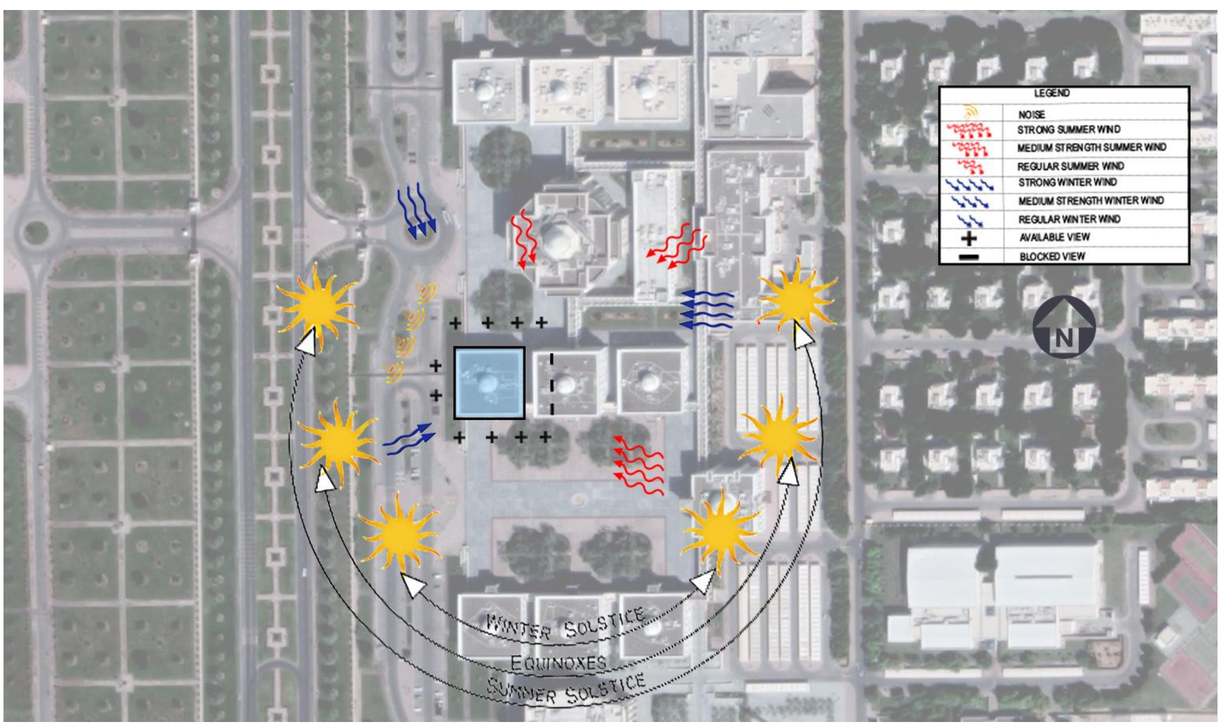


Figure 44: Site Analysis (Sun Path, Wind, Visibility) at University of Sharjah

3.3. Building chosen overview

University of Sharjah was established in 1998 under the patronage of Sheikh Dr.Sultan AlQassimi, Member of the Supreme Council and Ruler of Sharjah, the supreme leader of the University of Sharjah and the American University of Sharjah. It is located in the Emirate of Sharjah and is approximately 13 km away from Sharjah City Center.

The chosen building is the Architectural Engineering Department (also known as M8) is one of the largest university departments in the United Arab Emirates. The building is in the center of the university's campus near to the main entrance and within the main university building area. It has views from three sides, front elevation facing the main campus entrance courtyard, the back entrance facing the colleges courtyard and left elevation is facing the sub road leading to the campus entrance.

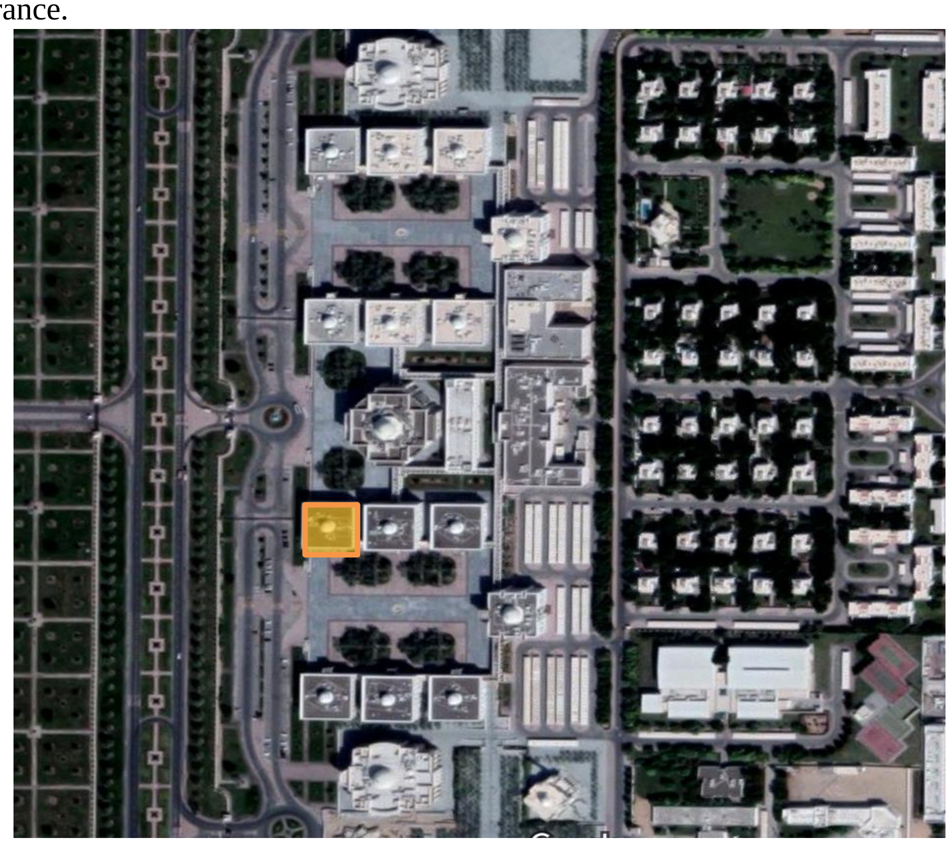


Figure 45: Architectural Department Location within University of Sharjah Campus

The measurements were taken of all windows on the dome drum, as well as the measurements of the hall and corridors to insert them later in Revit to create a model for simulations.

The windows type is uncoated double glazing, the glass is without coating and has aluminum frames with dimensions of (915 mm x 1220 mm). Those windows aluminum frames are quite strong, lightweight, and almost maintenance free, conducting heat very quickly since aluminum is a very poor insulating material. The dome consists of 20 windows with 1.95m spacing between windows.

Figure 46: Dome and openings in M8 Building

The dome has a radius of 9.00m (diameter of 18.0m), drum height (the cylinder that the dome is laying on and where windows are placed in) is approximately 2.00m and dome height is around 8.80m, as seen in figure 47.

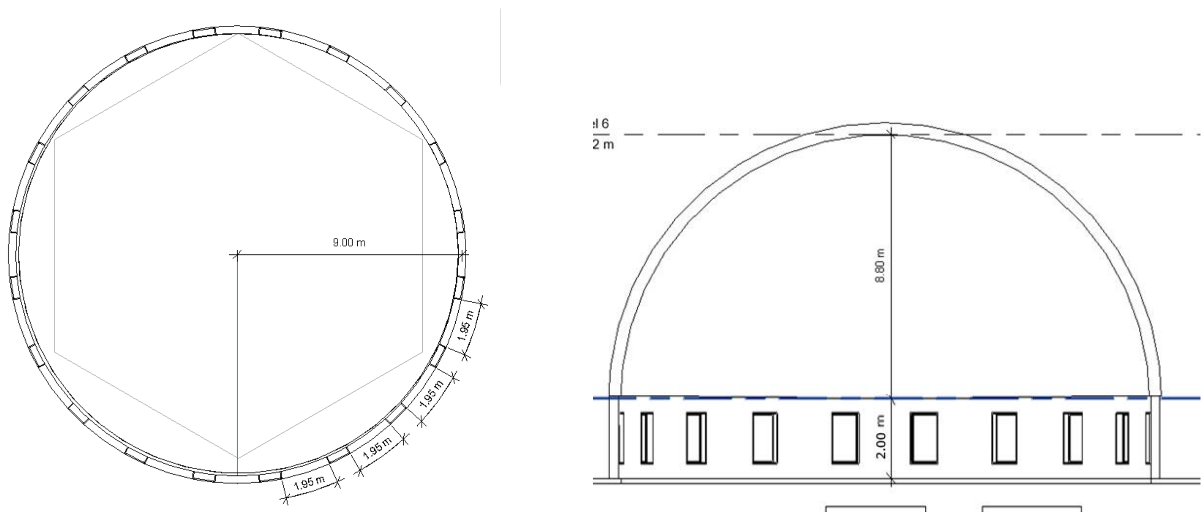


Figure 47: Dome and drum dimensions

Figure 48 shows the dimensions of building envelope and inner spaces for ground and first floor within the building.

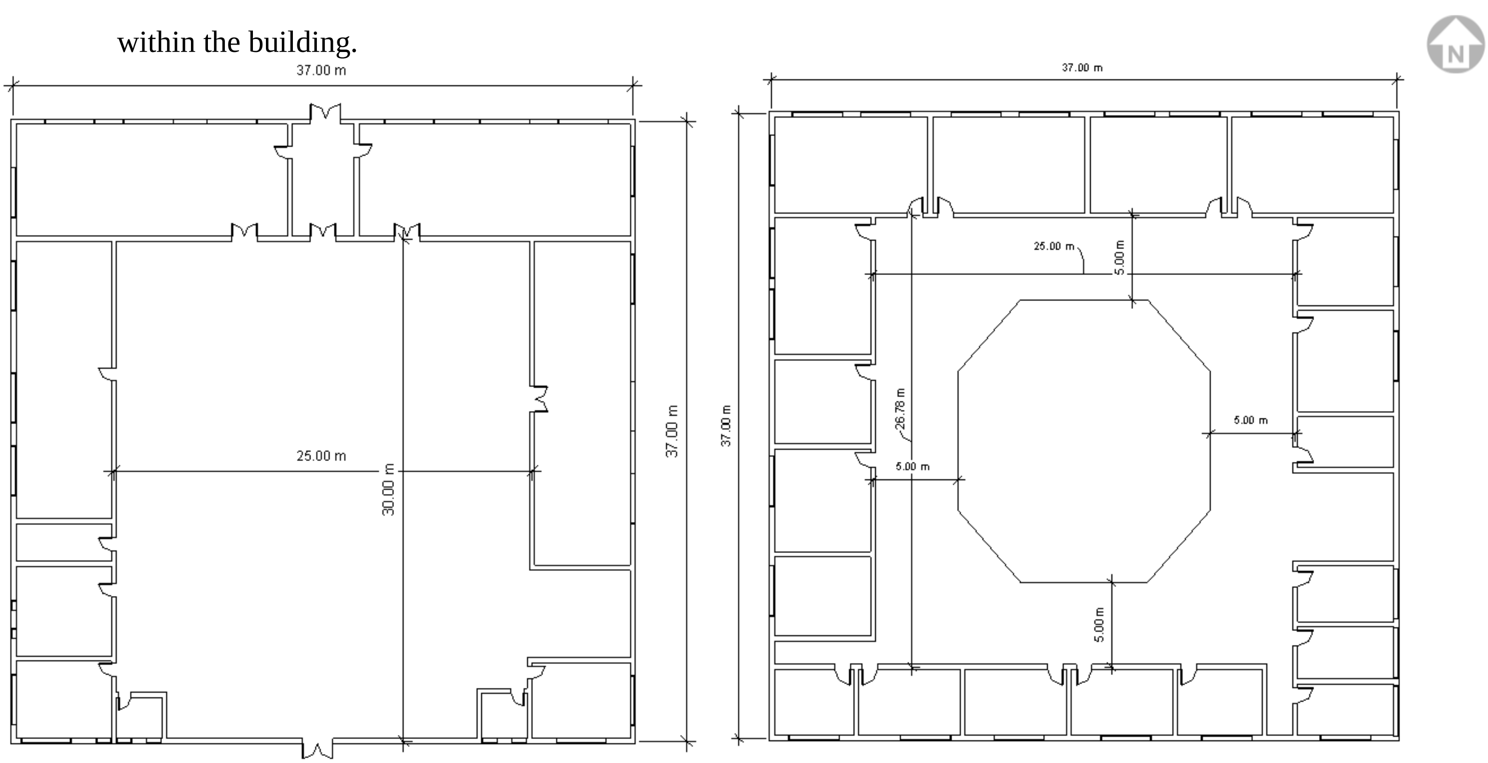


Figure 48: M8 ground and first floor (ground left, first right)

3.4. Computer simulation

The computer software was used to illustrate and model the building as well as the scenarios proposed using REVIT, and later on each case/scenario was analyzed using IES+Radiance and Revit+Insight. Simulations will be done on 21 June, 21 Sep, 21 Dec at 8:00 am, 12:00 pm and 4:00 pm, these timings of the year are the most appropriate to test in different sun altitude, 21 June (Summer Solstice) is when the sun is at the highest point in sky and being longest day of the year, 21 December (Winter solstice) where the solar altitude will be at its minimum and having shortest day in the year and 21 September (equinox) day and night of equal length so it's in between 2ljune and 21 December and the timings chosen are the sunrise with low sun angle on east at 8:00 am, mid of day when sun is at its highest 12:00 pm, and before sunset with low sun angle on west at 4:00pm. Another reason to choose these timings is that these are times when students are using the building. 8:00 am is the arrival timing, 12:00 pm is the design studio timings and training, 4:00 pm is the end of design classes and start of brainstorming sessions in the lobby area.

3.4.1. Software Use and Information

Two software were used in the simulations Revit with INSIGHT plugin to get illuminance (LUX), Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), IES with Radiance plugin to get Daylight Glare Probability (DGP) and Glare Threshold Differential (GTD). Two software were used since IES+Radiance is time consuming when it comes to sDA and ASE analysis (one simulation takes up to 6-8 hours) while in Revit+Insight it takes 4 -5 minutes, but Revit+insight doesn't calculate glare.

REVIT + INSIGHT PLUGIN:

Revit is a building information modelling software for engineers architects which give them the possibility to model their designs in 3D format, adding actual materials and components, run analysis in different disciplines (daylight, HVAC, structure, plumbing ,…), it also allow to annotate the designs with 2D drafting elements, and applying building information from the database of the building to ensure accuracy and nearest results to real life. In order for Revit to run the daylight analysis, it uses the Insight plugin which is a very powerful software created by Autodesk to enhance the Revit capabilities. Insight is a strong building performance analysis software from Autodesk. The software makes it possible to get details about different solar and daylight metrics, energy and lighting analysis creating very accurate results using advanced simulation engines that give them power to make smart, data driven design options. ("Autodesk Revit" 2019).

USE IN THESIS: Revit will be used to model the building in its different scenarios to later be imported into other software to get simulations results. Insight plugin is used to find out the illumination level (LUX) to measuring luminous flux per unit area. Also to measure Spatial Daylight Autonomy (sDA) to indicate how much of the room gets adequate daylighting annually, it gives the floor area percentage which receives at least 300 lux for 50% of annually utilized hours and another metric which is Annual Sunlight Exposure (ASE) indicating how much of the room gets extensive direct daylight that can lead to visual discomfort (glare), it shows the floor area percentage which gets at least 1000lux for 250 occupied hours in a year.

IES + RADIANCE PLUGIN:

Integrated Environmental Solutions (IES) is an energy analysis and performance modeling software which gives ability for users to test variety of options and designs and evaluate multiple building performance workflows. IES gives the opportunity to test sustainable building approaches and analysis. It has the ability to use worldwide assessment tools such as LEED and BREEAM credits and generate full reports highlighting if the design follow requirements or not throughout the design process. It can as well record the building's performance throughout its lifecycle. ("Integrated Environmental Solutions FAQ | Vectorworks" 2019). Radiance is a software and plugin used to generate lighting simulation created by Greg Ward. It has several tools to measure lighting levels for different simulated scenarios as well as a renderer drive to create 3D views and contour colours images. It has ray tracing to run all lighting calculations, generated by the use of an octree data structure. It's one of the first softwares that uses high dynamic range imaging, where light levels are (theoretically) open ended values rather than a decimal proportion or integer fraction of a maximum. It also integrates global illumination with the use of the MonteCarlo process to analyze light reaching a point. ("Radiance — Radsite" 2020)

USE IN THESIS: IES with RADIANCE plugin will be used to get Daylight Glare Probability (DGP) and Glare Threshold Differential (GTD) to check the visual discomfort percentage in space. DGP is a glare indicating metric used in predicting the existence of discomfort glare in daylighted areas. GTD gives a value of glare discomfort by getting the difference between the maximum luminance that the viewer is looking at with the threshold of the view dividing it by the same threshold at the same timing multiplied x100 to get the percentage of GTD (Humaid.A, 2019). Further explanation can be found in section 3.4.3. Simulation scenarios - Case3: Glare.

3.4.2. Controlled Variables to be modified

This paper will be testing several variables as well to check their effect on measured variables (ASE, sDA, Illuminance , glare). The controlled variables will be the dome's diameter, drum's height and $S_{windows}$ (W_{area}/ D_{area}). The explanation for each controlled variable will be done shortly. The simulation will be done for 3 different diameters each with 3 different heights and 4 different glazing percentages. This will be 36 models to be simulated in different timings depending on the measured variable tested. The existing building will be the case with diameter =18.0m, drum height = 2.0 m and $S_{windows}$ = 15%.

<u>1) Dome's Diameter:</u>

A. Diameter = 7.0 m

B. Diameter = 14.0 m

C. Diameter = 18.0 m

The daylight coming from the dome will be recorded with the adjustments of the dome's diameter. This will give an idea if dome diameter as a parameter has an effect on visual comfort within space and how much it contributes. The increase of dome diameter is limited since it will be exceeding the roof boundaries and the lobby limits. The scenario will be modeled in Revit and then place it in several software to get the glare, illuminance and sDA and ASE to evaluate the results. The diameter of the dome will be adjusted and tested to three cases. First is diameter of 7.0 m, the second will be increasing the diameter up to 14.0m and third will be the current situation with diameter of 18.0m.

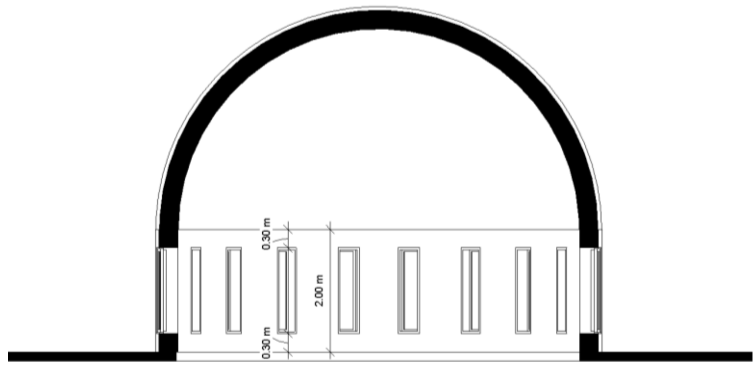
2) Dome’s drum height

A. Drum Height = 2.0 m (sill height = 0.3m)

B. Drum Height = 3.0 m (sill height = 0.8 m “0.3 m + 0.5 m”)

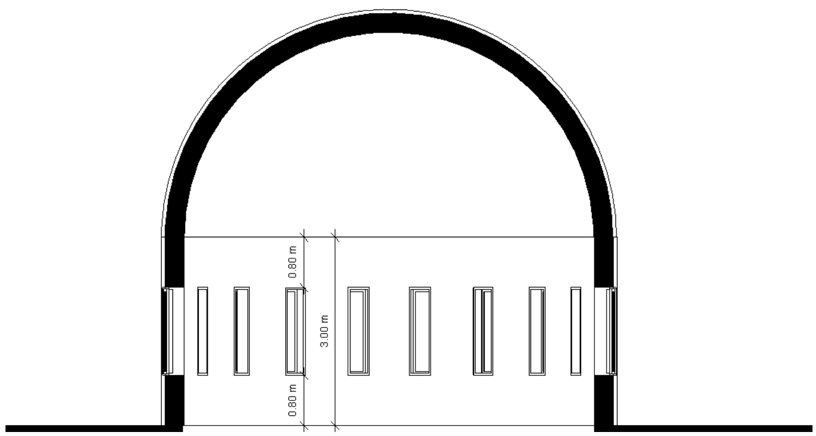
C. Drum Height = 4.0 m (sill height = 1.3 m “0.3m + 1.0 m”)

The daylight coming from the dome will be recorded with the adjustments of the dome’s drum height. The dome’s drums will increase from 2.0m up to 3.0 m and 4.0 m, some adjustments on windows position vertically and dimensions will be tested as well. The windows to be located in the middle of the drum whenever the drum height is adjusted. The scenario will be modeled in Revit and then place it in several software to get the glare, DF, illuminance and sDA and ASE to evaluate the results. Three tests will be made, existing situation with drum height of 2.0m and sill height of 0.3m (figure 49-A), second with drum height of 3.0 m (+1.0m) and sill height of 0.8m to make it in the middle of drum (figure 49-B) and third with drum height of 4.0m (+2.0 m) and sill height of 1.3m to make it in the middle of drum (figure 49-C). The figures shown below represent the drum height for case of diameter 7.0m and glazing percentage of 10%, these diagrams are only to clarify the position of glazing when height is changing, it will be always be in the center of the drum.



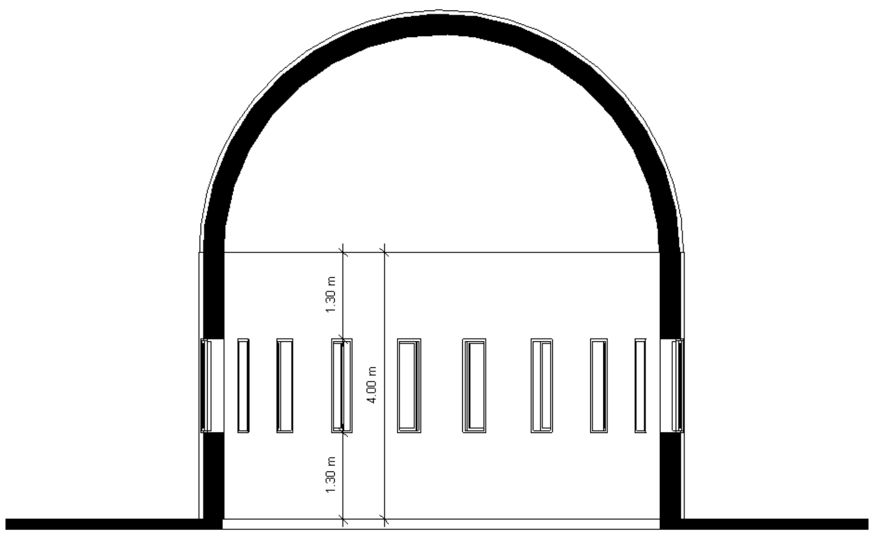
(A)

Figure 49 - A : Dome’s drum height of 2.0 m (D=7m, Swindow=10%)



(B)

Figure 50 - B : Dome’s drum height (3.0 m) (D=7m, Swindow=10%)



(C)

Figure 51 - C : Dome’s drum height (4.0 m) (D=7m, Swindow=10%)

3) S windows (W area/ D area)

A. 10%

B. 15%

C. 25%

D. Full glazing

Last case will be modifying the amount of glazing in the dome by adding more windows and enlarge the windows size or make the dome entirely glazing. The existing case has a window area to drum area = 15%, the cases will be having 10% of dome made out of glass, second will be with the drum being 15% made out of glass, third where quarter of the drum is made out of glass (25%) and a scenario where the drum is entirely made of glass will be simulated as well allowing in the maximum amount of natural light. The scenario will be modeled in Revit and then place it in several software to get the glare, DF, illuminance, sDA and ASE to evaluate the results. The percentage was calculated by dividing the amount of glazing in the drum on overall area of drum, the drum was chosen to be tested instead of the full dome and you mentioned that having the dome glazed will cause more variables from angle, height and position of the windows within the dome so we decided to do it for drum only, also because in the real case the windows were on the drum not dome. To clarify more, the following figure shows the percentage glazing of 10% in all diameter and height cases, as well as table 7 showing the exact calculation that have been done to get the percentages (Drum area and glazing area used in simulation to get the percentages tested) .

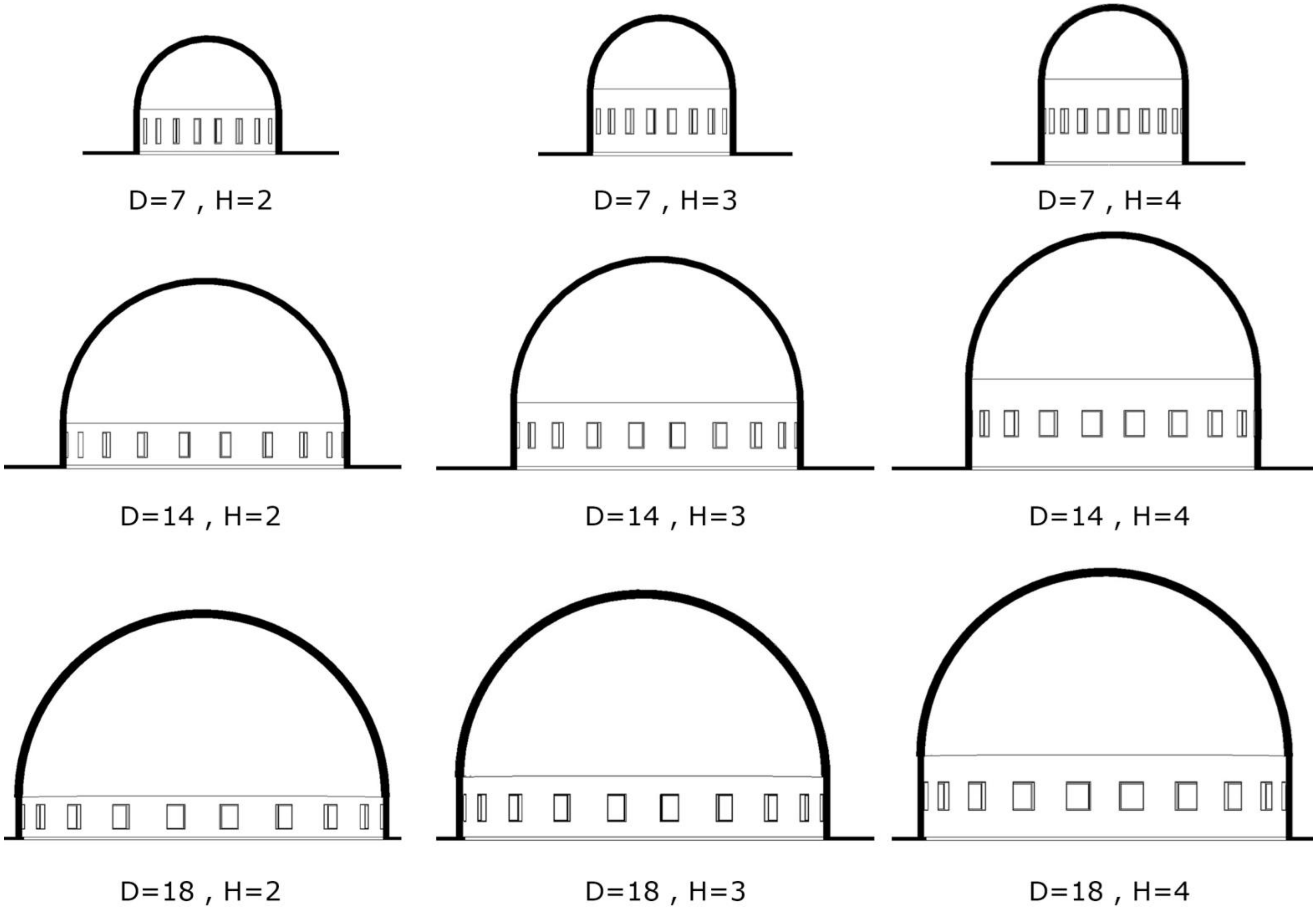


Figure 52: The different cases with 10% glazing percentage

Table 7: Drum area and glazing area used in simulation to get the percentages tested

	Drum Area	Glazing Area (m^2)	Percentage
Dome Diameter = 7m Drum Height = 2m	22.943	2.29	10%
	22.943	3.44	15%
	22.943	5.74	25%
	22.943	22.94	100%
Dome Diameter = 7m Drum Height = 3m	34.4	3.44	10%
	34.4	5.16	15%
	34.4	8.6	25%
	34.4	34.4	100%
Dome Diameter = 7m Drum Height = 4m	45.867	4.59	10%
	45.867	6.88	15%
	45.867	11.47	25%
	45.867	45.87	100%
Dome Diameter = 14m Drum Height = 2m	43.354	4.34	10%
	43.354	6.50	15%
	43.354	10.84	25%
	43.354	43.35	100%
Dome Diameter = 14m Drum Height = 3m	65.031	6.50	10%
	65.031	9.75	15%
	65.031	16.25	25%
	65.031	65.00	100%
Dome Diameter = 14m Drum Height = 4m	86.708	8.67	10%
	86.708	13.00	15%
	86.708	21.68	25%
	86.708	86.71	100%
Dome Diameter = 18m Drum Height = 2m	57.491	5.75	10%
	57.491	8.62	15%
	57.491	14.37	25%
	57.491	57.49	100%
Dome Diameter = 18m Drum Height = 3m	86.237	8.62	10%
	86.237	12.96	15%
	86.237	21.56	25%
	86.237	86.23	100%
Dome Diameter = 18m Drum Height = 4m	114.982	11.50	10%
	114.982	17.25	15%
	114.982	28.75	25%
	114.982	115.0	100%

3.4.3. Simulation Scenarios/Cases (Measured Variables)

The simulation scenarios / Cases that will be investigated are the following:

Case 1: Annual Variables

This case will measure two variables annually which are sDA and ASE. SDA values answer the question "Is There Enough Daylight?" An sDA value of 75% means that the space gets an amount of daylight "preferred" by occupants; in another words, occupants will be working comfortably without having to use artificial lighting and the usage of daylight will be highly sufficient. Although sDA doesn't include glare or direct sun exposure, it has been proved to be reliable in predicting occupants' satisfactory by giving a value for percentage of the space. It ranges from 0%-100% of floor area. (Approved Method: IES Spatial Daylight Autonomy and Annual Sunlight Exposure 2013)

ASE is meant to complement sDA, it represents the annual number of hours in which direct daylight is incident on a surface and cause potentially discomfort, glare or increasing cooling load. ASE records the existence of daylight using annual hourly horizontal illuminance grids instead of luminance measures. The main objective of this metric is to assist the designers in reducing the over-lit condition in space (Architectural lighting 2016).

The term $sDA_{300/50}$ (>300 lux, >50% of year) is presenting the floor area percentage getting over 300 lux for 50% of 3650 annual hours (LEED points are earned for values between 55%-75% of area). $ASE_{1000/250}$ is presenting the floor area percentage getting over 1000 lux for more than 250/3650 annual hours. An sDA value between 55-75% means that the space has amount of daylight "nominally accepted" by occupants. (Approved Method: IES Spatial Daylight Autonomy and Annual Sunlight Exposure 2013)

Therefore, results should reach sDA values of 75% or above in order to achieve the requirements for sufficient daylight as per LEED. To reduce the potential for glare, designers must have low ASE values. ASE values that exceed 10% will increase possibilities of visual discomfort to happen, LEED stated that only areas in rooms with ASE<20% room area can qualify. In another words, as per LEED V4 having ASE value less than 10% means is perfect for occupants satisfactory and comfort, a value between 10% and 20% means potential for glare, and having a value higher than 20% means too brightly illuminated (overlit). The time range for sDA and ASE will be from 1st January to 31st December (8:00am–6:00pm) which is equal to a total of 3650 hours. Several papers and journals have used these two variables to evaluate educational building daylight.

A.Pellegrinoa and S.Cammaranoa in their research proposing some recommendation for daylight as a part of green schools strategy focusing on indoor quality and energy efficiency in educational facilities, clarifying and investigating a way to enhance daylight in classrooms by testing the performance indicators based on LEED protocols which ask for calculation of the Spatial Daylight Autonomy ($sDA_{300/50}$) and Annual Sunlight Exposure ($ASE_{1000/250}$), these two new daylighting metrics were recently proposed by the Illuminating Engineering Society of North America (I.E.S.N.A). (Pellegrino, Cammarano and Savio 2015)

M. Trudeau, C. Li in their paper “models for Daylighting Autonomy for LEEDV4” discuss the degree to which daylight performance is affected by latitude and weather using simulations to generate the sDA values within floor area and get the percentage of which the room area reaches illuminance levels of 300lux for more than 50% of utilized hours between 8AM and 6PM, as specified by LEED v4 and IES LM 83-12. (Trudeau, Li and Frisque 2018)

V. Costanzo and G. Evola were discussing relationships between local climate, occupants’ need and design restrictions in schools by displaying several methodologies implemented and technology solutions recommended. For Assessing Daylight Exploitation according to multiple regulations, the average illuminance level in classes must stay higher than 300lux that’s why they decided to use spatial Daylight Autonomy (sDA), to indicate floor area percentage that is within the range of recommended illuminance levels annually per hour (50% of hours 8:00am-6:00pm). Because sDA doesn't indicate an upper threshold for daylighting illuminance, the calculations have to be along with the evaluation of Annual Sunlight Exposure (ASE) a value of (1000 lux) for a specified number of hours annually (250h). (Costanzo and Evola 2017)

<u>Case 2: Light Properties</u>

This case measures the illuminance level (lux) in different dates and timing around the year. The simulation will be done on 21 June – 21 Sep – 21 Dec at timings 8:00am – 12:00pm – 4:00pm. At 8:00 am is the arrival timing, 12:00 pm is the design studio timings and training, 4:00 pm is the end of design classes and start of brainstorming sessions in the lobby area. From literature review, several research papers such as:

- Arab, Y. and Sanusi, A. (2012). Daylighting Analysis of Pendentive Dome's Mosque Design during Summer Solstice with Casestudies in Istanbul, Turkey. *International Transaction Journal of Engineering*, vol. 1 (1).

- Aljofi, E. (2018). The Potentiality of Domes on Provision of Daylight in Mosques. *International Journal of Applied Engineering Research*, vol. 13 (7).

- Hassan, A. and Arab, Y. (2014). Reliability of Computer Simulation on Illuminance Level of Pendentive Dome Mosque in Comparison with On-Field Data Collection. *Modern Applied Science*, vol. 8 (2).

have used a Measurable scale of indoor lighting performance which evaluate and highlight recommended ranges of minimal illuminance levels. What is recommended is around 200-500lux to have good visibility with normal brightness for reading or using computer and around 2000 lux for highly demanding work and tasks that demand high visibility like drawing small details, this parameter will be used in the research to evaluate illuminance level.

Case 3: Glare

Glare will be investigated using two metrics which are daylight glare probability (DGP) and Glare Threshold Differential (GTD). From literature review, the Daylight Glare Probability (DGP) index is known as one of the most reliable metrics when it comes to light analysis because the process of driving it came from experiments with actual human subjects. DGP is newest and recently metric used for evaluation of glare due daylighting, it recognizes the glare coming from the direct daylight falling on work place and the reflections from surfaces as well. This metric is considering most aspects and factors participating in causing visual discomfort compared to other metrics. It can predict the presence of discomfort glare in the space even without having significant visual contrast. DGP solved several issues that Hokinson had when he was creating the DGI metric by adding several variables within the equation which included adding other sources to glare rather than only direct light from sky, which is something that wasn't done by any previous metric. A.Humaid in his paper (Comparative analysis of daylight glare metrics) proposed the GTD metric is as a new metric to evaluate the glare within a space (Humaid,A. 2019). DGP considers contrast and vertical illuminance as contributors to visual discomfort, GTD gives a value of glare discomfort by differentiating the maximum luminance that the viewer is looking at with the threshold of the view, threshold received from the software is calculated by the software to be seven times the average luminance level. (IES,"Glare" 2018). Glare is a function of the location of the viewer and the observation direction. Therefore, simulations will be taking in several locations. The simulation will be running on two days 21 June and 21 December at 8:00am, 12:00pm and 4:00pm testing 15 points each point looking horizontally in four directions as shown in figure 54.

The case that would be tested is the case with diameter = 14m, drum height = 4.0 m and drum fully glazed (as shown in figure53).

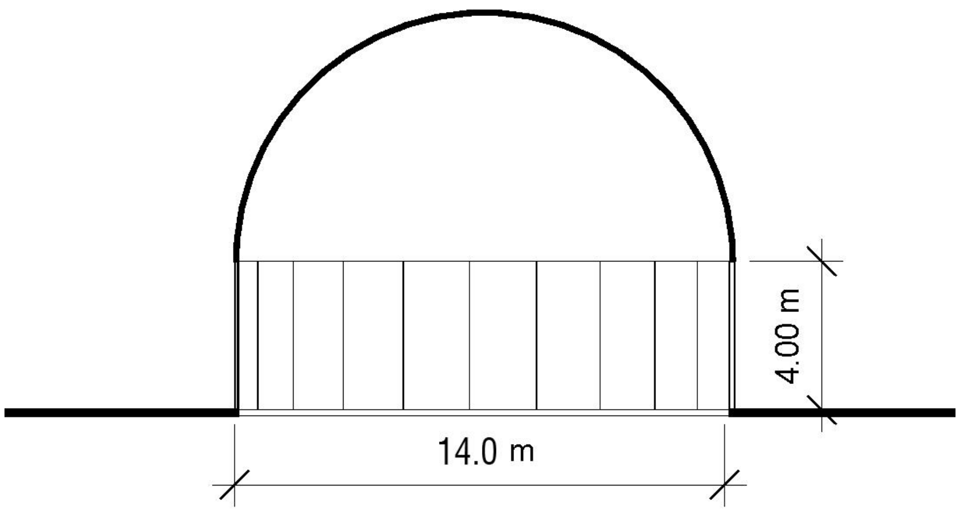


Figure 53: Case with diameter = 14m, drum height = 4.0 , Glazing percentage =100%

Glare threshold differential will be calculated as per the following equation (Humaid,A. 2019).:

$$Glare\ Threshold\ differential = \frac{Highest\ luminance\ level - Threshold\ level}{Threshold\ level}\ x\ 100\%$$

Table 8 shows the evaluation of the glare depending on the value that software will be given.

Table 8:Glare rating for glare metrics (GTD, DGP) (Humaid,A. 2019)

Degree of Glare	DGP	GTD Range
Imperceptible	Less than 35%	Less than 25% (Including negative numbers)
Perceptible	35% - 40%	25% - 80%
Disturbing	40% - 45%	80% - 300%
Intolerable	Above 45%	Greater than 300%

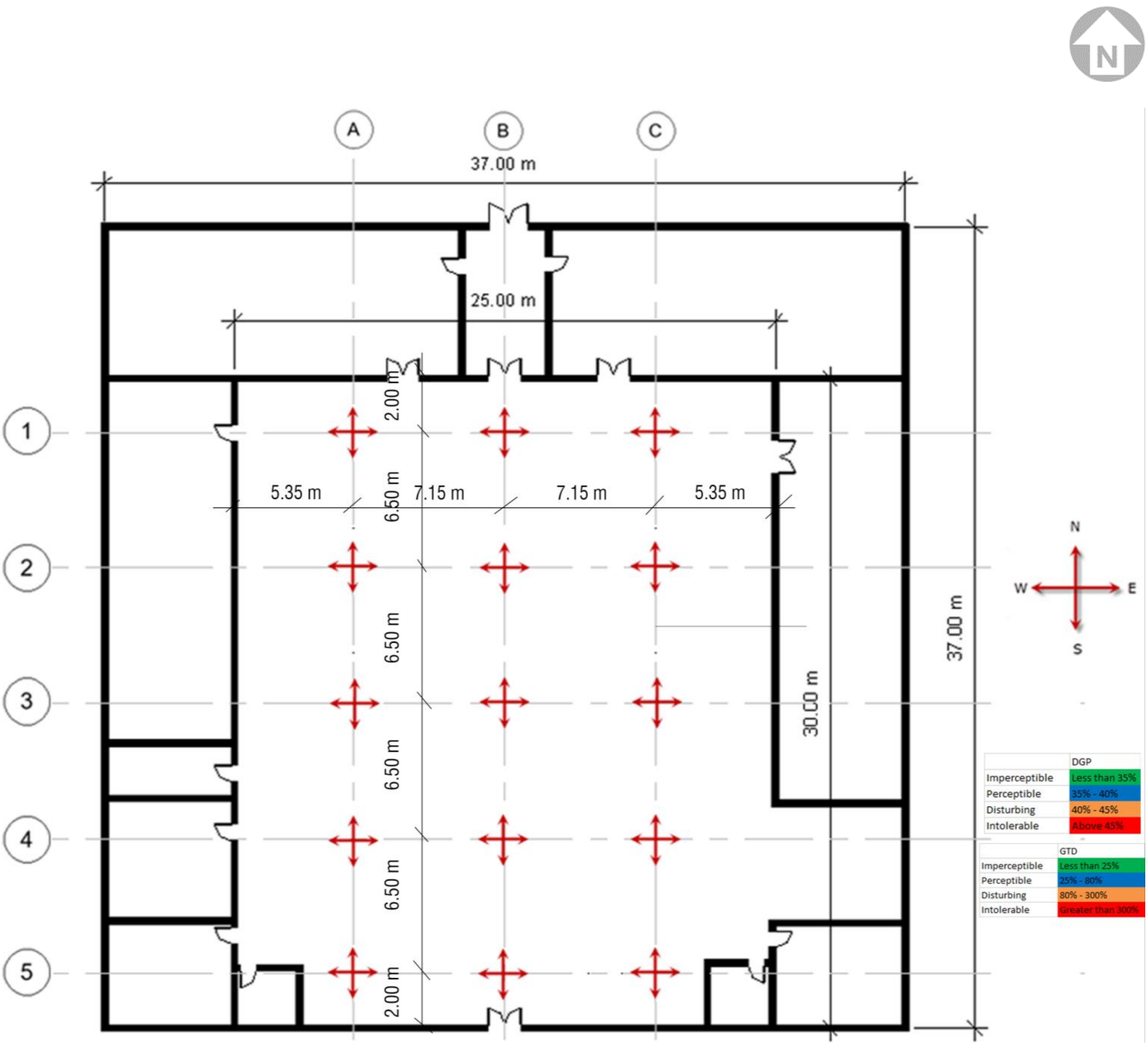


Figure 54: Location where the glare measurements will be taken and the observer direction

<u>Summarized measured variables Table per Case:</u>

Table 9: Simulations measured variables Table

Fixed Variables for all cases	Case Number	Case variables
1) Room Dimensions Height = 7.50 m Width = 37.0 m Length = 37.0 m 2) Wall Material and Reflectance= Paint Varnish - 50%	Case 1 = **Annual Variables**	1) $sDA_{300/50\%}$ 2) $ASE_{1000/250}$ Simulation Day and Time: **Annual**
3) Floor Material and Reflectance = Tile Porcelain Ceramic - 20% 4) Ceiling Material and Reflectance = Ceiling tile 600x 600 - 80%	Case 2 = **Light properties**	1) Illuminance level (lux) Simulation Day and Time: **21 June – 21 Sep – 21 Dec** **8:00am – 12:00pm –4:00pm**
5) Dome location within space 6) Simulations working plane was placed on a height of 0.80 from floor (desk height).	Case 3 = **Glare**	1) Daylight Glare Probability (DGP) 10) 2) Glare Threshold Differential (GTD) Will be taking in several locations. Simulation Day and Time: **21 June –21 Dec** **8:00am -12:00pm – 4:00pm**

The **table sample** that will be used to present simulation results for Case 1: Annual Variables and Case2:Light properties which can be found fully filled in the Appendix having Case1: **Appendix D** and Case2: **Appendix A :**

Table 10: Simulation Results for Case 1 (sDA + ASE) and Case 2 (Illuminance)

Date and Time: -------			
Diameter	Height of Drum	S windows (W area/ D area)	Variable
7.0	2.0 (sill height = 0.3 m)	10%	
		15%	
		25%	
		100%	
	3.0 (sill height = 0.8 m)	10%	
		15%	
		25%	
		100%	
	4.0 (sill height = 1.3 m)	10%	
		15%	
		25%	
		100%	
14.0	2.0 (sill height = 0.3 m)	10%	
		15%	
		25%	
		100%	
	3.0 (sill height = 0.8 m)	10%	
		15%	
		25%	
		100%	
	4.0 (sill height = 1.3 m)	10%	
		15%	
		25%	
		100%	
18.0	2.0 (sill height = 0.3 m)	10%	
		15%	
		25%	
		100%	
	3.0 (sill height = 0.8 m)	10%	
		15%	
		25%	
		100%	
	4.0 (sill height = 1.3 m)	10%	
		15%	
		25%	
		100%	

The **table sample** that will be used to present simulation results for Case 3 (GLARE) which can be found fully filled in the **Appendix B** :DGP and **Appendix C**: Glare Threshold :

Table 11: Simulation Results for Case 3 (Glare)

Date and Time: -------					
Location	Direction	DGP (%)	Threshold (cd/m^2)	Max Luminance (cd/m^2)	GTD (%)
A1	N				
	S				
	E				
	W				
A2	N				
	S				
	E				
	W				
A3	N				
	S				
	E				
	W				
A4	N				
	S				
	E				
	W				
A5	N				
	S				
	E				
	W				
B1	N				
	S				
	E				
	W				
B2	N				
	S				
	E				
	W				
B3	N				
	S				
	E				
	W				
B4	N				
	S				
	E				
	W				
B5	N				
	S				
	E				
	W				
C1	N				
	S				
	E				
	W				
C2	N				
	S				
	E				
	W				
C3	N				
	S				
	E				
	W				
C4	N				
	S				
	E				
	W				
C5	N				
	S				
	E				
	W				

CHAPTER 4: Results Analysis and Discussion

CHAPTER 4: Results Analysis and Discussion

The final results were achieved after analyzing the indoor light level coming from the dome of the selected building. Results from computer simulation will be discussed shortly.

4.1. Computer simulation

This paper will be testing several variables as well to check their effect on measured variables (ASE, sDA, Illuminance , glare). *Case 1: Annual Variables* : $sDA_{300/50}$ and $ASE_{1000/250}$, the time range will be annually from 1st January - 31st December (8:00am – 6:00pm) **.** *Case 2: Light Properties:* The illuminance level (lux) simulation will be done on 21 June – 21 Sep – 21 Dec at timings 8:00am – 12:00pm – 4:00pm. *Case 3: Glare :* Glare will be investigated as daylight glare probability (DGP) and Glare Threshold Differential (GTD). Glare is a function of the location of the viewer and the observation direction. Therefore, simulations will be taking in several locations. The simulation will be running on two days 21 June and 21 December at 8:00am, 12:00pm and 4:00pm testing 15 points each point looking horizontally in 4 directions as shown in figure 54. The case that would be tested is the case with diameter = 14m, drum height = 4.0 m and drum fully glazed as being the worst-case scenario for glare. Simulation will be taken on a height of 0.80 from floor. Table12 summarizes the cases and what variables that will be tested in each.

Table 12: Cases tested and the simulated variable per case

<table>
<tr><th>Fixed Variables for all cases</th><th>Case Number</th><th>Case variables</th></tr>
<tr><td rowspan="3">1) Room Dimensions
Height = 7.50 m Width = 37.0 m
Length = 37.0 m

2) Wall Material and Reflectance=
Paint Varnish - 50%

3) Floor Material and Reflectance =
Tile Porcelain Ceramic - 20%

4) Ceiling Material and Reflectance =
Ceiling tile 600x 600 - 80%
5) Dome location within space

6) Simulations working plane was placed on a height of 0.80 from floor.</td><td>Case 1 = Annual Variables</td><td>1) $sDA_{300/50\%}$
2) $ASE_{1000/250}$
Simulation Day and Time:
Annual</td></tr>
<tr><td>Case 2 = Light properties</td><td>1) Illuminance level (lux)
Simulation Day and Time:
21 June – 21 Sep – 21 Dec
8:00am – 12:00pm –4:00pm</td></tr>
<tr><td>Case 3 = Glare</td><td>1) Daylight Glare Probability (DGP)
2) Glare Threshold Differential (GTD)
Will be taking in several locations.
Simulation Day and Time:
21 June –21 Dec
8:00am -12:00pm – 4:00pm</td></tr>
</table>

4.1.1. Case 1: Annual Variables

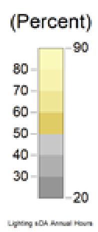
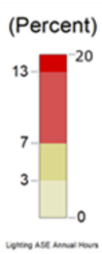
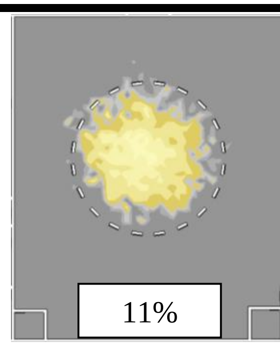
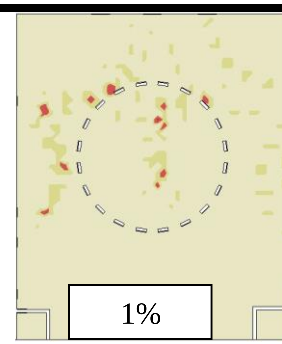
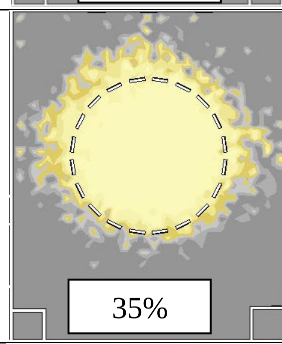
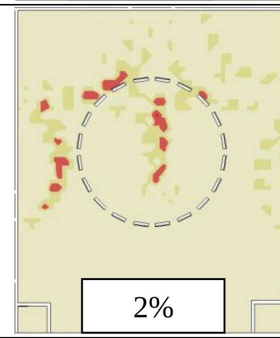
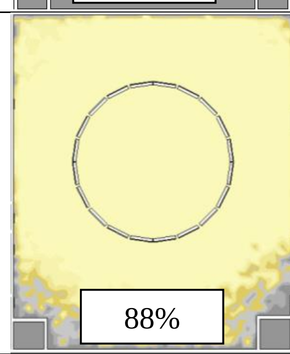
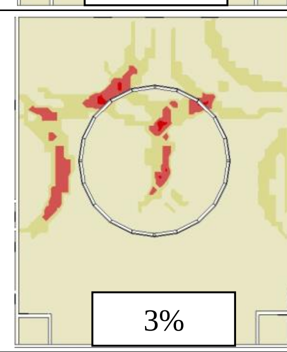
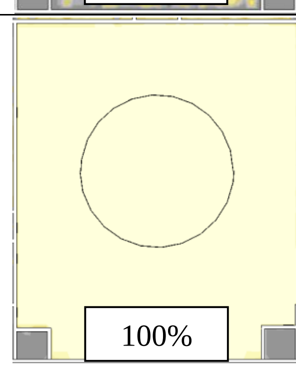
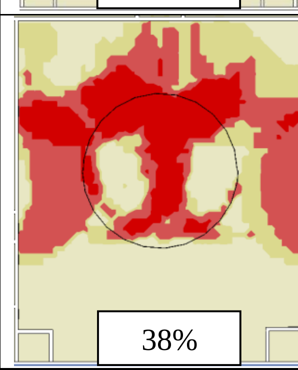
$sDA_{300/50}$ and $ASE_{1000/250}$, will be calculated from 8:00 am till 6:00 pm from 1st January till 31st December which is around 3650 hours._The term $sDA_{300/50}$ (>300 lux, >50% of year) is presenting the floor area percentage getting over 300 lux for 50% of 3650 annual hours (LEED recommend values between 55%-75% of area). $ASE_{1000/250}$ is presenting the floor area percentage getting over 1000 lux for more than 250/3650 annual hours. The following table13 demonstrates the results for sDA and ASE simulations, they will be discussed and analyzed shortly. Table 14 shows a sample of SDA and ASE results for (D=14, H=4, S=10,15,25,100). The rest of the results can be found in **Appendix D - Annual Variables Results (SDA and ASE).**

Table 13: Case 1 (Annual Variable) SDA and ASE simulation results

Date and Time: Annual

Diameter	Height of Drum	S windows in drum (W area/ D area)	SDA	ASE
7.0	2.0 (sill height = 0.3 m)	10%	0	0
		15%	0	0
		25%	0	1
		100%	81	8
	3.0 (sill height = 0.8 m)	10%	0	0
		15%	9	1
		25%	16	1
		100%	96	12
	4.0 (sill height = 1.3 m)	10%	3	0
		15%	18	1
		25%	27	1
		100%	97	16
14.0	2.0 (sill height = 0.3 m)	10%	0	0
		15%	9	0
		25%	67	1
		100%	100	20
	3.0 (sill height = 0.8 m)	10%	3	0
		15%	27	1
		25%	76	2
		100%	100	28
	4.0 (sill height = 1.3 m)	10%	11	1
		15%	35	2
		25%	88	3
		100%	100	38
18.0	2.0 (sill height = 0.3 m)	10%	0	0
		15%	29	1
		25%	75	3
		100%	100	30
	3.0 (sill height = 0.8 m)	10%	10	1
		15%	45	1
		25%	84	4
		100%	100	43
	4.0 (sill height = 1.3 m)	10%	16	2
		15%	65	3
		25%	96	9
		100%	100	55

Table 14: SDA and ASE results for (D=14 , H=4, S=10,15,25,100)

<table>
<tr><td colspan="5">Date and Time: Annual</td></tr>
<tr><td>Dome Diameter</td><td>Height of Drum</td><td>S windows in drum (W area/ D area)</td><td>SDA</td><td>ASE</td></tr>
<tr><td rowspan="4">14.0

</td><td rowspan="4">4.0 m
(sill height = 1.3 m)</td><td>10%</td><td></td><td></td></tr>
<tr><td>15%</td><td></td><td></td></tr>
<tr><td>25%</td><td></td><td></td></tr>
<tr><td>100%</td><td></td><td></td></tr>
</table>

SDA and ASE results discussion

SDA values answer the question "Is There Enough Daylight?" An sDA value represents if occupants will be working comfortably without having to use artificial lighting and the usage of daylight will be highly sufficient. It has been proved to be reliable in predicting occupants' satisfactory by giving a value for percentage of the space. It ranges from 0%-100% of floor area. ASE is meant to complement sDA, it represents the annual number of hours in which direct daylight is incident on a surface and cause potentially discomfort, glare or increasing cooling load. ASE records the existence of daylight using annual hourly horizontal illuminance grids instead of luminance measures. The main objective of this metric is to assist the designers in reducing the over-lit condition in space (Architectural lighting 2016). An sDA value between 55%-75% means that the space has amount of daylight "nominally accepted" by occupant. Therefore, results should get sDA values of 75% or more in order to achieve the requirements for sufficient daylight as per LEED. To reduce the potential for glare, designers must have low ASE values. ASE values that exceed 10% will increase possibilities of visual discomfort to happen, LEED stated that only areas in rooms with ASE<20% room area can qualify (Approved Method: IES Spatial Daylight Autonomy and Annual Sunlight Exposure 2013). In another words, as per LEED V4 having ASE value less than 10% means is perfect for occupants satisfactory and comfort, a value between 10% and 20% means potential for glare, and having a value higher than 20% means too brightly illuminated (overlit).

This section will be explained as following:

4.2.1.1. Effect of the increase in the diameter of the dome
  a) On ASE
  b) On sDA

4.2.1.2. Effect of the increase of the drum Height
  a) On sDA
  b) On ASE

4.2.1.3. Effect of the increase of the percentage of glazing
  a) On sDA
  b) On ASE

4.2.1.4. Best and worst cases for sDA and ASE

4.1.1.1. Effect of the increase in the diameter of the dome

a. On sDA

Comparing sDA values by increasing dome sizes and fixing height of drum and glazing percentage showed similar impact (increasing) through the cases except one case which is the case of H=2m, S=10%. Although the diameter was increased from 7m to 14m and 18m, the case with H=2m, S=10% showed no improvement with sDA value = 0%. Increasing the diameter had less effect on cases of 10% glazing comparing to other percentages. Doubling the diameter (from 7 m to 14m) had its higher impact on cases of glazing percentage =25% "increased the value of sDA more than the rest" by 60%- 67% which made the cases pass the sDA evaluation, and for the rest of the cases it increased but in a lower range 3%-19%. Increasing the diameter by 1.25 (14m to 18m) had its higher impact on cases of glazing percentage =15% "increased the value of sDA more compared to the rest cases" by 20%- 30%, it increased the rest for the cases in a lower range 0%-8% "the 0% are the cases were both sDA=100% which is the highest amount sDA could be, those cases were H=2m S=100% , H=3m S=100% and H=4m S=100%".

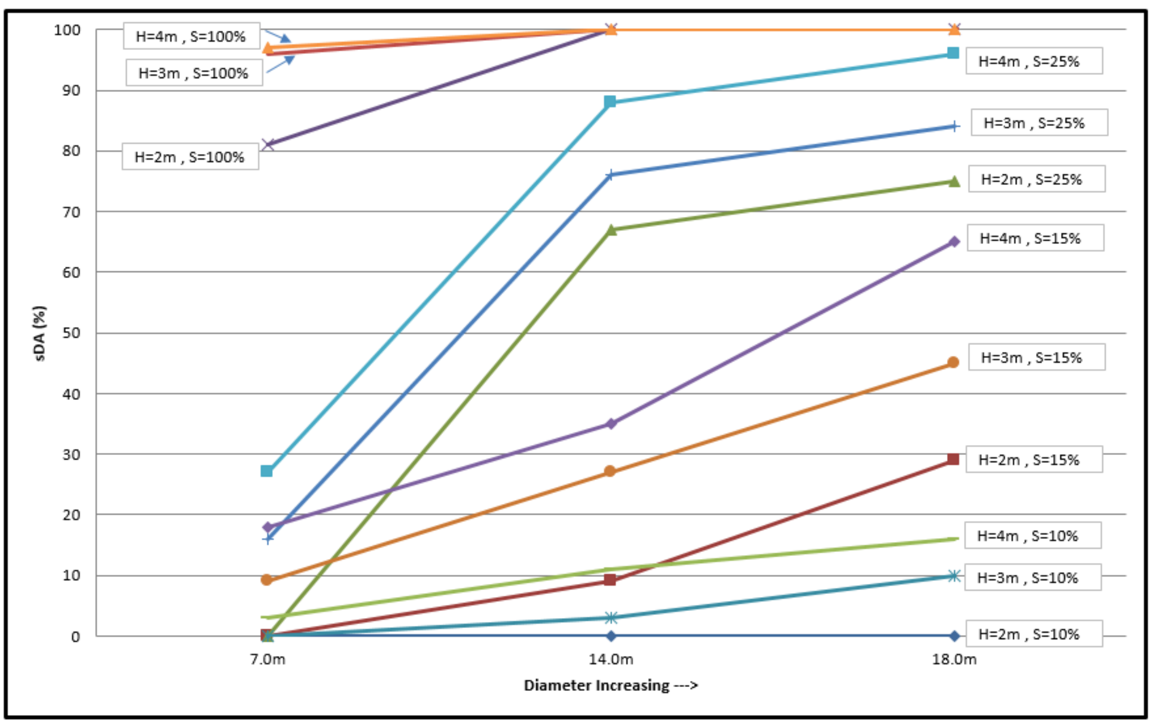


Figure 55: Comparing sDA values of diameter 7m,14m and 18m

b. On ASE

Comparing ASE values by increasing dome sizes and fixing height of drum and glazing percentage showed variety in impact (some stayed the same, increased slightly, increased highly). The cases that stay the same although the diameter was increased from 7m to 14m and 18m were: the case with H=2m, S=10% showed same results with ASE value = 0% which means no overlit or glare potential, and the case with H=3m,S=15%. Other cases had a high increase in ASE value ranges (10%-22%) which are: H=2m, S=100% and H=3m,S=100% and H=4m, S=100%. The rest of the cases were with slight changes in ASE percentage (increase of 1%- 6%), although there was an increase in ASE level but those cases were within the adequate range for ASE values.

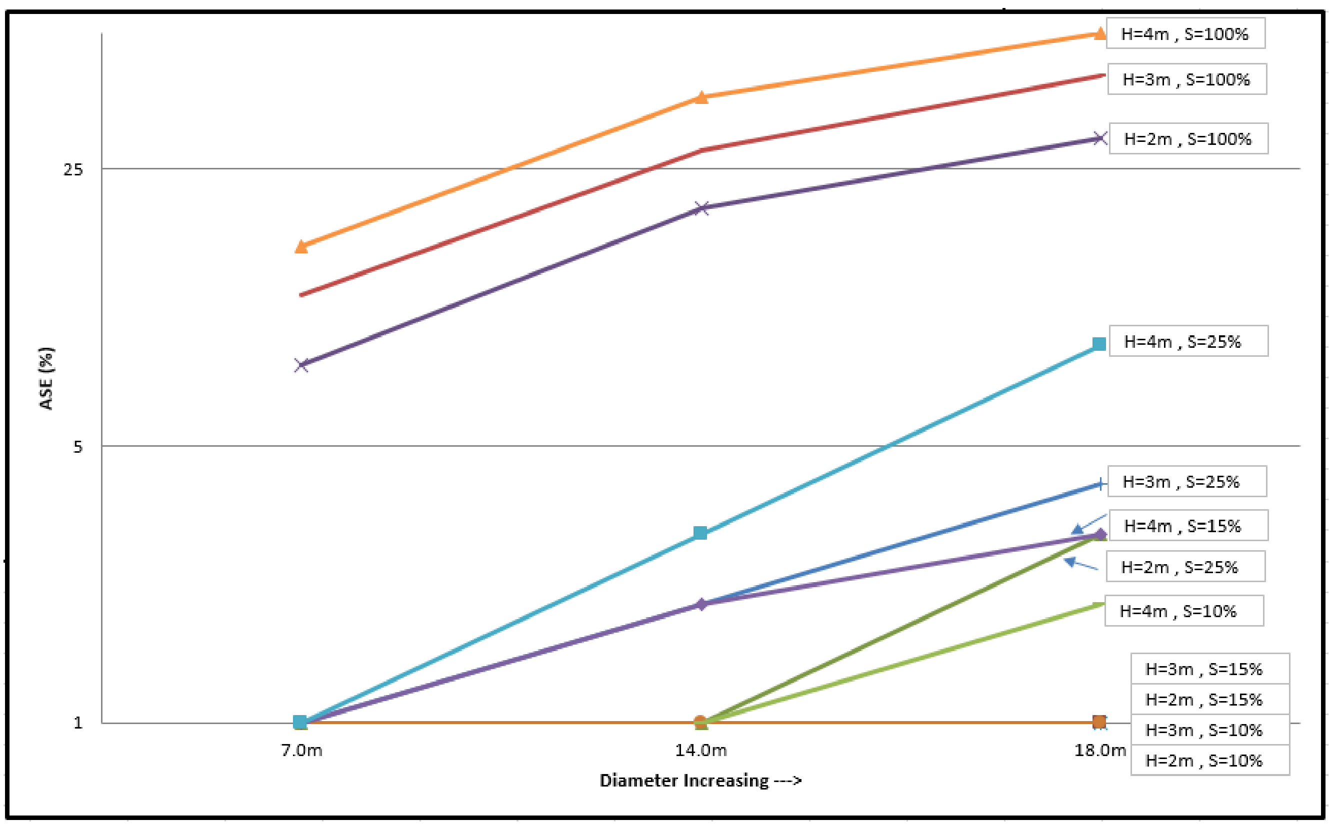


Figure 56:Comparing ASE values of diameter 7m, 14m and 18m

4.1.1.2. Effect of the increase of the drum Height

a. On sDA

Comparing the results and enhancement of sDA compared to diameter effect, the height showed minimal enhancement to the values. Increasing the height from 2m to 3m increased the sDA value in a range of 0% to 18%. Increasing the height one more meter from 3m to 4m didn't increase it that much as well, it increased with a range between 0% to 20% which wasn't actually enough for the cases to pass sDA evaluation.

Increasing the diameter by 1m (2m to 3m), didn't help much in making the values which didn't pass when the height was 2m, all of them were still under the required sDA levels. Doubling the height (2m to 4m) also didn't help in making the cases pass sDA evaluation, they were all below the required. Increasing the height isn't as much as effective in enhancing the sDA levels.

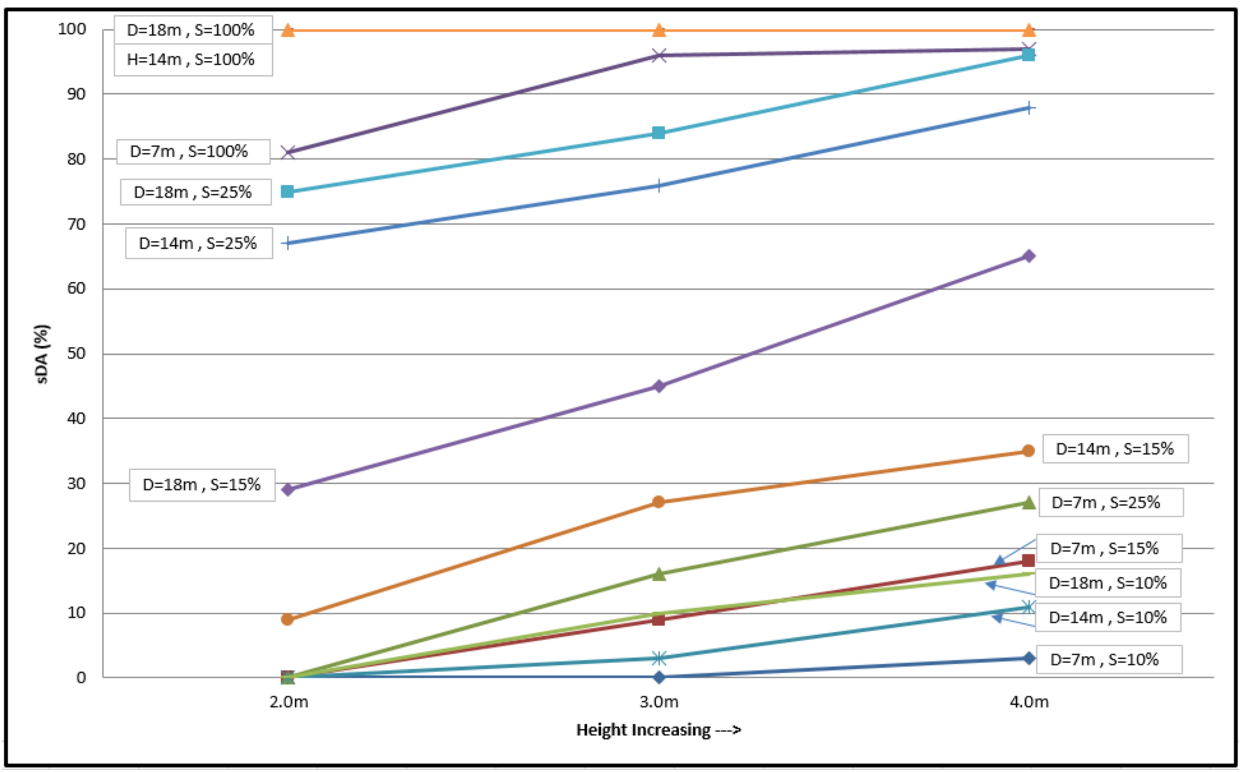


Figure 57: Comparing sDA values of drum height of 2m,3m and 4m

b. On ASE

For the increase in drum's height, ASE values didn't show that much of difference, very slight increase in ASE value (0-1%) for most of the cases, but it was only obvious with cases of S window=100% where the increase was around 4% to 13%. Regardless to the diameters (8m,14m,18m) and glazing percentages (10%,15%,25%), all cases were within the accepted range for ASE (<10%) even when increasing from 2m to 3m or 4m, the increase within 1m (2m to 3m) had an increase of 0% to 1% for ASE value, becoming one more meter higher (3m to 4m) had an increase of 0% to 3%, considering the range for the ASE to be acceptable for occupants is (0% to 10%) having an increase of 3% is quite high. Increasing the height effected more the cases with glazing percentages=100% throughout all diameter sizes, the height increase of 1m (2m to 3m) caused the ASE to be increased by (4%-13%), and increasing the height even more (3m to 4m) caused an additional increase in ASE by (4%-12%), those cases failed dramatically in achieving the ASE preferred range. Increasing the height make it possible to keep ASE in the adequate and preferred level and in the same time increase sDA levels yet not to the extent that makes sDA level

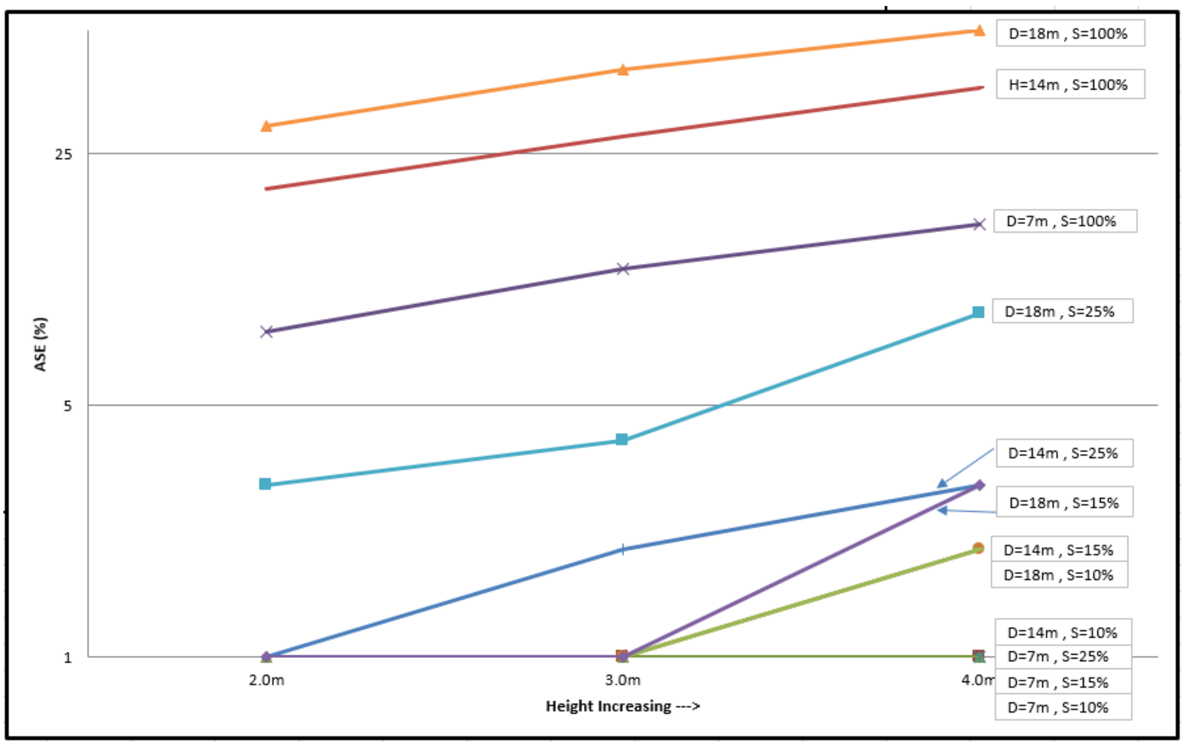


Figure 58: Comparing ASE values of drum height of 2m,3m and 4m

higher enough to pass.

4.1.1.3. Effect of the increase of the percentage of glazing

a. On sDA

For sDA values, increasing the percentage of glazing for the smallest dome (D=7m, h=2m) didn't affect at all in any of the glazing cases except when the glazing become 100%. For the rest of the cases the increase in glazing type did increase in the sDA values in a larger amount compared to changing in heights or diameter. Increasing the percentage by 5% (10%-15%) increased the sDA value by 9% for small diameter '7m' up to 49% for large diameter '18m'. Additional 10% on glazing percentage (15%-25%) effected more the medium size diameter '14m' compared to the other sizes by an increase rate 49%-53% while the small and large diameters were only7%-30%. The increasing in glazing percentage enhanced the sDA value the maximum when the glazing was 100%, all the cases have passed the sDA level when the glazing was 100% regardless to the diameter size or drum height. In another words, increasing the glazing percentage had more impact on sDA values compared to diameter and height.

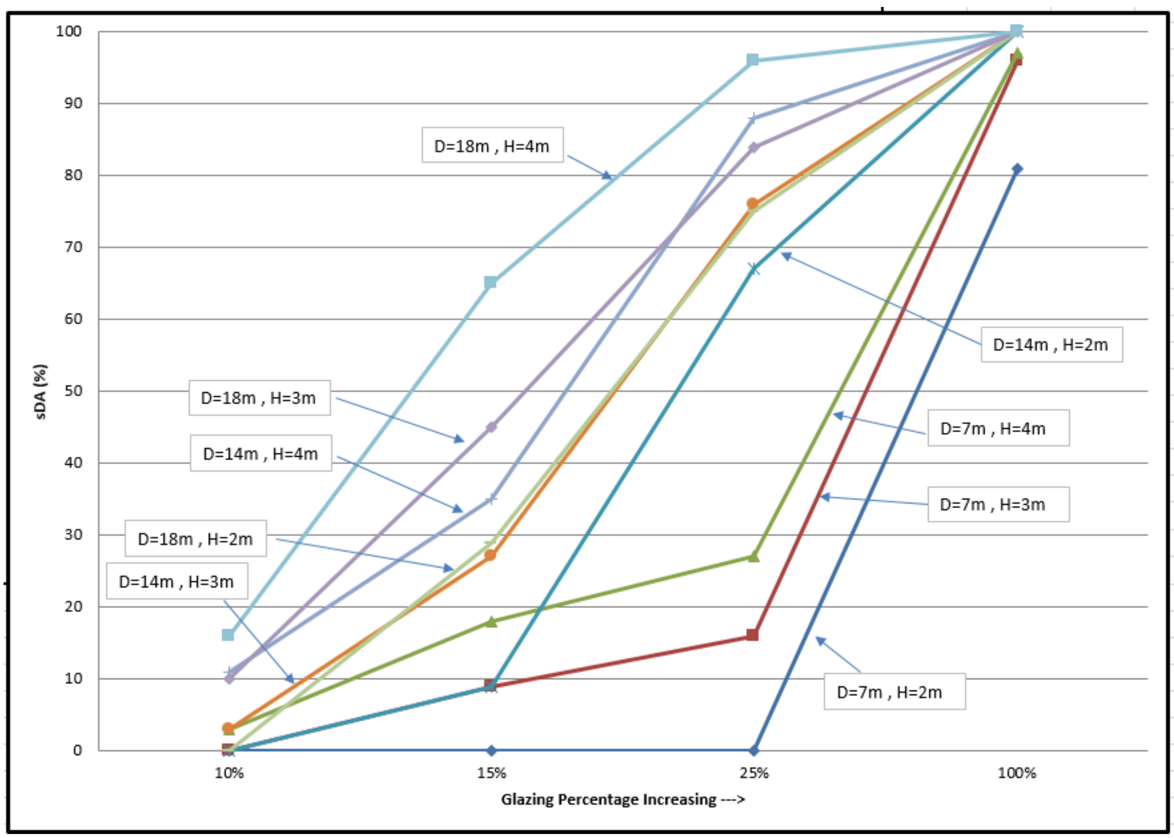


Figure 59: Comparing sDA values of glazing percentage 10%,15%,25%,100%

b. On ASE

Increasing the glazing percentage didn't affect that much the ASE level except with the cases of 100%. All 100% cases (except the smallest dome D=7, H=2) failed to be in the sufficient range of ASE, all of them have exceeded 10%. Other than that, the percentages (10%, 15% and 25%) all passed ASE and presented sufficient results. Up to glazing percentage of 25% with different sizes of diameter and drum height, all cases have passed, exceeding the percentage after that caused ASE to fail the ASE evaluation. Although comparing to the diameter and heights, the effect on the ASE values is higher, increase the glazing percentage showed higher increase to ASE compared to diameter and heights cases which makes the potential of glare to occur higher. For the small dimeter 7m and having glazing percentage up to (100% for H=2, 87.5% for H=3m, 70% for H=4m) can pass, for the medium diameter 14m and having glazing percentage up to(60% for H=2m, 48.5% for H=3m, 37.5% for H=4m) can pass for the big diameter18m and having glazing percentage up to(40% for H=2m , 36% for H=3m , 27.5% for H=4m)can pass.

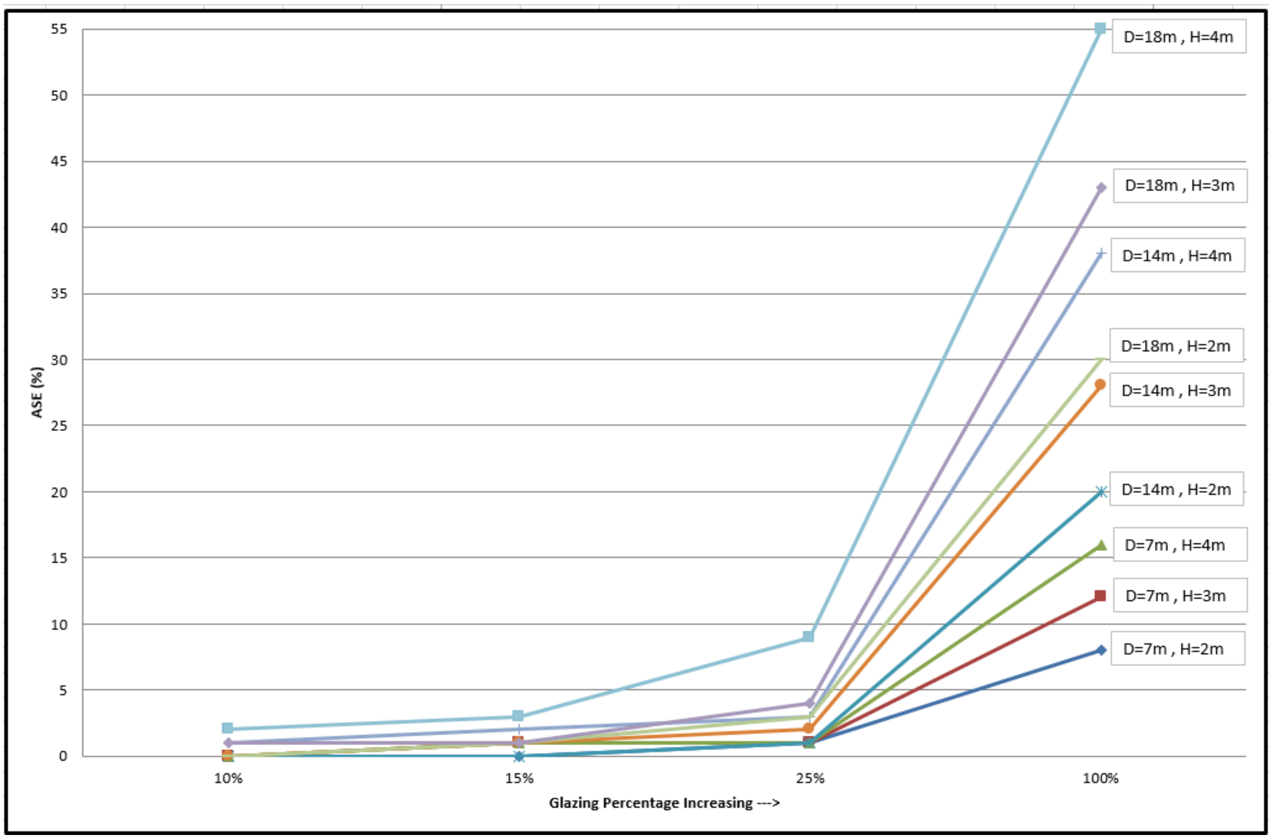


Figure 60: Comparing ASE values of glazing percentage 10%,15%,25%,100%

4.1.1.4. Best and worst cases for sDA and ASE:

Figure 61 shows the $sDA_{300/50\%}$ and $ASE_{1000/250}$ values for the different simulated scenarios, where an sDA value lower than 55% is not acceptable (red), between 55%-75% considered “nominally accepted” by occupant (yellow), values of 75% or more achieved the requirements for sufficient daylight as per LEED (green). ASE value less than 10% is perfect for occupants’ comfort (green), a value between 10% and 20% potential for glare (yellow), and having a value higher than 20% indicate overlit (red).

Date and Time: Annual

Diameter	Height of Drum	S windows (W area/ Drum area)	Glazing Area (m^2)	SDA	ASE
7.0	2.0 (sill height = 0.3 m)	10%	2.29	0	0
		15%	3.44	0	0
		25%	5.74	0	1
		100%	22.94	81	8
	3.0 (sill height = 0.8 m)	10%	3.44	0	0
		15%	5.16	9	1
		25%	8.6	16	1
		100%	34.4	96	12
	4.0 (sill height = 1.3 m)	10%	4.59	3	0
		15%	6.88	18	1
		25%	11.47	27	1
		100%	45.87	97	16
14.0	2.0 (sill height = 0.3 m)	10%	4.34	0	0
		15%	6.50	9	0
		25%	10.84	67	1
		100%	43.35	100	20
	3.0 (sill height = 0.8 m)	10%	6.50	3	0
		15%	9.75	27	1
		25%	16.25	76	2
		100%	65.00	100	28
	4.0 (sill height = 1.3 m)	10%	8.67	11	1
		15%	13.00	35	2
		25%	21.68	88	3
		100%	86.71	100	38
18.0	2.0 (sill height = 0.3 m)	10%	5.75	0	0
		15%	8.62	29	1
		25%	14.37	75	3
		100%	57.49	100	30
	3.0 (sill height = 0.8 m)	10%	8.62	10	1
		15%	12.96	45	1
		25%	21.56	84	4
		100%	86.23	100	43
	4.0 (sill height = 1.3 m)	10%	11.50	16	2
		15%	17.25	65	3
		25%	28.75	96	9
		100%	115.0	100	55

sDA	Not Accepted (<50%)	Nominally accepted (50%-75%)	Adequate (>75%)
ASE	Overlit (>20%)	Potential of Overlit (10%-20%)	Adequate (<10%)

Figure 61: Best and worst cases for sDA and ASE

It has been noticed that the first three values of $sDA_{300/50\%}$ are equal to zero. To ensure that the simulation has been done correctly, another simulation was done to verify the numbers with threshold of 100 lux instead of 300 lux, simulation was done with $sDA_{100/50\%}$ for case D=7m H=2m S=10% and results showed some values, which mean the sDA annual value for these cases is less than 100 lux that's why they weren't recorded in $sDA_{300/50\%}$ measurement. Figure 62 shows the simulation result for both sDA evaluations.

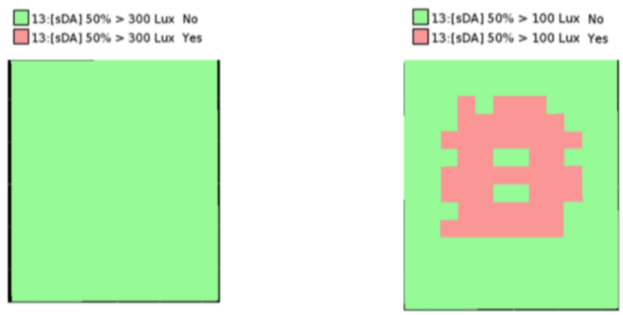


Figure 62: For case D=7m H=2m S=10%, sDA300/50% showed no values and sDA 100/50%had value

The cases of 7.0 m diameter have failed to reach requirements for sDA values except in three cases with 100% glazing, and all cases have passed ASE requirements with having two cases with potential of glare (H=3m , S=100% and H=4, S=100%).

Cases with 14m diameter, half of the cases passed and half failed for sDA, cases with S=10% and 15% all failed sDA and cases with S= 25% and 100% all passed. All cases passed ASE except one case that recorded as potential for glare (H=2m , S=100%) and two failed (H=3m, S=100% and H=4m, S=100%).

Cases with diameter of 18.0m scored similar outcomes as 14.0 m diameter cases, with having half of the sDA values passing (cases with S= 25% and 100%) and half failed (cases with S=10% and 15%).

ASE values also recorded all passed except cases with 100% glazing percentage throughout the different heights (H=2, S=100%, H=3, S=100% and H=4, S=100%).

All cases with different diameter (D=7,14,18m) and heights (H=2,3,4m) and glazing percentage (S=10%,15%,25%) all passed the ASE evaluation and were less than 10%, the rest of different height cases with glazing percentages S=100% have all either failed the ASE evaluation which means definite ovelit happening or were within the range for potential overlit.

There were no cases that failed to reach recommended levels in both metrics, but the depending on the values some scored worse than others, some cases got 0% or lower than required as sDA value including:

- All cases with glazing percentage = 10% and 15%
- Cases with glazing percentage =25% only for diameter =7.0m.

Percentage of glazing had the major impact on the sDA metric, all cases which didn't have enough glazing percentage regardless to the height of drum or diameter failed. Starting from glazing percentage of 25% and above the sDA metric started to show pass results. It's true that for the case of diameter=7m the percentage of glazing =25% failed but because that the diameter was too small to cover most of the floor area, when the diameter increased more area was exposed to the light and the glazing percentage = 25% passed for later cases. Diameter change would help in distributing the light more to the space when it's in the right diameter range (as mentioned before diameters of 7m and 18m failed most of their cases but diameter of 14m had better results), but percentage of glazing is the main contributor for getting sufficient sDA value. Increasing the height of the drum had an effect of increasing the sDA value while maintain the ASE value in the acceptable range, which means increasing drum height helps to satisfy both aspects (less ASE, higher sDA). In another words, increasing the height make it possible to keep ASE in the adequate and preferred level and in the same time increase sDA levels but yet not to the extent that makes sDA level higher enough to pass.

Others failed ASE metric by exceeding 10%-20% range by much including:

- D=14m, H=3m , S=100% with ASE value of 28%
- D=14m, H=4m , S=100% with ASE value of 38%
- D=18m, H=2m , S=100% with ASE value of 30%
- D=18m, H=3m , S=100% with ASE value of 43%
- D=18m, H=4m , S=100% with ASE value of 43%

Since all cases that failed or had potential to fail had glazing percentage of 25% or 100%, we can conclude that increasing percentage of glazing makes it more likely to fail in reaching the recommended values for the ASE metric compared to increasing diameter or height.

The best cases were the one who passed for both ASE and sDA metrics which includes:

- D=7m, H=2m, S=100%, glazing area = 22.94 m^2 - sDA = 81% , ASE=8%
- D=14m, H=3m, S=25% , glazing area = 16.25 m^2 - sDA = 76% , ASE=2%
- D=14m, H=4m, S=25% , glazing area = 21.68 m^2 - sDA = 88% , ASE=3%
- D=18m, H=3m, S=25% , glazing area = 21.56 m^2 - sDA = 84% , ASE=4%
- D=18m, H=4 m, S=25%, glazing area = 28.75 m^2 - sDA = 96% , ASE=9%

In order to investigate the relation of the glazing area along with sDA and ASE, graphs were created whereby the x axis is the Glazing area, regardless of other dome configurations, the Y axis is either ASE or sDA.

For ASE, polynomial curve of 5th order was created and an equation was concluded to clarify the relation of the glazing area with ASE values. Figure 63 shows this relation. The R square value was also measured, this value should be as close to 1 as possible to indicate a good fit. Following are the graphs for each curve tested along with the equation and R square value: **<u>The equation was as follow:</u>**

$$\mathbf{ASE = -0.000001A^5 + 0.0003A^4 - 0.0116A^3 + 0.1657A^2 - 0.7891A + 1.0098}$$

whereby A = the glazing area (m^2) , ASE = $ASE_{(1000/250)}$(%) , $R^2 = 0.976$

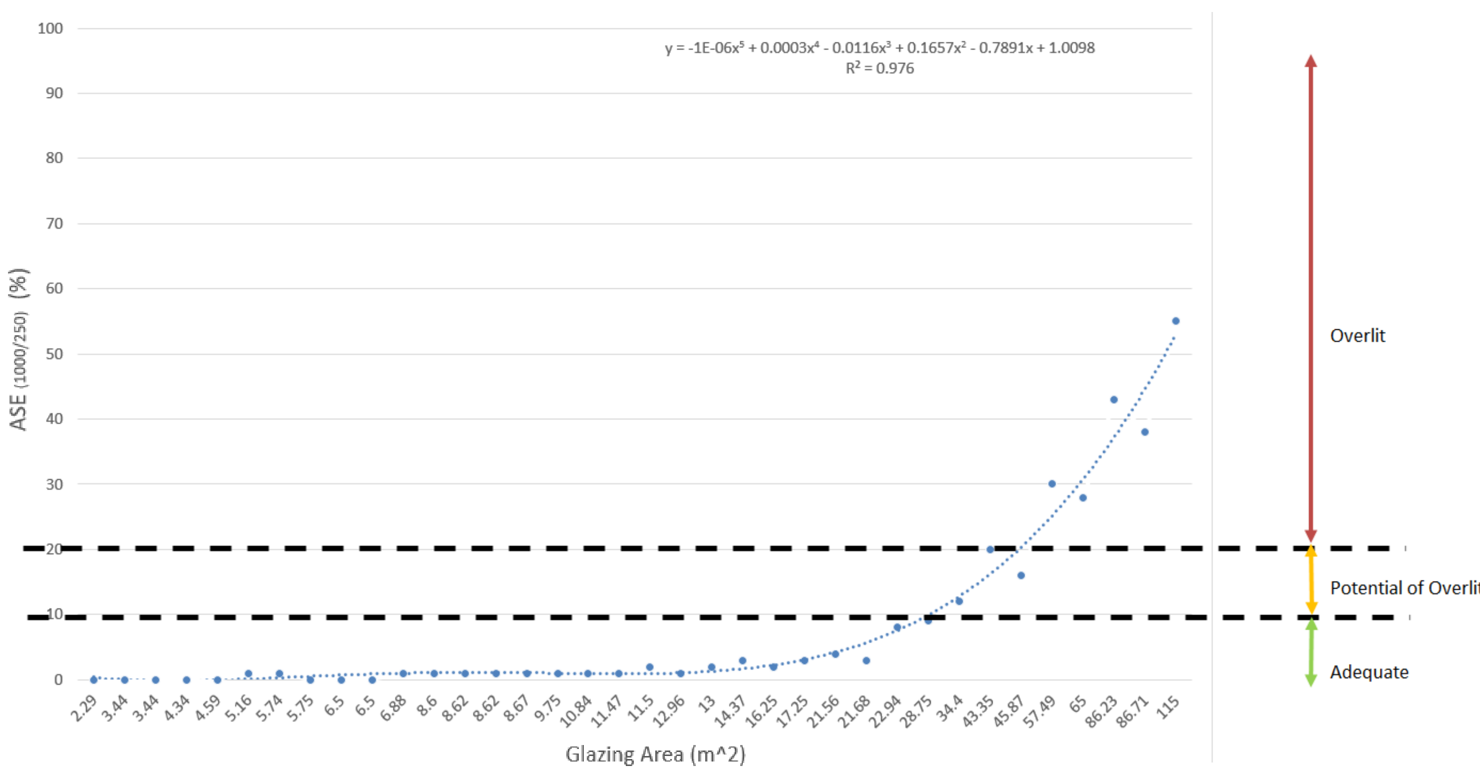


Figure 63: Relationship between Glazing area and ASE metric

For sDA, several curves were tested in order to find the best fit that matches the curve created from the values of simulation. Exponential, power, linear and Polynomial (2,3,4,5,6) curves were tested. The R square value was also measured, this value should be as close to 1 as possible to indicate a good fit. Following are the graphs for each curve tested along with the equation and R square value:

Exponential : $\mathbf{y = 0.0262e^{0.2991x}}$, R^2 = 0.6068

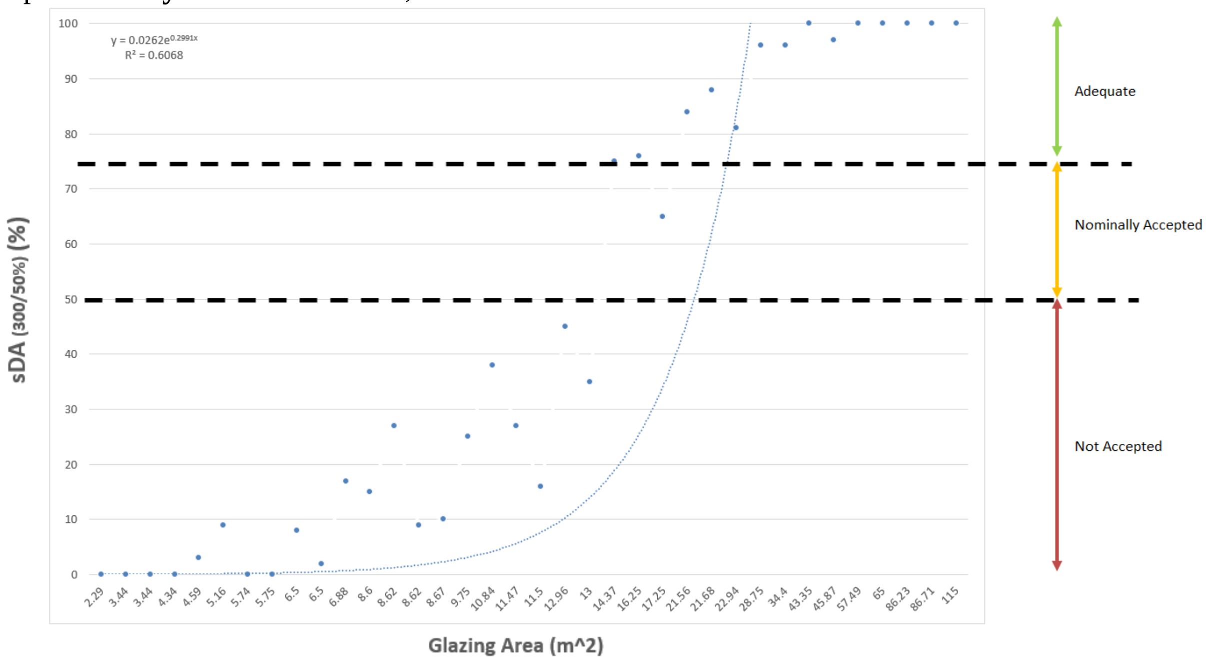


Figure 64: Exponential Curve presentation for sDA300/50% values

Power equation is $\mathbf{y = 0.00008\ x^{4.272}}$, R^2 = 0.8353.

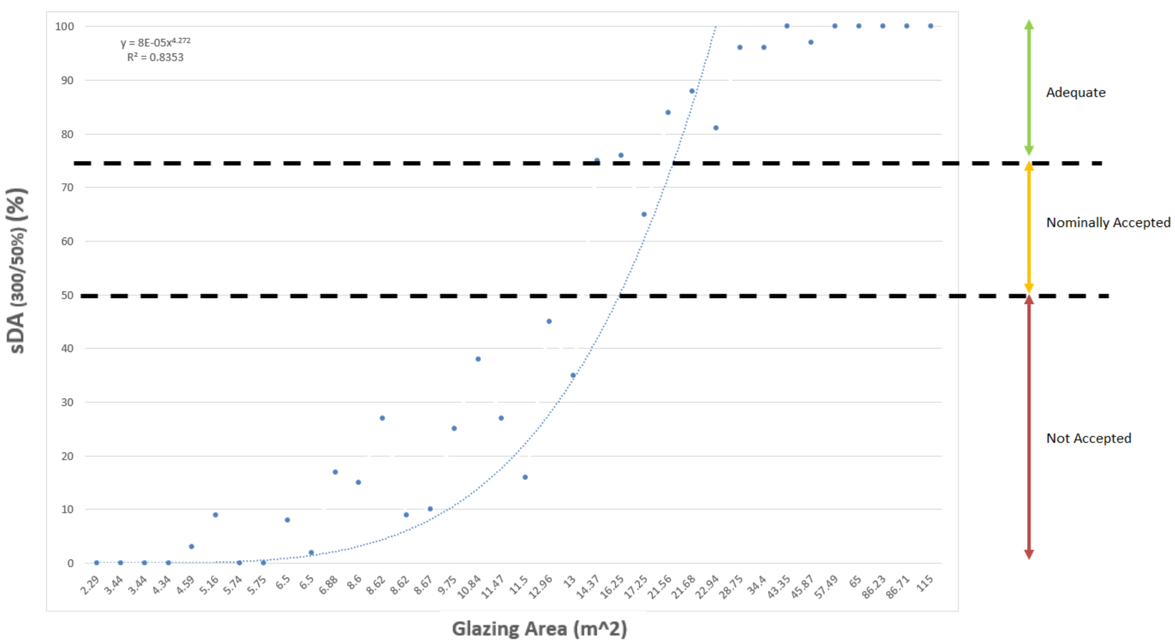


Figure 65:Power Curve presentation for sDA300/50% values

Linear equation : **y = 3.6612x - 22.064** , R^2 = 0.9035

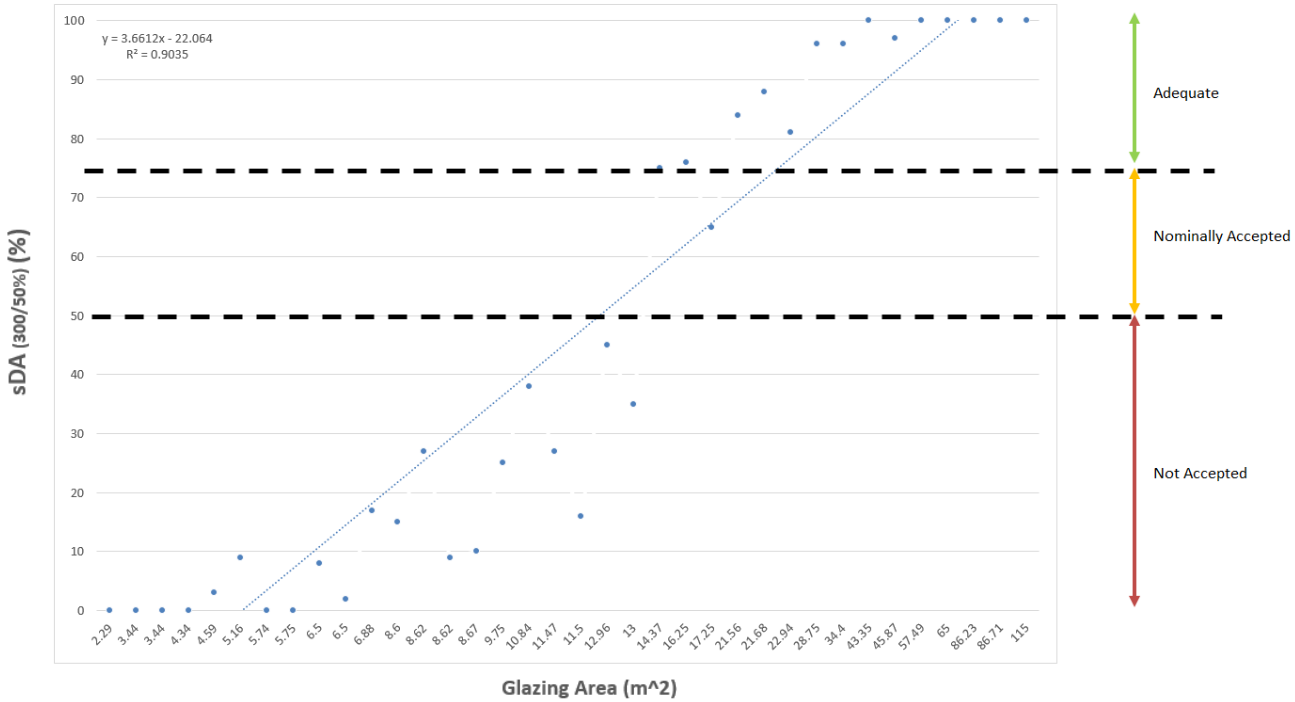


Figure 66: Line graph presentation for sDA300/50% values

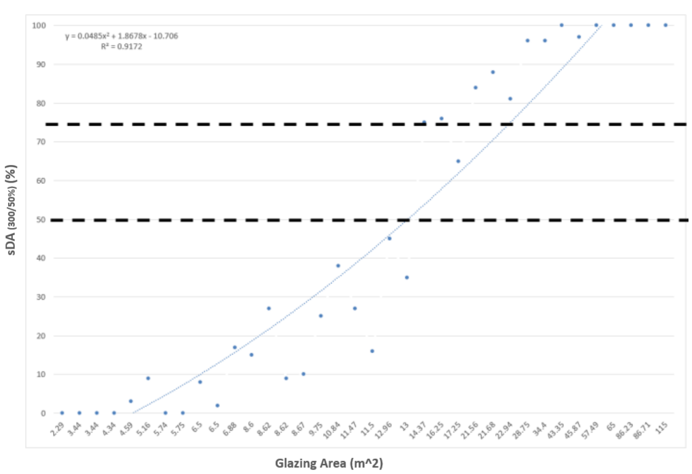
Polynomial : **Order 2**: $y = 0.0485x^2 + 1.8678x - 10.706$, R^2 = **0.9172**

Order 3: $y = -0.0085x^3 + 0.5211x^2 - 5.2227x + 12.64$, R^2 = **0.952**

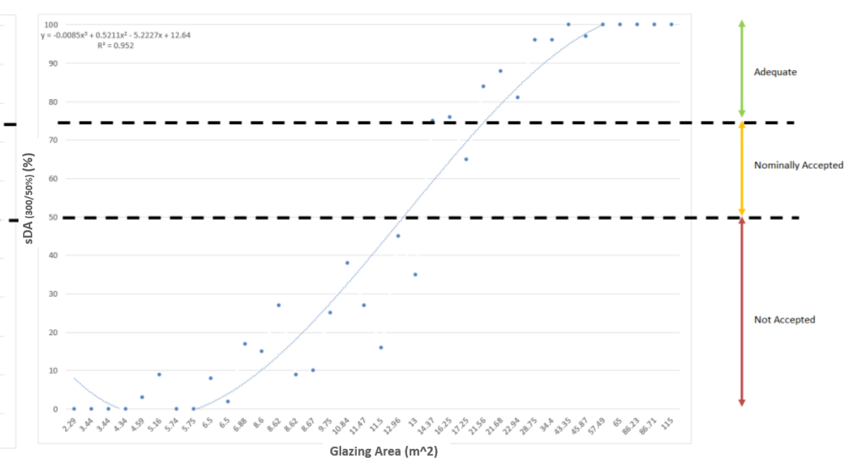
Order 4: $y = -0.0005x^4 + 0.0271x^3 - 0.3352x^2 + 2.0472x - 2.4604$, R^2 = **0.9611**

Order 5: $y = 2E\text{-}05x^5 - 0.0022x^4 + 0.0832x^3 - 1.1292x^2 + 6.4836x - 8.9824$, R^2 = **0.9621**

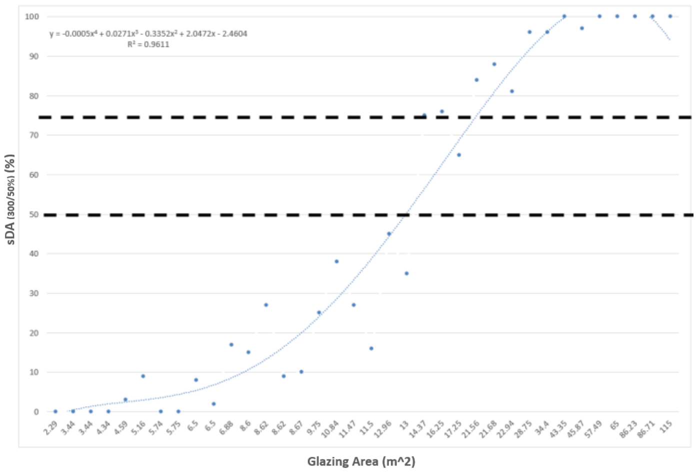
Order 6: $y = 4E\text{-}06x^6 - 0.0004x^5 + 0.0159x^4 - 0.2786x^3 + 2.3417x^2 - 7.4824x + 6.7135$, R^2 = **0.9658**



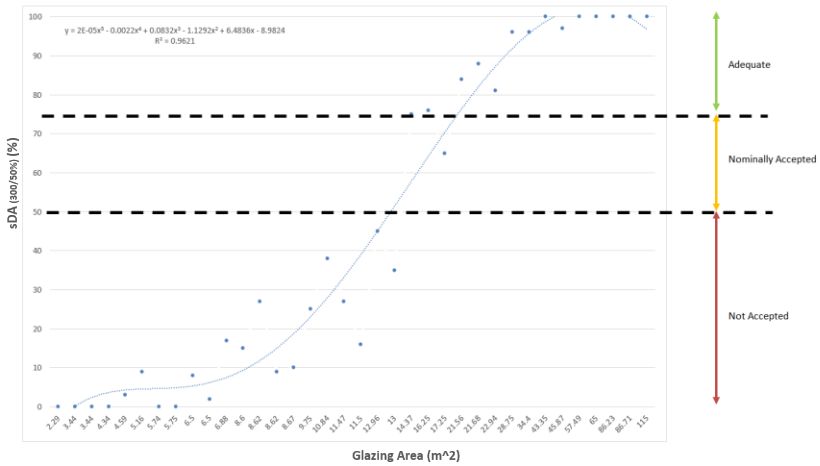
Order 2



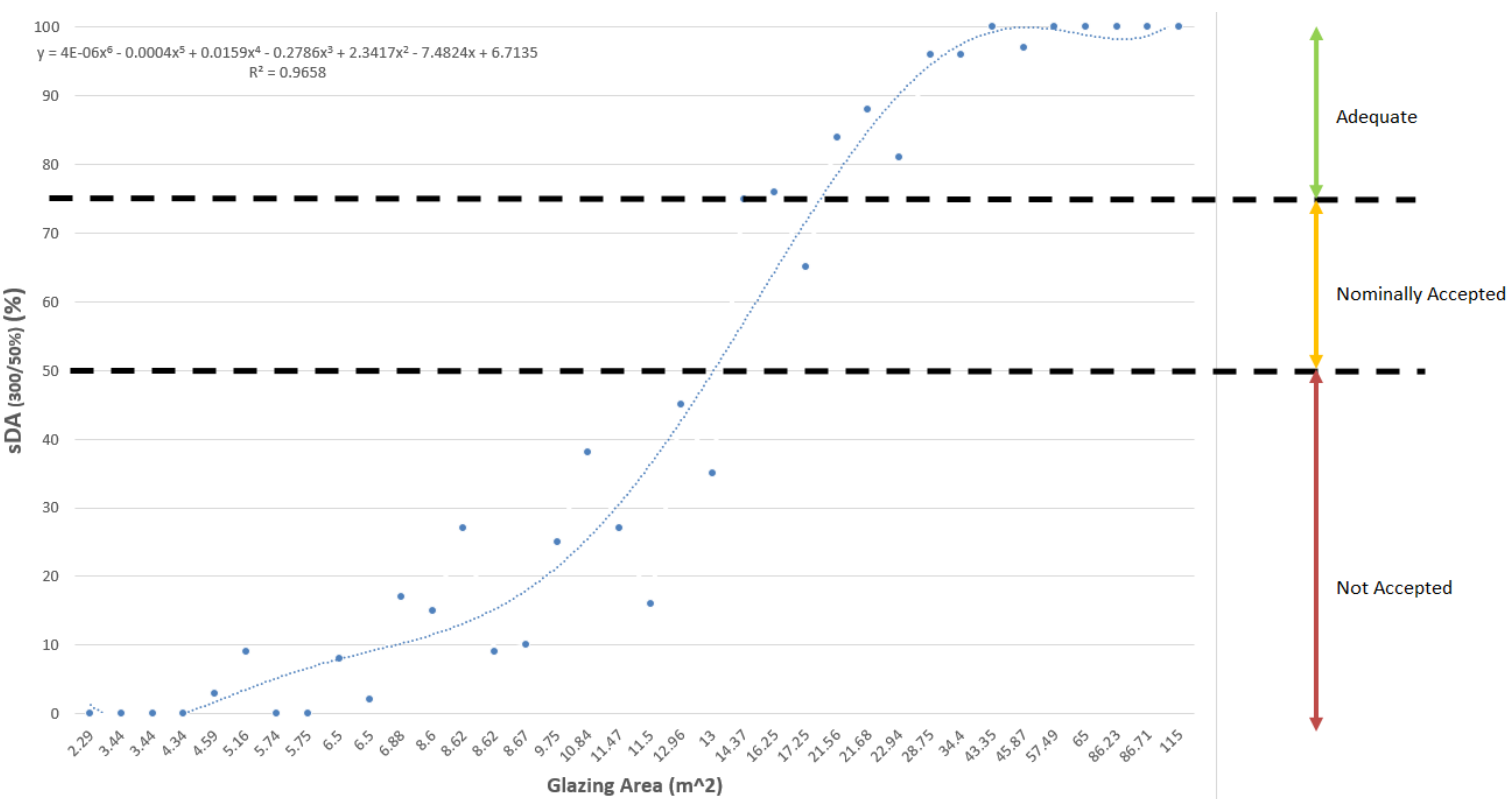
Order 3



Order 4



Order 5



Order 6

Figure 67:Polynomial Curve (order 2,3,4,5,6) presentation for sDA300/50% values

After investigating several possible equations, the best fit was having the order 6 because it has the highest R square value and also it's the only equation which gets through the flattening of the curve at high glass areas and follow the path of most of the points. For sDA, polynomial curve of order 6 was created and an equation was concluded to clarify the relation of the glazing area with sDA values. Figure 67 - Order 6 shows this relation. **<u>The equation was as follow</u>**:

$$\mathbf{sDA = 0.000004}A^6 \mathbf{- 0.0004}A^5 \mathbf{+ 0.0159}A^4 \mathbf{- 0.2786}A^3 \mathbf{+ 2.3417}A^2 \mathbf{- 7.4824}A \mathbf{+ 6.7135}$$

whereby A= glazing area (m2) , sDA = $sDA_{(300/50\%)}$ (%), R^2 = 0.9658

Cases with glazing percentage of 25% are more likely to pass for both ASE and sDA. When having a small diameter of low height, it's better to increase the percentage into 100%. For other heights and diameters having glazing percentage of 25% is enough to get sufficient daylight and ensure no glare is going to occur. Figure 68 shows the limits for glazing percentage which architects shouldn't go beyond to satisfy both metrics (ASEand sDA), it will be detailed in conclusion chapter (5.1.1.Case1: Annual Variables):

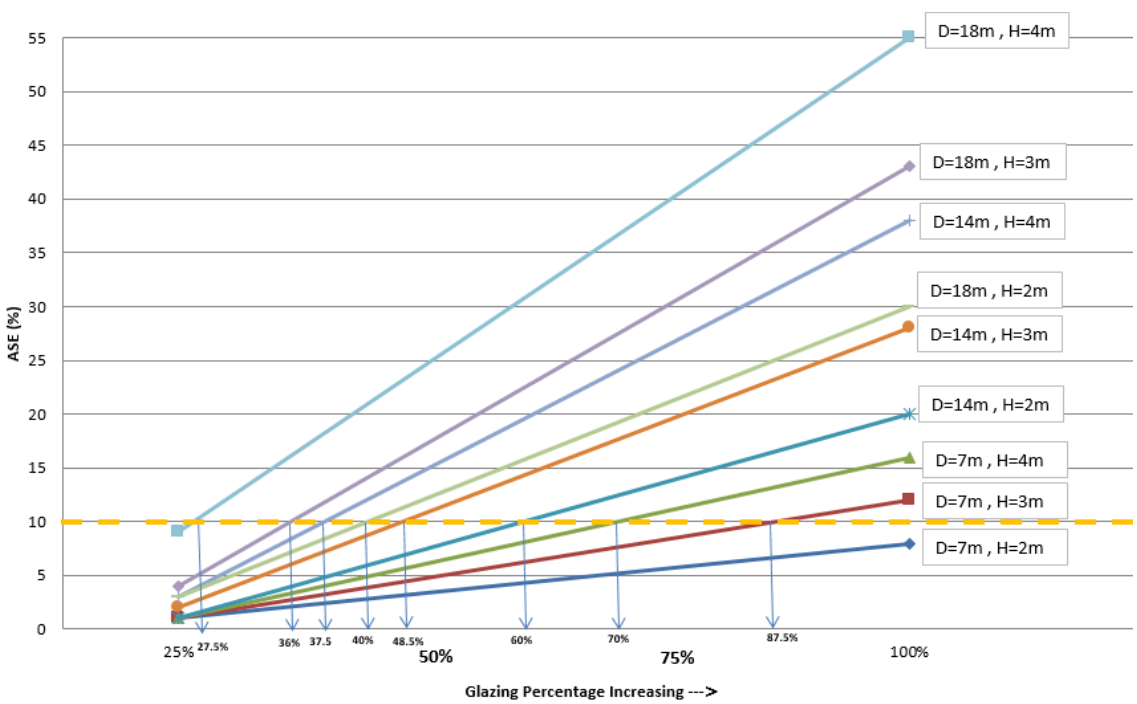


Figure 68: Maximum allowable glazing percentage per each case simulated

What can be concluded from figure 68 is that, for the small diameter 7m, the preferred glazing percentage would be 100% for H=2m, 87.5% for H=3m, 70% for H=4m to reach recommended values for both metrics, for the medium diameter 14m its more preferable to have glazing percentage up to 60% for H=2m, 48.5% for H=3m, 37.5% for H=4m, and for the big diameter18m a glazing percentage of 40% for H=2m , 36% for H=3m , 27.5% for H=4m. Table 15 summarizes this paragraph showing the preferred glazing percentage per each diameter and height case in order to satisfy both sDA and ASE metrics.

Diameter	Drum's Height	Glazing Percentage in Drum
7m	2m	100%
7m	3m	87.5%
7m	4m	70%
14m	2m	60%
14m	3m	48.5%
14m	4m	37.5%
18m	2m	40%
18m	3m	36%
18m	4m	27.5%

Table 15: The preferred glazing percentage per each diameter and height case

4.2.2. Case 2: Light Properties

This case measures the illuminance level (lux) in different dates and timing around the year. The simulation will be done on 21 June – 21 Sep – 21 Dec at timings 8:00am – 12:00pm – 4:00pm. Table15,16,17 are case of D=7.0m H=2m and S=10,15,25,100% cases on 21 June – 21 Sep – 21 Dec displayed as a sample for the simulation results, the rest of the simulation results can be found in **Appendix A – Illumination Results**

Table 16: 21st June Illuminance level for (D=7 , H=2 , S=10,15,25,100)

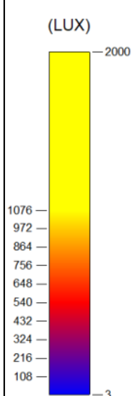
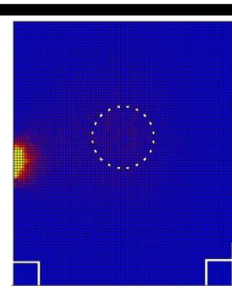
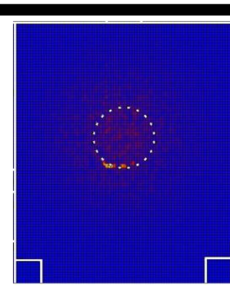
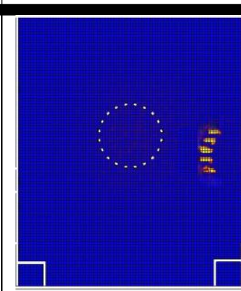
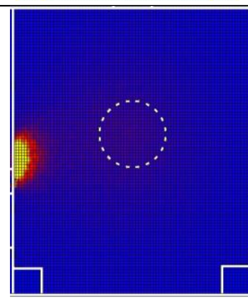
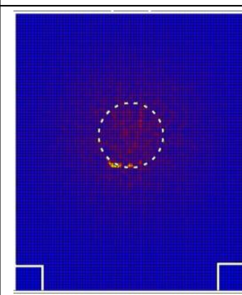
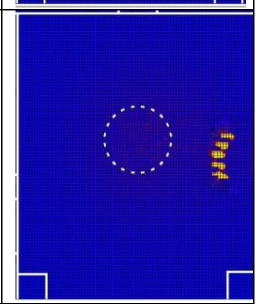
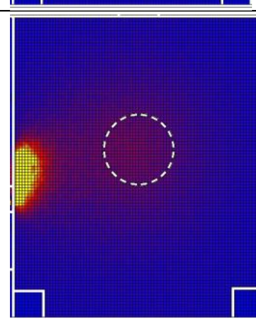
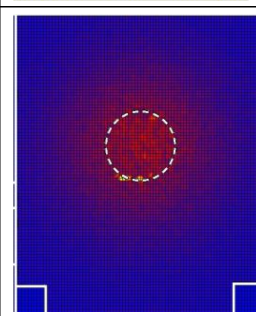
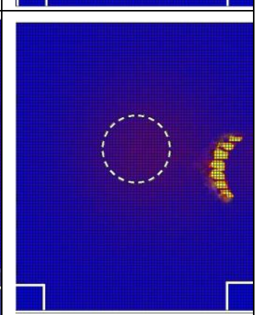
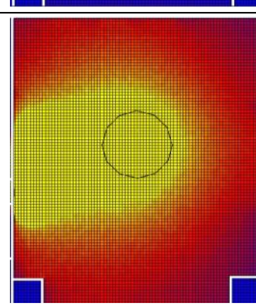
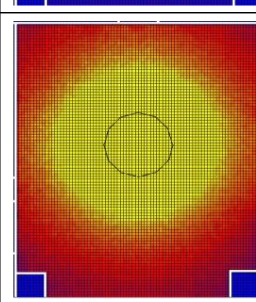
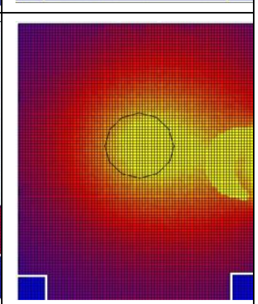
Date: 21st June					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00AM	12:00PM	4:00PM
7.0 	2.0 m (sill height = 0.3 m)	10%			
		15%			
		25%			
		100%			

Table 17: 21st September Illuminance level for (D=7, H=2 , S=10,15,25,100)

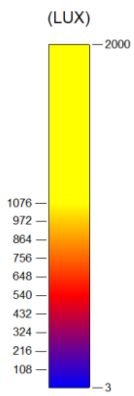
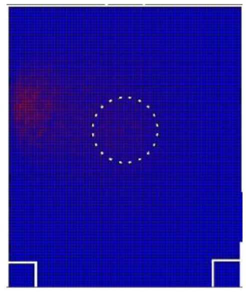
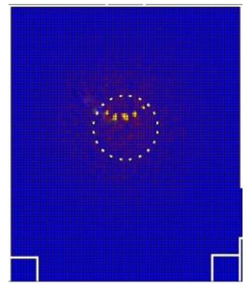
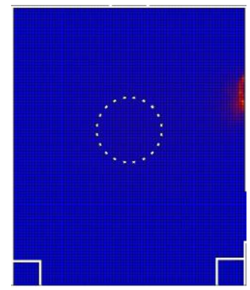
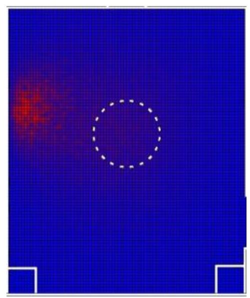
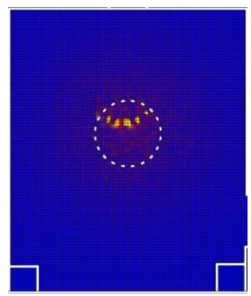
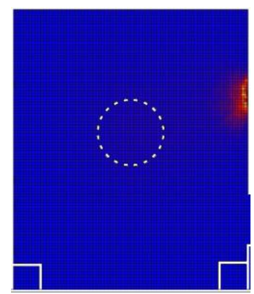
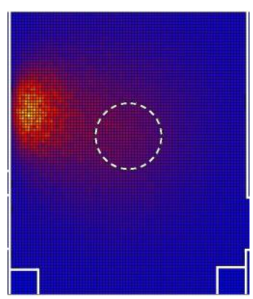
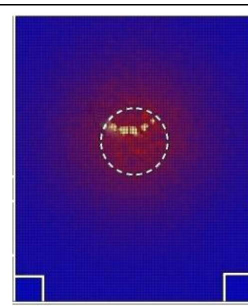
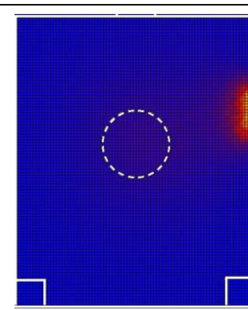
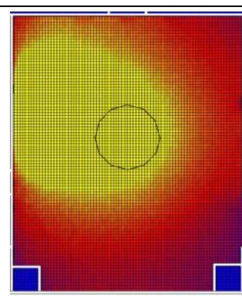
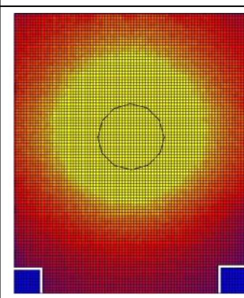
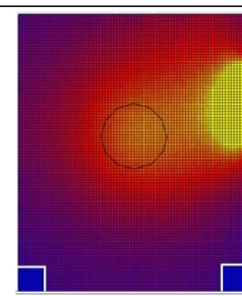
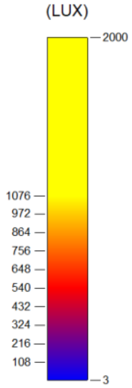
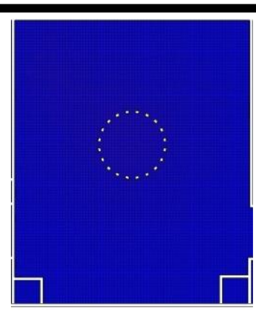
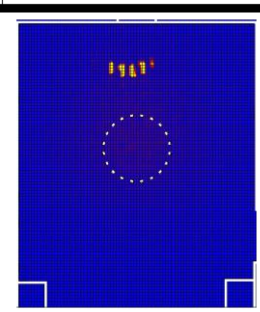
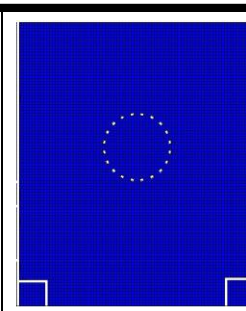
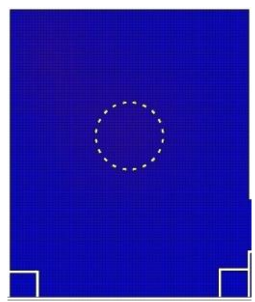
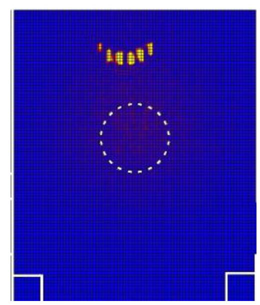
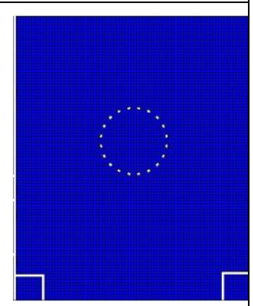
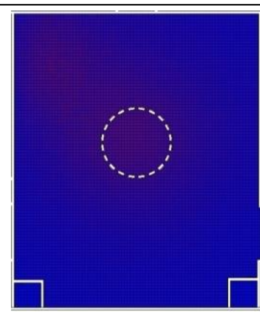
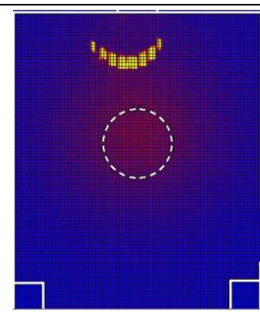
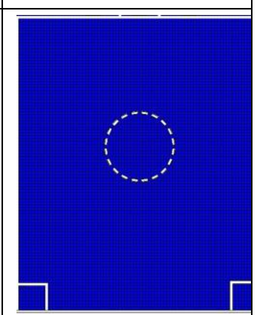
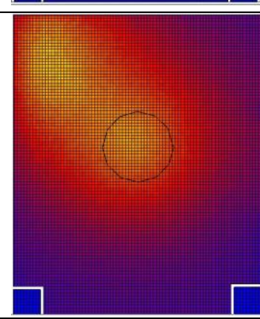
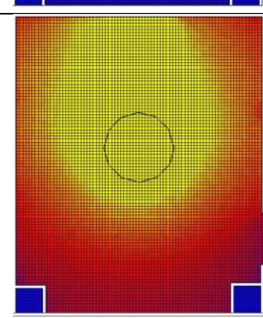
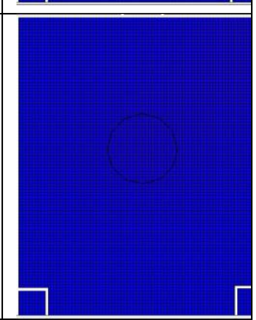
Date: 21st September					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00AM	12:00PM	4:00PM
7.0 	2.0 m (sill height = 0.3 m)	10%			
		15%			
		25%			
		100%			

Table 18: 21st December Illuminance level for (D=7, H=2 , S=10,15,25,100)

Date: 21st December					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00AM	12:00PM	4:00PM
7.0 (LUX) 	2.0 m (sill height = 0.3 m)	10%			
		15%			
		25%			
		100%			

Illumination results discussion :

For educational spaces, preferred illumination levels are between 300to500 lux at the working plane and for detailed drawing work to be 1,500-2,000 lux. (Mills E, Borg N.1999). The simulation results can be found in **Appendix A – Illumination Results**

This section will be explained as following:

4.2.2.1. Comparing brightness between months

4.2.2.2. Trends within results

4.2.2.3. Effect of increasing diameter

4.2.2.4. Effect of increasing drum's height

4.2.2.5. Effect of increasing glazing percentage

4.2.2.6. Maximum and minimum illuminance levels

4.2.2.7. Impact of independent variables "D, H, S" on dependent variable "illuminance level"

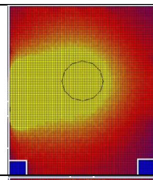
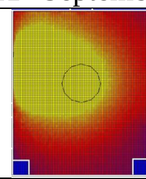
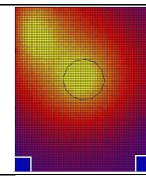
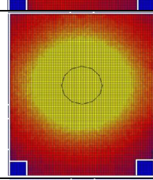
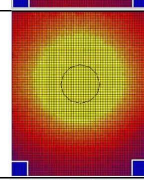
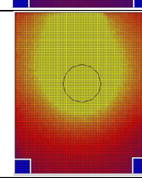
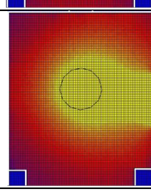
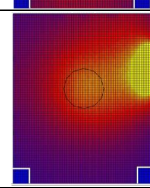
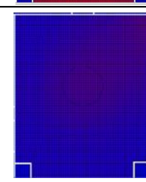
4.2.2.1. Comparing brightness between months

Comparing the simulation results, the concentration “higher illuminance lux” was always within the center creating a bright circle in the center surrounded by an area of lower illuminance “calling it tail of light” and it gradually decreases when going further away from bright center. It has been noticed from the comparison that the bright circle is located/shifted differently between the months, also the tail of light is oriented and distributed differently. For explanation, the case with D=7m H=4m S=100% was used, table18 shows that case within different timings and dates. At 8:00am, in 21st June the bright circle is slightly shifted towards west within the central space and tail of light is oriented towards west “slightly tilted to south”, in 21st September the bright circle is also within west of the center but tail of light is oriented towards north-west, in 21st December the size of the bright circle is smaller which means less illuminance lux reaching the 2000lux and the tail of light is oriented north-west but in a higher angle compared to September. At 12:00pm, in 21st June the bright circle is exactly in the mid of the space shaping almost a perfect circle, that space has the highest illuminance level reaching up to 5,500 lux, in 21st September the bright circle is shifted towards north with an illuminance level reaching 3,500 lux, in 21st December the bright circle is shifted the highest towards north and its spread from center towards the north façade but with an illuminance level of 2,000lux. At 4:00 pm, in 21st June the bright circle is slightly shifted towards east within the central space and tail of light is oriented towards east “slightly tilted to south”, in 21st September the bright circle is also within east of the center but tail of light is oriented towards north-east, in 21st December the size of the bright circle is smaller and has much lower illuminance level and the tail of light is oriented north-west but in a higher angle compared to September.

This could be explained due to sun path in those timing of the year in that area. Table 19 shows the sun path within the tested timings. As can be noticed, in June at 8:00am the sun is at the east (tilted slightly to north), at 12:00 pm the sun is at its highest position in skyat 12 with an angle of 88° (almost prepdicular 90° on roof top), at 4:00 pm the sun is at west (tilted slightly to north). In September, at 8:00am the sun is at southeast, at 12:00pm the sun path is slightly curved towards the south which explains why the bright circle is slightly shifted, deformed and lower in illuminance compared to June since the sun light that is coming in coming in with an angle (sunlight component), at 4:00 pm the sun is at south-west. In

December, the sun at 8:00am is the furthest towards southeast, at 12pm it's also curved towards south as September but much deeper and lower angle which explains why it has bigger illuminance spread compared to June and September but in a lower illuminance (bigger sunlight component so less illuminance magnitude) and at 4:00 pm the sun is the furthest towards south-west. Depending on the sun location, the direction of daylight is defined as the opposite, for example in September at 8:00 am the sun is at south-east so the illuminated space will be north-west. Table 18 shows how the sun is lighting up the space within simulated timings.

Table 19: The case of D=7m H=4m S=100% within different months and timings

	21st June	21st September	21st December
8:00am			
12:00pm			
4:00pm			

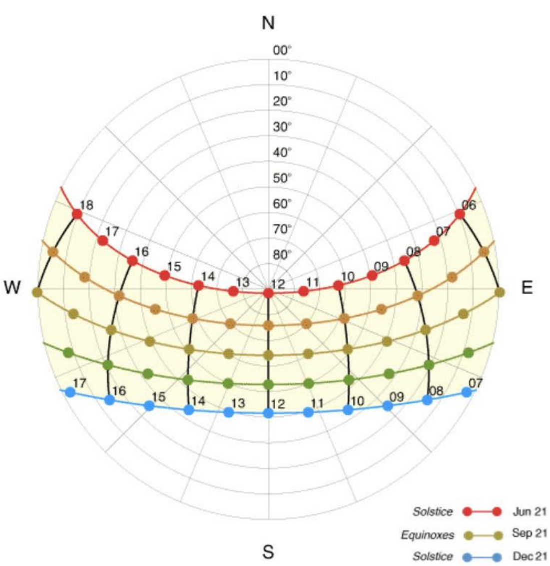
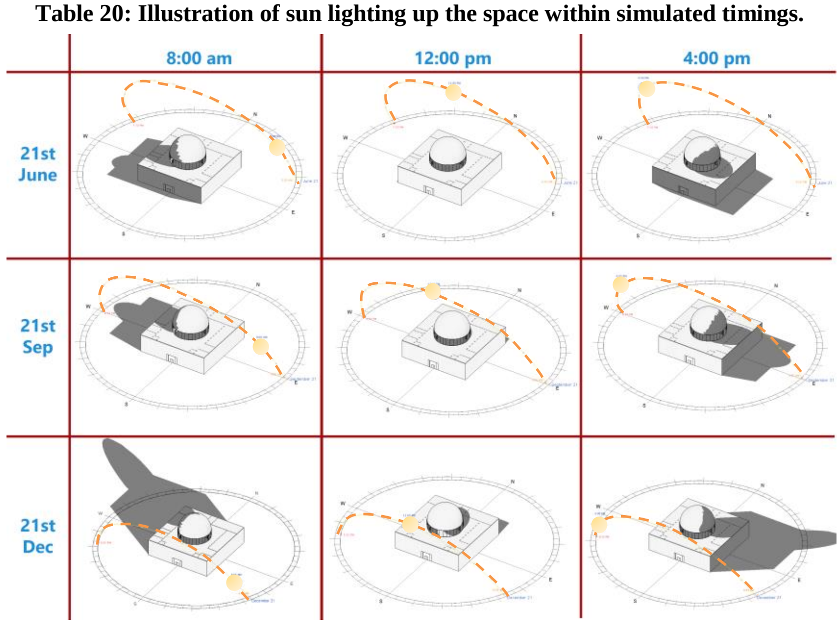


Figure 69:The sun path within the tested timings

Table 20: Illustration of sun lighting up the space within simulated timings.



4.2.2.2. Trends within results

Comparing modification done in each variable, it has been noticed that: for diameter, using 18m as a diameter gave better results and much brighter (higher illuminance level and better distribution), followed by 14m and last 7.0m. For drum's height, a 4.0m height was giving the highest illuminance in followed by 3.0m and last 2.0m. For glazing percentage, the best was having 100% of drum as glazing, it even had higher impact and more brightness compared to biggest drum and height, followed by having drum as 25% glazed, then 15% and last with 10%.

Comparing any case with the results it had in different months, it has been noticed that 21st June had always the highest illuminance level compared to 21st September and 21st December of the same case. As illuminance distribution within floor area, 21st December had bigger area with illuminance level being around 2,000 lux, on the other hand 21st June had smaller spot with high illuminance but the illuminance level in it was reaching up to 5,500 lux.

The degree of impact of drum's height =3m is equal to the effect of glazing percentage =15% (Justified in details in section 4.2.2.7.)

Within all cases, it has been noticed that the results at 8:00am is brighter than 4:00 pm. This can be explained with weather data base from Energy Plus weather data file (*.EPW) which was used in simulation. The illuminance data collectors are limited, on the other hand big amounts of solar irradiance data are available from data recorded at weather stations all around the world. Many building software and energy analysis like Revit+Insight provide irradiance information, either from weather data tapes or from calculation. For that, an interrelationship between solar radiation conditions and illumination conditions will make it possible for outdoor illumination levels to be estimated. In another word, illuminance is largely dependent upon irradiance. The "NATIONAL BUREAU OF STANDARDS" in Washington, USA published a standard book under name of "Solar

Radiation and Illumination” and used experimental data were gathered and analyzed under several cloud cover conditions to indicate the relationship between solar irradiance and illuminance. It concluded an equation illuminance as a function of irradiance which is (Treado and Kusuda, National Bureau of Standards 1984) :

$\boldsymbol{E_T}$ **= 110 x** $\boldsymbol{I_T}$

Where : E_T = Total illuminance (lux) , I_T= total irradiance (w/m^2)

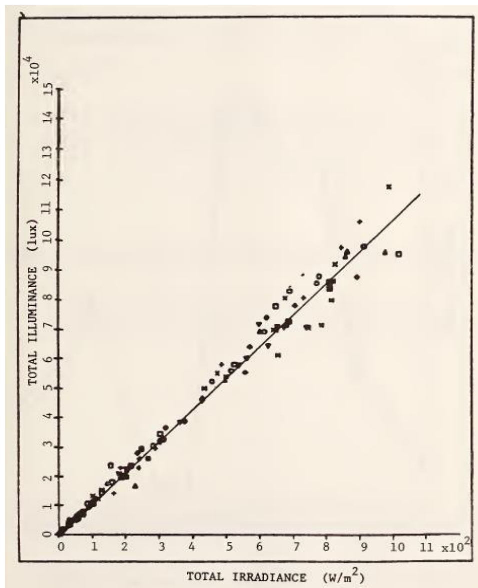


Figure 70: Total Illuminance as a Function of Total Irradiance (Treado and Kusuda, National Bureau of Standards 1984)

The equation shows that irradiance is directly proportional with illuminance values. irradiance Solar data generated by Revit+Insight using EnergyPlus weather database can be used to explain the illumination behavior in those specific timings. Solar radiation reaches the earth in two components, diffuse and direct. The sum of diffuse and direct Irradiance equals total Irradiance, also for the illuminance it’s composed of diffuse and direct. Direct Normal Irradiance (DNI) is the quantity of the direct solar radiation that reaches the surface in a perpendicular path from the sun direction at its current position in the sky. Diffuse Horizontal Irradiance (DHI) is the not-direct (reflected) quantity of radiation hitting a surface from sun and has been scattered by particles in the atmosphere. Global

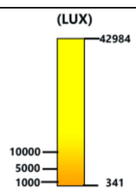
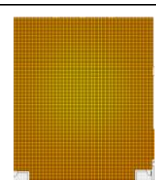
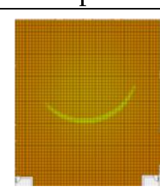
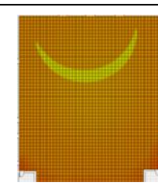
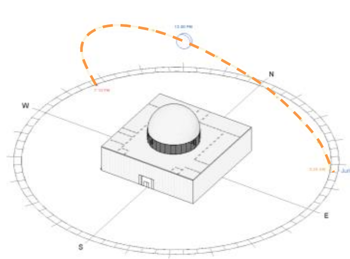
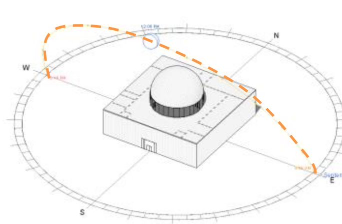
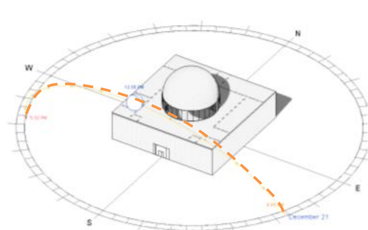
Horizontal Irradiance (GHI) is the total quantity of radiation. Table 20 shows the GHI,DNI and DHI values coming from EnergyPlus weather database. As can been seen in the table, the values for GHI DNI DHI are higher at 8:00 in all cases compared to 4:00 pm especially direct sunlight which means more illuminance is coming directly into the area. This can also explain why the illuminance level in June is much higher (as a magnitude) followed by September and lastly December.

Table 21: GHI,DNI and DHI values coming from EnergyPlus weather database in the months tested

Timing	8:00 AM			12:00 PM			4:00 PM		
Solar Data (W/m2)	GHI	DNI	DHI	GHI	DNI	DHI	GHI	DNI	DHI
21-Jun	634	731	85	896	831	87	260	462	72
21-Sep	533	691	85	781	807	89	103	236	52
21-Dec	263	476	76	497	680	87	10	3	8

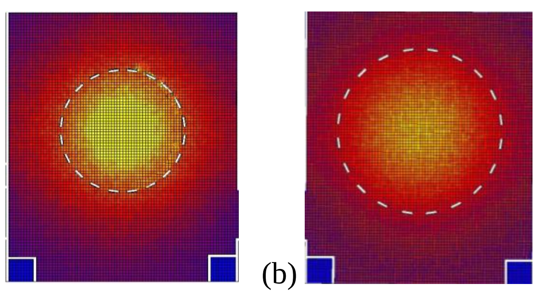
- From the comparison between the cases, it has been noticed that the average lux in 21st December at 12:00pm is higher than 21st June and 21st September. As can be seen from table21 , the daylight coming into the space at 21st December at 12:00pm is entering with an angle due to the sun path at that timing of the year with an angle of 41°, while the sun in 21st June at 12pm is perpendicular (around 88°) on the top of the dome, so the dome top surface is blocking the sun from coming in, it also can be seen in the illustration of the average illuminance level in space (row1 of table 21) that the average lux in 21st December is higher followed by 21st September since the sun path is also with an angle (around 65°) and last 21st June.

Table 22: Comparison of average lux between months at 12:00pm

	21st June	21st September	21st December
Average Illuminance Level 			
Illustration for daylight coming in at 12:00 pm			

4.2.2.3. Effect of increasing diameter

In 21st June and 21st September: Comparing diameter of 7m 14m 18m , the cases with 7m diameter were the lowest compared with using 14m and 18m. Increasing the diameter to 14m and 18m had insignificant effect with the cases with glazing percentage 10% and 15%. When the glazing percentage become 25%, the diameter effect starts to be noticed, the diameter of 18m showed much more brightness inside compared to 14m. This means that diameter is related to the glazing percentage, for the diameter to be effective in bigger sizes (14m,18m) the glazing percentage should be 25% or above other than that (smaller glazing percentage) there will be no effect to very minimal on illuminance level. This statement matches and supports the conclusion from annual variables simulation (sDA and ASE results). D14m and D18m have almost equal illuminance average but the bigger diameter helped in distributing the light in bigger area (better spreading of illuminance) but in lower illuminance value. An example is figure 71 showing case of D=14,18m H=2m H=25%, D14 had some areas with 5,500lux "yellow spot" but in small portion, D18 has no yellow but bigger spread of red.



(a) (b)

Figure 71: Case of H=2m H=25% D=14 (a) , 18m (b)

In 21st December, increasing the diameter shows significant changes in illuminance level. The values of illuminance level are lower in December compared to June and September, that's why the impact of diameter is more visible, doubling the diameter (7m to 14m) almost doubled illuminance (80%-100% increase percentage), and increasing diameter by 30% (14m to 18m) increased the illuminance by 25% - 30% compared to the value at D=14m.

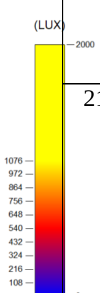
4.2.2.4. Effect of increasing drum's height

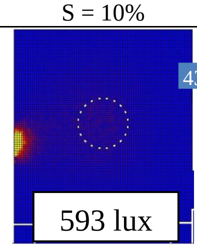
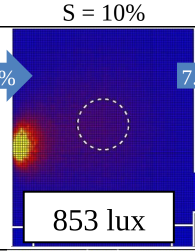
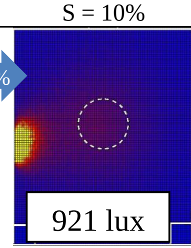
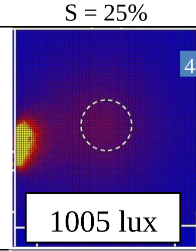
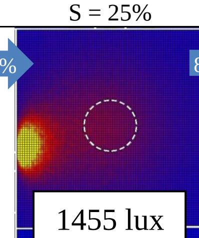
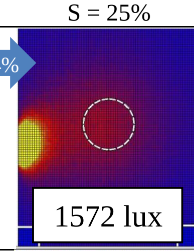
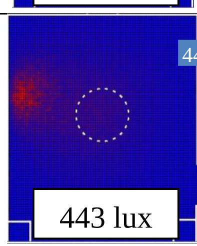
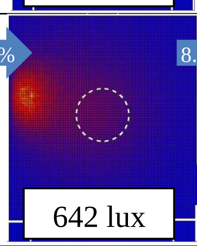
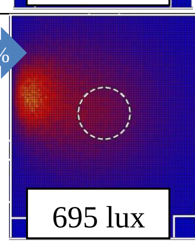
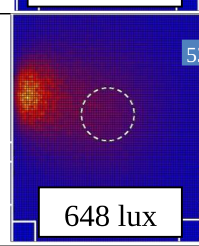
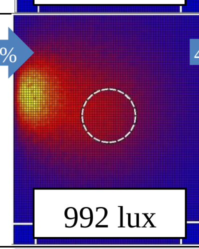
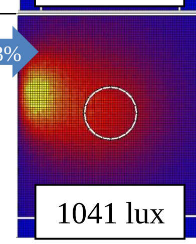
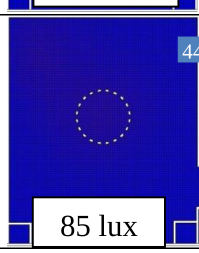
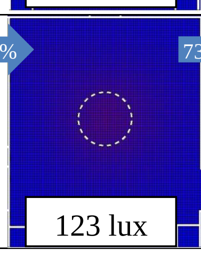
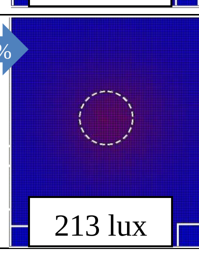
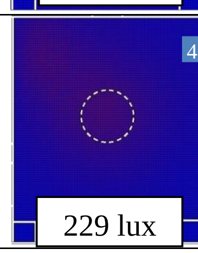
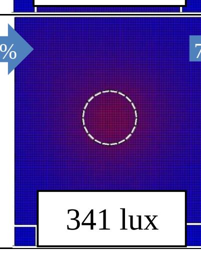
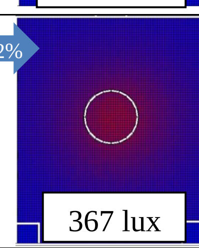
Compared to diameter, increasing the height showed higher illuminance value throughout all tested months. Increase the height from 2m to 3m ("3m" is an increase of 50% of original height "2m") showed significant increase by around 45% - 50% increase in average lux from original case.

Increasing it further more up to 4m (double of the original size) showed insignificant difference compared to 3m height for September and June, results for both H=3m and 4m are almost the same (4m is slightly higher by 8%), while in December increasing height up to 4m had higher impact on average lux around 40% - 70% increase from H=3m for cases with glazing percentage equals to 10% and 15%, but with higher glazing percentage (25% and 100%) the impact become less around 9%-13%.In another words, increasing the height from 2m to 3m enhances the illuminance throughout all months in all cases, however increasing it even higher up to 4m doesn't show any significant difference in illuminance levels except for the case of December with small glazing percentage (10%,15%) where the rate of increase on the average lux can reach up to 30% - 40%. Table 22 show a sample that clarifies the above statements and shows illustrations of illuminance level having different heights in the three tested months.

$$\boldsymbol{Calculation}: Average\ lux\ 1 + (Average\ lux1\ x\ Increase\ Rate) = Average\ lux\ 2$$

Table 23: Comparison of the height effect on average illuminance level within tested months



	H = 2m S = 10%	H = 3m S = 10%	H = 4m S = 10%	H = 2m S = 25%	H = 3m S = 25%	H = 4m S = 25%
21st June	 593 lux	43.8%  853 lux	7.97%  921 lux	 1005 lux	44.7%  1455 lux	8.04%  1572 lux
21st Sep	 443 lux	44.9%  642 lux	8.25%  695 lux	 648 lux	53.1%  992 lux	4.93%  1041 lux
21st Dec	 85 lux	44.7%  123 lux	73.1%  213 lux	 229 lux	48.9%  341 lux	7.62%  367 lux

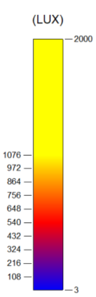
4.2.2.5. Effect of increasing glazing percentage

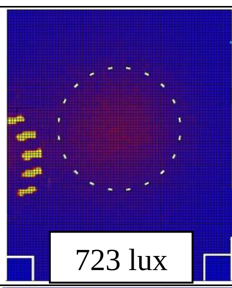
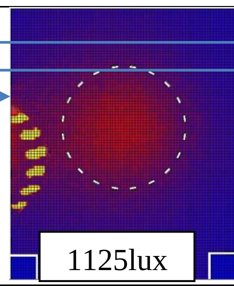
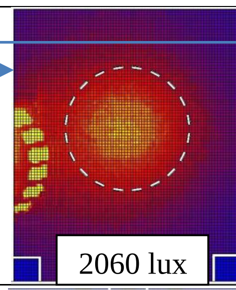
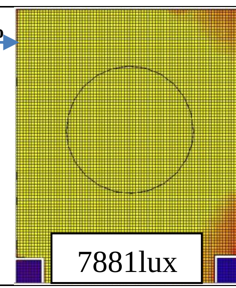
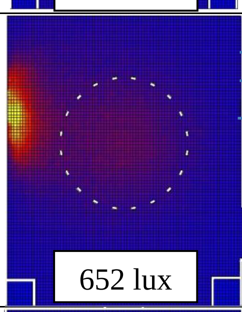
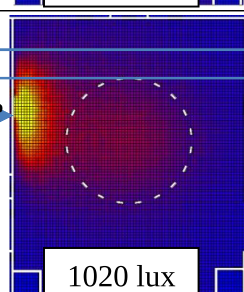
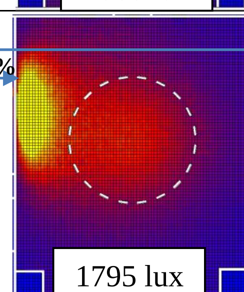
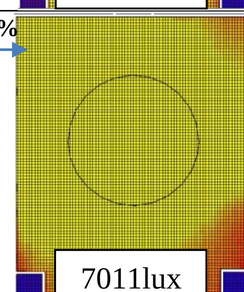
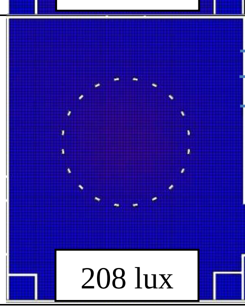
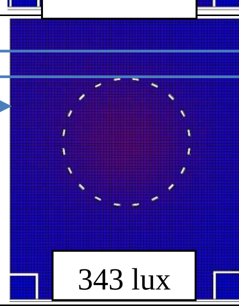
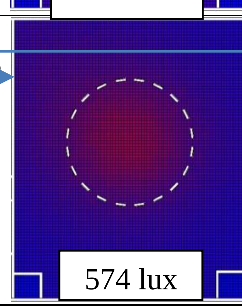
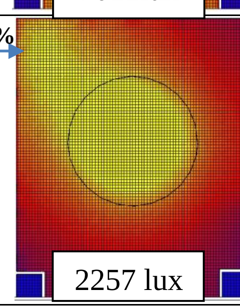
The highest impact among the three variables is the glazing percentage. Increasing the percentage of glazing enhanced the illuminance level for all cases throughout the months. Compared to the original case (10%), having an increase in glazing percentage by 5% (10%-15%) enhanced the average illuminance level up to (55% - 65%). Increasing the glazing by 15% (10%-25%) enhanced the illuminance level by (175% - 200%) , and increasing it by 90% (10%-100%) the illuminance level enhanced by (965% -1000%) which is ten times the original case.

Table 23 shows the case of D=14m H=2m case with different glazing percentage in tested months.

Table 24: Comparison of the glazing percentage effect on illuminance level within tested months

Calculation: *Average lux 1* + (*Average lux1 x Increase Rate*) = *Average lux 2*



	S = 10%	S = 15%	S = 25%	S = 100%
21st June	 723 lux	55.6%  1125lux	185%  2060 lux	990%  7881lux
21st Sep	 652 lux	56.3%  1020 lux	175.3%  1795 lux	975.3%  7011lux
21st Dec	 208 lux	64.9%  343 lux	176%  574 lux	985.1%  2257 lux

4.2.2.6. Maximum and minimum illuminance levels

Comparing all possibilities and combinations for the three variables, the simulations showed the cases with highest illuminance levels are (when the full floor exceeding 2,000 lux):

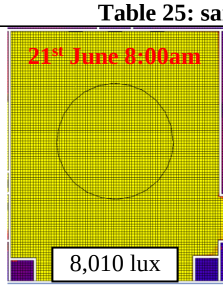
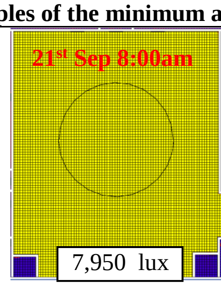
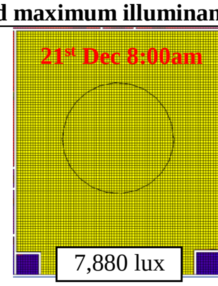
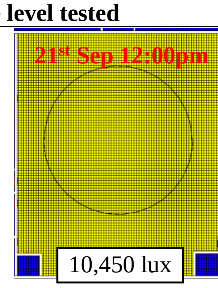
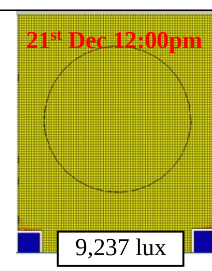
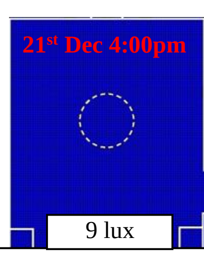
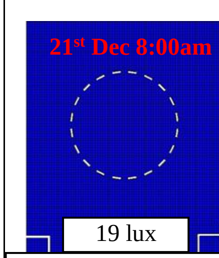
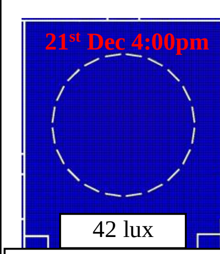
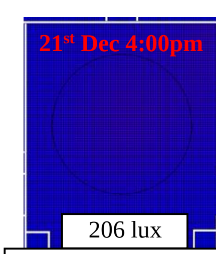
- D=14m, H=3m,4m, S=100% (21st Jun all timings, 21st Sep at 8:00am and 12:00pm ,21st Dec at 12:00pm)
- D=18m, H=2m , S=100% (21st Jun all timings, 21st Sep at 8:00am and 12:00pm)
- D=18m, H=3m , S=100% (21st Jun all timings, 21st Sep at 8:00am and 12:00pm, 21st Dec at 12:00pm)
- D=18m, H=4m , S=100% (21st Jun and 21st Sep all timings , 21st Dec at 8:00am and 12:00pm)

The combinations that had the lowest illuminance levels were the following (when the full floor doesn't exceed 220 lux):

- D=7m,14m,18m , H=2m,3m,4m , S=10%,15%,25%100% (21st Dec at 4:00pm)
- D=7m,14m,18m , H=2m,3m,4m , S=10%,15% (21st Dec at 8:00am)

Table 24 shows samples of the minimum and maximum illuminance level tested:

Table 25: samples of the minimum and maximum illuminance level tested

Minimum Lux	 21st June 8:00am 8,010 lux D=14m,H=3m,S=100%	 21st Sep 8:00am 7,950 lux D=14m,H=3m,S=100%	 21st Dec 8:00am 7,880 lux D=14m,H=4m,S=100%	 21st Sep 12:00pm 10,450 lux D=18m,H=3m,S=100%	 21st Dec 12:00pm 9,237 lux D=18m,H=4m,S=100%
Maximum Lux	 21st Dec 8:00am 85 lux D=7m,H=2m,S=10%	 21st Dec 4:00pm 9 lux D=7m,H=3m,S=15%	 21st Dec 8:00am 19 lux D=14m,H=4m,S=10%	 21st Dec 4:00pm 42 lux D=18m,H=3m,S=25%	 21st Dec 4:00pm 206 lux D=18m,H=4m,S=100%

4.2.2.7. Impact of independent variables "D, H, S" on dependent variable "illuminance level"

Comparing the three variables, all the simulated cases were organized and a mean for their impact was done to test the effectiveness of each variable on the illuminance level for the base case which is D=7m ,H=2m, S=10%. This was done by dividing the average lux gotten when changing each variable individually and dividing it on the base case average lux, to get how much the average illuminance was increased "multiplied". The effectiveness of them on the illuminance level can be summarized in the following figures:

June:

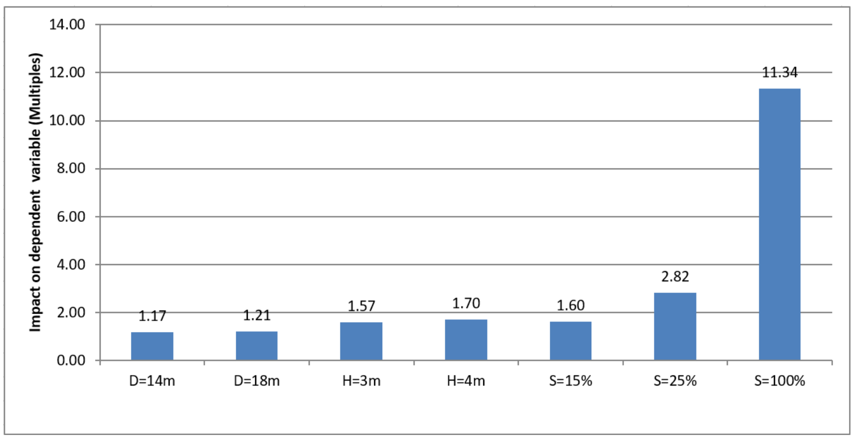


Figure 72: Impact on illuminance level at 21st June "average lux gotten when changing each variable individually and dividing it on the base case average lux"

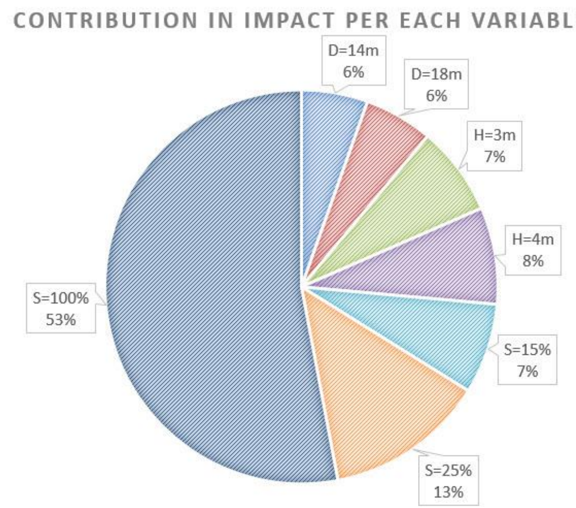


Figure 73:Impact on illuminance level "in Percentages" at 21st June

Sep:

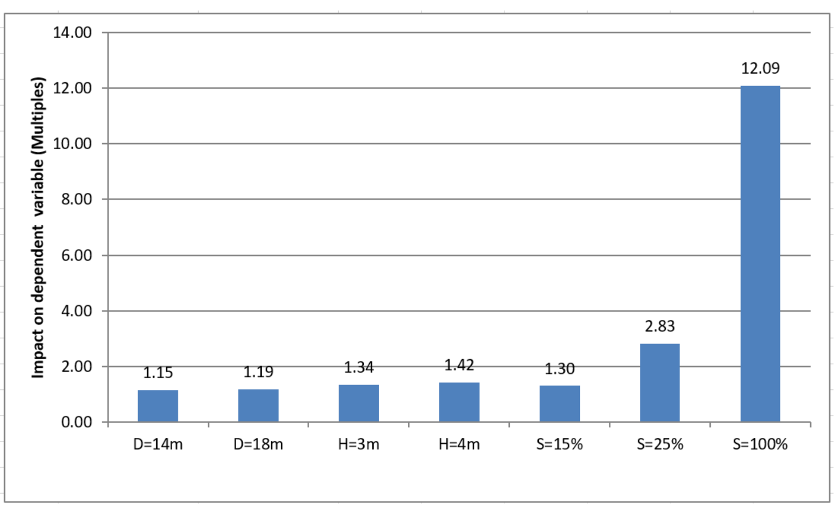


Figure 74: Impact on illuminance level at 21st September "average lux gotten when changing each variable individually and dividing it on the base case average lux"

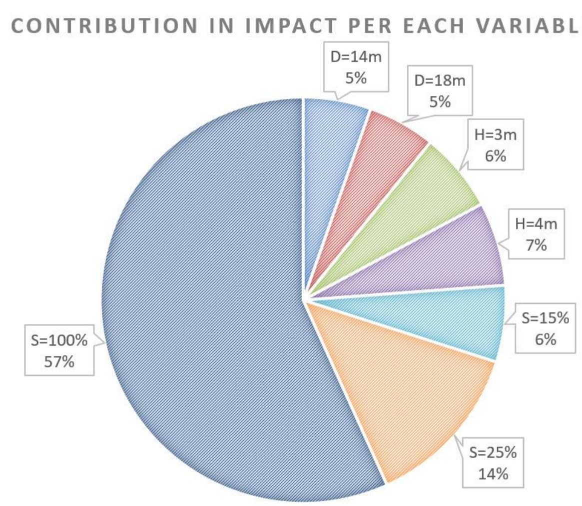


Figure 75:Impact on illuminance level "in Percentages" at 21st September

Dec:

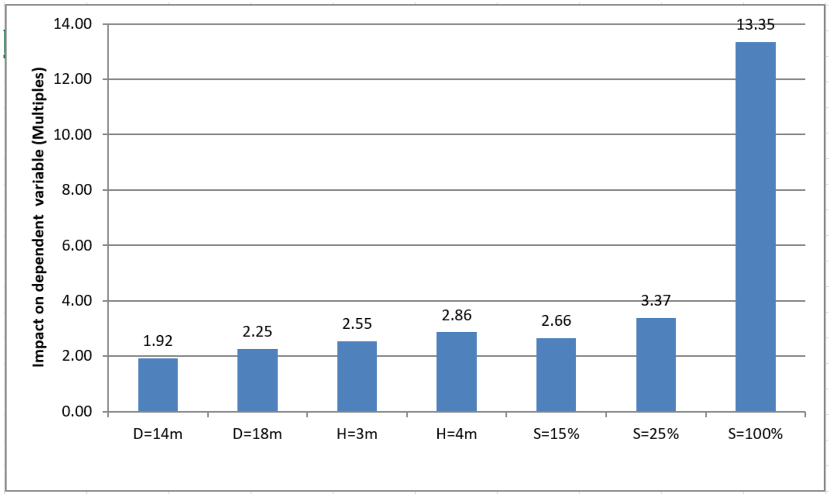


Figure 76: **Impact on illuminance level at 21st December "average lux gotten when changing each variable individually and dividing it on the base case average lux"**

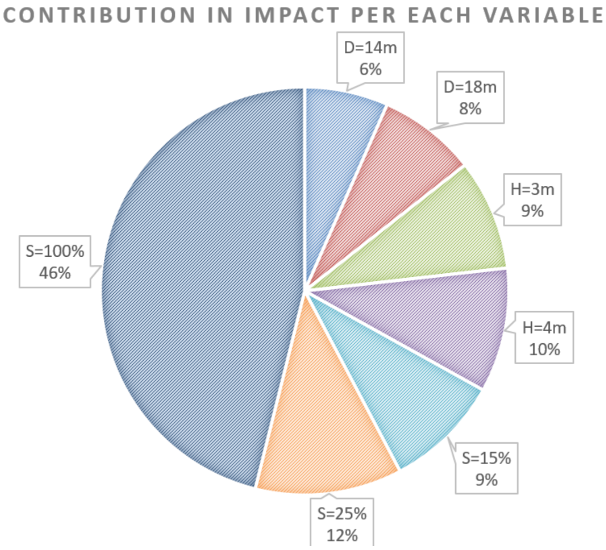


Figure 77: Impact on illuminance level "in Percentages" at 21st December

As noticed:

1) Ranking of impact was, highest impact is the glazing percentage =100%, followed by glazing percentage=25%, then height =4m, glazing percentage=15% and height=3m are almost the same, followed by diameter of 18m and last diameter of 14m. The values vary depending on the month as can be seen in figure 72-74-76.
2) When creating a chart to classify the participation of each variable in enhancing the illuminance average level, the findings where:
    a. 21st June, a glazing percentage of 100% has the potential to enhance the average illuminance level by 53% compared to others, followed by percentage glazing of 25% with capability of 13% to improve the average illuminance level, then height of 4m with 8%, the height of 3 and glazing of 15% are similar with 7%, and last the diameter of 18m and 14m with similar contribution which is 6%, this approves the statements in the previous sections. (Check figure.73 for the chart).

b. 21st September, glazing percentage of 100% have higher impact on illuminance level compared to 21st June with 57% ability to enhance illuminance level compared to other variables, followed by glazing percentage of 25% with 14% contribution, then height of 4m with 7%, followed by glazing percentage of 15% and height of 3m with 6%, and finally diameter of 18m and diameter of 14m with 5%. (Check figure.75 for the chart).

c. 21st December, the other variables had higher impact on the illuminance average which means December month is more sensitive "more effected" towards dome's changings compared to other months. Glazing percentage of 100% can enhance the illuminance level by 46%, followed by glazing percentage of 25% with contribution of 12%, then height of 4m with 10%, height of 3m and glazing percentage of 155% with 9%, diameter of 18m had higher impact than 14m compared to results in June and September (which approves the statements mentioned in previous sections) with contribution of 8%, and last diameter of 14m with 6%.(Check figure.77 for the chart).

3) in 21st June and 21st September, the effect of D14m and D18m is almost equal, while in 21st December the effectiveness of diameter 18 is significantly higher which proves what was highlighted in section 4.2.2.3. Effect of increasing diameter.

4) Increase the height up to 3m showed significant increase. Increasing it higher up to 4m showed not much difference for September and June compared to December which had higher impact on average lux .

5) The degree of impact of drum's height =3m is equal to the effect of glazing percentage =15%.

6) The highest impact among the three variables is the glazing percentage. Increasing the percentage of glazing enhanced the illuminance level for all cases throughout the months.

7) Having a 100% glazing percentage, can increase the illuminance level up to 11-13 times its original (10% glazing).

4.2.3. Case 3: Glare

Glare will be investigated using two metrics which are daylight glare probability (DGP) and Glare Threshold Differential (GTD). DGP considers contrast and vertical illuminance as contributors to visual discomfort, GTD gives a value of glare discomfort by differentiating the maximum luminance that the viewer is looking at with the threshold of the view. Glare is a function of the location of the viewer and the observation direction. Therefore, simulations will be taking in several locations. The simulation will be running on two days 21 June and 21 December at 8:00am, 12:00pm and 4:00pm testing 15 points each point looking horizontally in 4 directions. The case that would be tested is the case with diameter = 14m, drum height = 4.0 m and drum fully glazed. The first part will be showing DGP and GTD simulation results on plan view for each day and time, the second part will be line charts for DGP and GTD results individually comparing the 15 points four directions values per each date and time. For further details please refer to *Case3: Glare* in section (3.4.3.Simulation Scenarios). The simulation results can be found in **Appendix B – DGP simulation results** and **Appendix C – Glare threshold simulation results for GTD calculations**.

This section will be discussed and explained as following:

4.2.3.1. DGP and GTD results on Plan View and comparison between points.

- 21st Jun at 8:00am
- 21st Jun at 12:00pm
- 21st Jun at 4:00pm
- 21st Dec at 8:00am
- 21st Dec at 12:00pm
- 21st Dec at 4:00pm

4.2.3.1. DGP and GTD results on Plan View and comparison between points.

- 21st Jun at 8:00 am

Comparing the glare evaluation throughout the floor, glare was recorded to be either intolerable (grid A towards east) or disturbing (grid C towards west). All the cases looking towards the walls had glare to be imperceptible. Cases on grid A were all intolerable (except the cases looking to the walls) and scored the highest values looking towards east and north, this is because of the sun position at 8:00am in 21st June “Summer Solstice”, the sun rises as far to the northeast lighting up the west side of the room (grid A). Cases on grid B showed variety in glare evaluation, the cases looking towards east and north all were either intolerable or disturbing (the case under the dome) for the same reason as grid A. The cases with precipitable where in grid B, looking towards west (B2, B4) or towards south(B3). For grid C, looking towards north and west recorded to be disturbing it’s also because of the sun angle at that timing but as a value its less than grid A since grid C is located east of the dome and hence the right side of the dome couldn’t be reached by the sun, that space is affected by diffused sun light from drum glazing and reflection from dome. An illustration for the following analysis can be seen in figure 78.

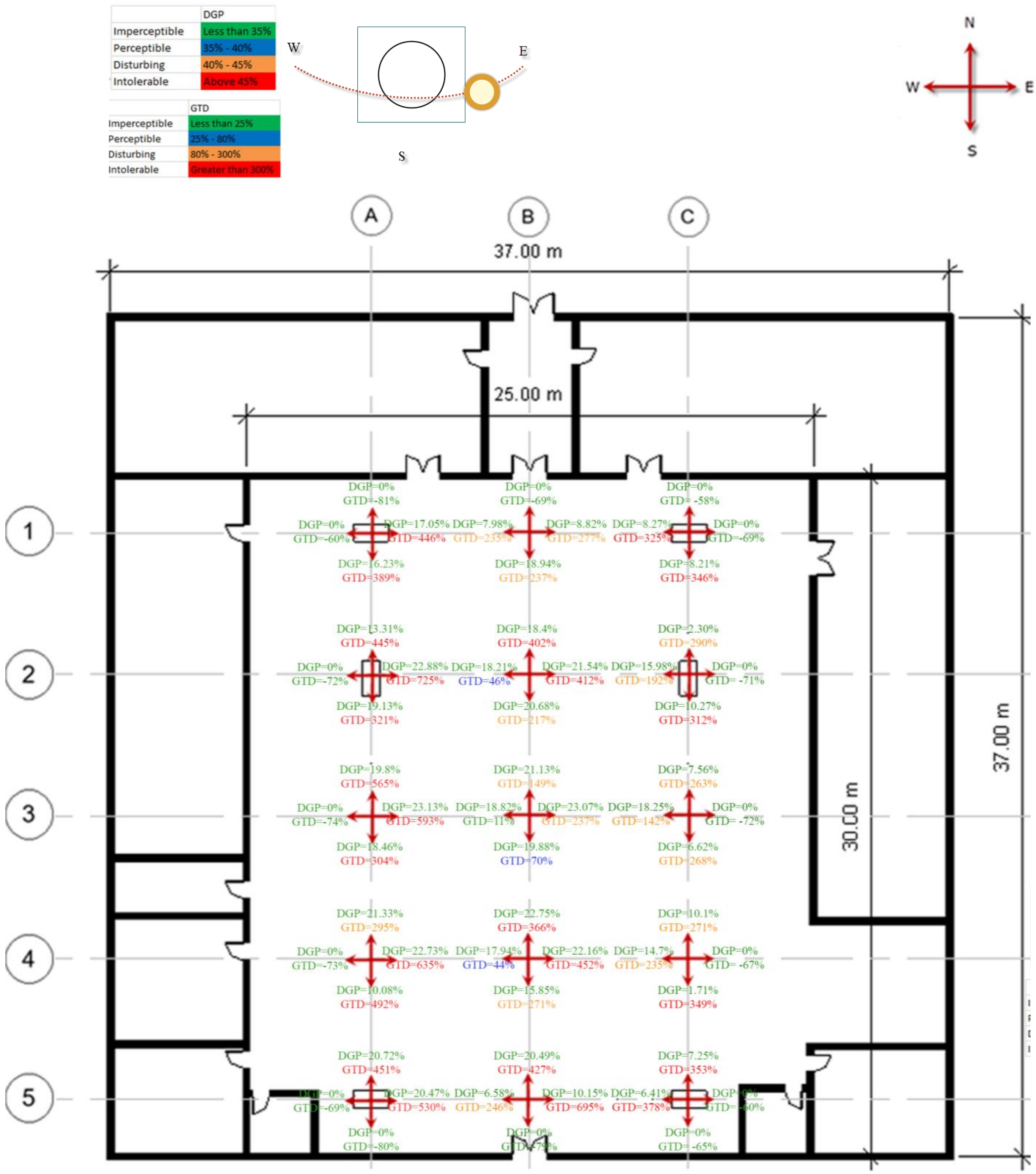


Figure 78: Glare simulation results for DGP and GTD - 21 Jun at 8am

Comparing DGP results, highest values as an overall were east having A3 (23.13%) and B3 (23.07%) as the highest, followed by north having A4 (22.73%) and B4 (22.16%) as the highest. This can be justified by the sun angle since at 8:00 am on 21st June the sun rises from northeast with an angle of 31°, so the most effected points will be the points on row 3 (central space) and 4 (the line facing the sun directly when its rising). All points facing the walls (around the area perimeter) got a DGP=0% which are all west points in grid A, all east points in grid C, the north of row 1 in all grids, and the south of row 5 in all grids. Figure 79 illustrates the results for DGP highest and lowest points.

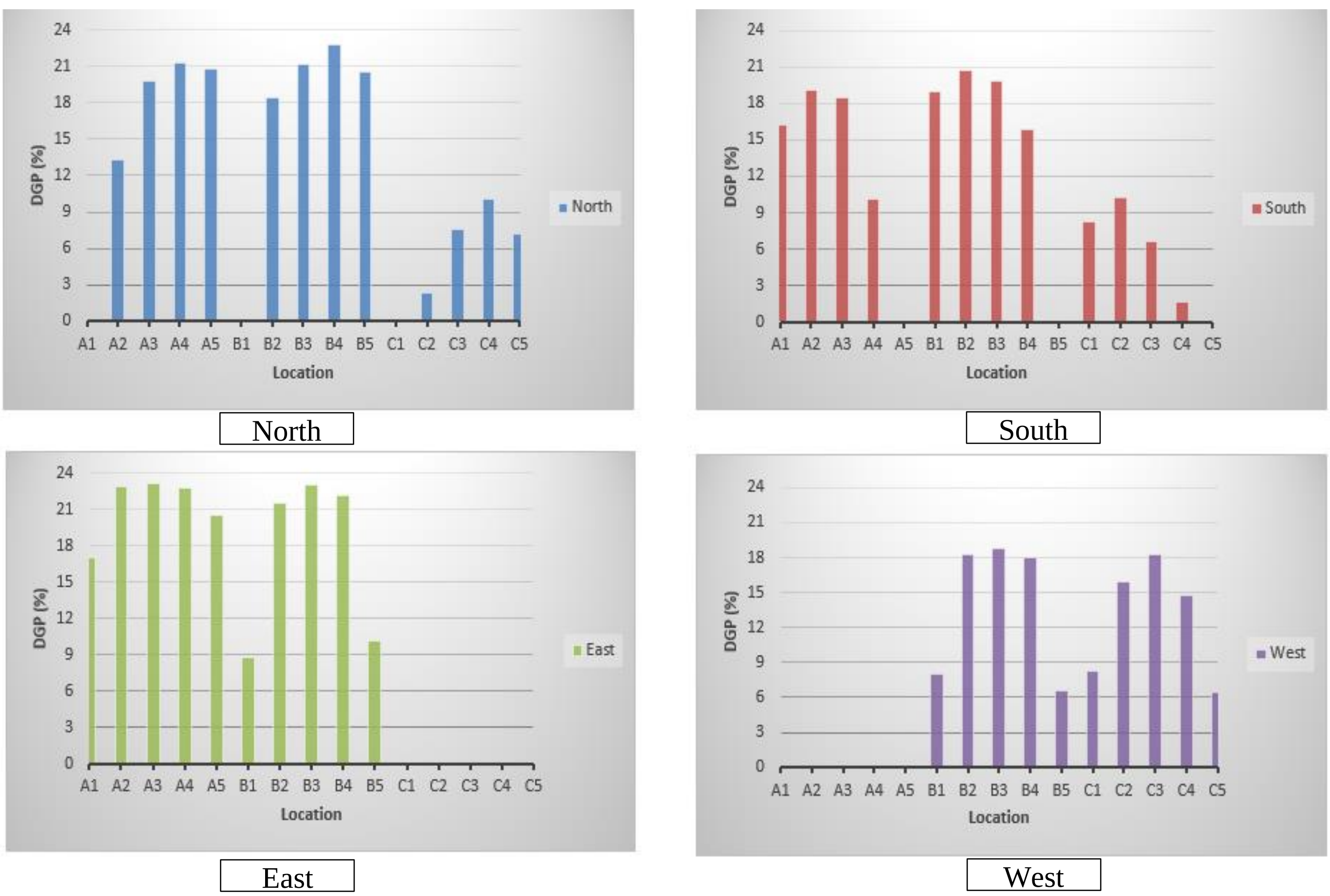


Figure 79: 21st Jun at 8:00 am - DGP(%) results

Comparing GTD results, it showed similar results as DGP by having as on overall east points been the highest such as A2 (725%) and B5 (695%), followed by north points. All points facing the walls (around the area perimeter) got a GTD=negative% which are all west points in grid A, all east points in grid C, the north of row 1 in all grids, and the south of row 5 in all grids. As an overall, the points were either in disturbing range or intolerable, and the points towards space perimeter were imperceptible. The only cases which passed GTD test were (B2, B4) looking west and (B3) looking south which makes sense because they are looking away from the sun direction. Figure 80 illustrates the results for GTD highest and lowest points.

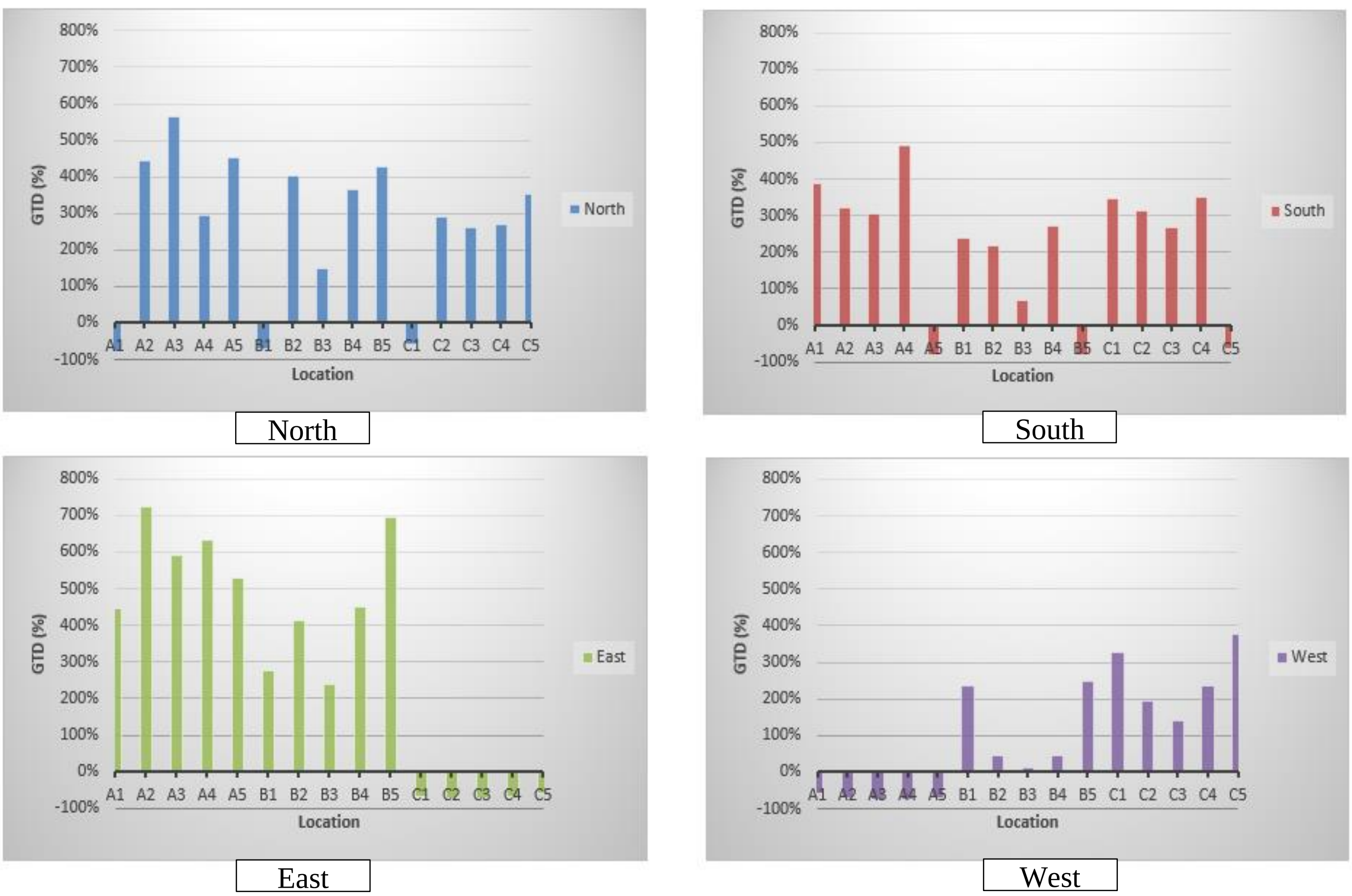


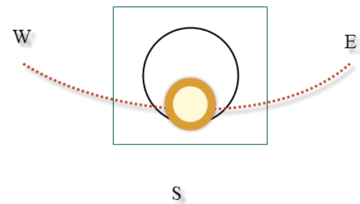
Figure 80: 21st Jun at 8:00 am - GTD(%) results

- 21st Jun at 12:00 pm

Comparing the glare evaluation throughout the floor, glare was recorded to be either intolerable for points around the edges or disturbing for the points surrounding the center of the space. Cases on row1 (first row) and 5 (last row) on the three grids A,B and C looking towards all direction (except wall direction) plus grid A (looking north) and C (looking south) in row 2 and 4 were intolerable. In another words, all points which are not located below dome or facing it were founded interlobate. The points directly below the dome diameter which are row 2 and 4 grid B looking at all directions (except towards the center) plus row 2and4 grid A B C looking towards the center were all recorded as disturbing. The central point B3 which is located at the center below the dome recorded perceptible in all direction as well as B2 (looking towards center) and B4 (looking towards the center). This can be justified by the sun angle at that timing of the year, in 21st June the sun is at its highest position in skyat 12 pm with an angle of 88° (almost prepdicular 90° on roof top), so whatever is below the dome is hiding and only receive minimal daylight from reflections of daylight on dome, walls or floors, while the points below diameter directly recieves more diffused light becayuse they are closer to the walls and some of sunlight from windows at very sharp angle, while the other points around the dome are receiving most of the direct sunlight and though have the highest values in GTD and DGP. All the cases looking towards the walls had glare to be imperceptible. An illustration for the following analysis can be seen in figure 81.

	DGP
Imperceptible	Less than 35%
Perceptible	35% - 40%
Disturbing	40% - 45%
Intolerable	Above 45%

	GTD
Imperceptible	Less than 25%
Perceptible	25% - 80%
Disturbing	80% - 300%
Intolerable	Greater than 300%



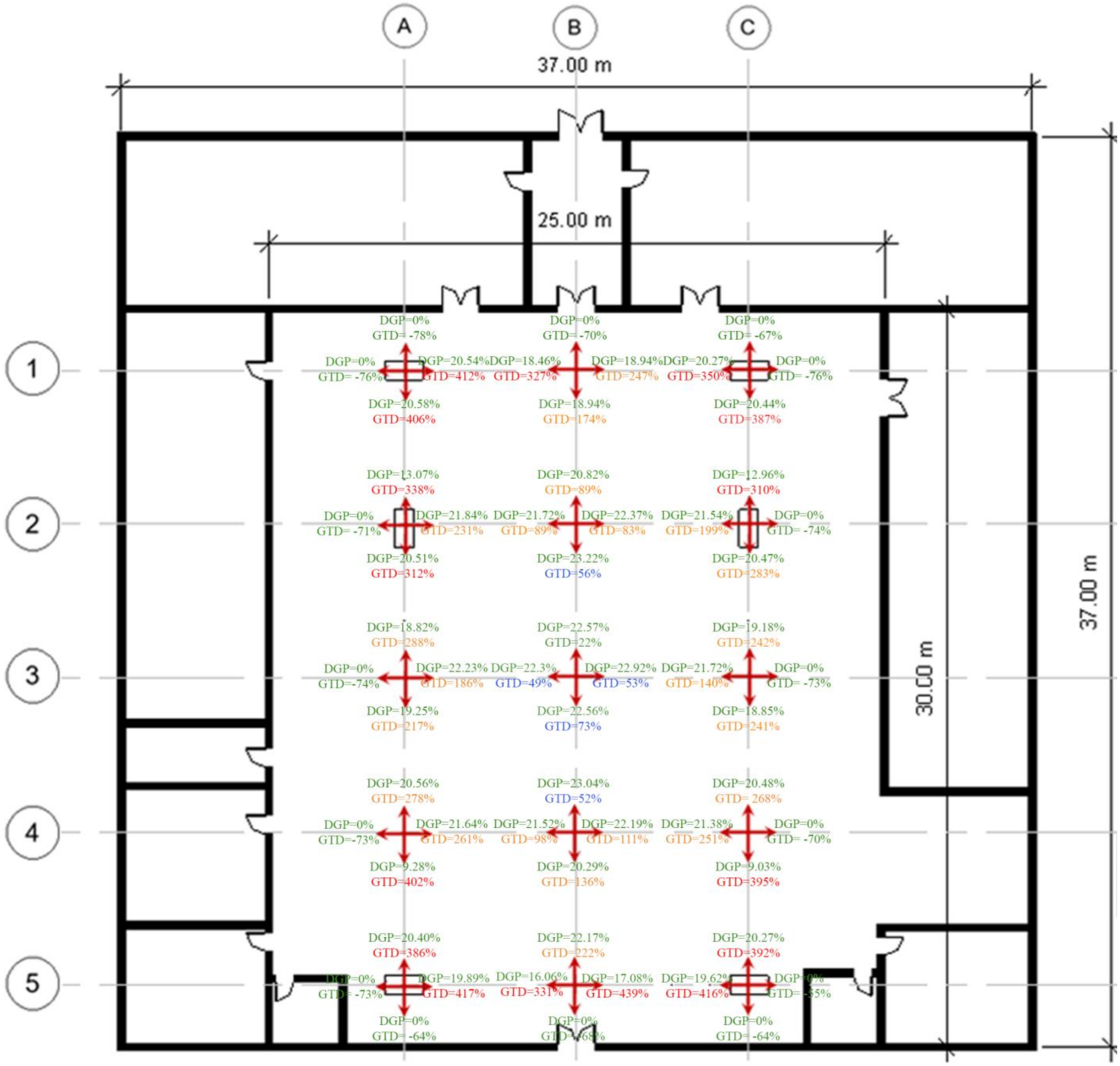


Figure 81: Glare simulation results for DGP and GTD - 21 Jun at 12 pm

Comparing DGP results, most of the points in all direction (except the points with direction looking towards the wall) are all in the same range between 18.85% - 23.2%. All points facing the walls (around the area perimeter) got a DGP=0% which are all west points in grid A, all east points in grid C, the north of row 1 in all grids, and the south of row 5 in all grids. The points that were in between were the points below diameter directly which are A2 and C2 (north) and A4 and C4 (south) looking away from dome as explained in the previous paragraph. Figure 82 illustrates the results for DGP highest and lowest points.

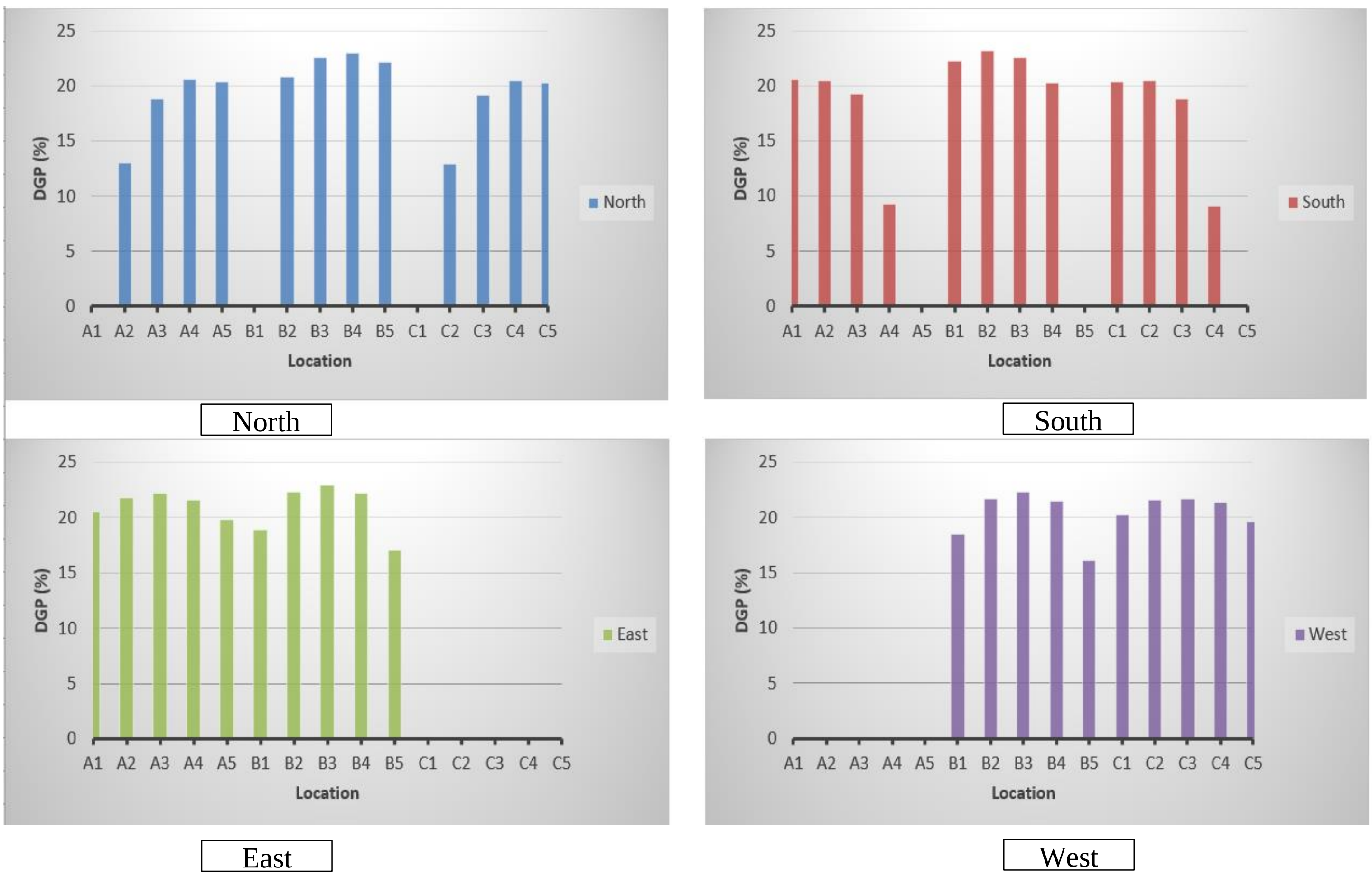


Figure 82: 21st Jun at 12:00 pm - DGP(%) results

Comparing GTD results, similar to DGP the highest value were the points around the dome having the highest to be B5 east 439%, A5 east 417%, C5 west 416%, A1 east 412%. The points on row 5 had higher values than in row 1 since the sun path moves towards south so its lighting up row 5 more than its doing with row 1. All points facing the walls got a GTD=negative% which are all west points in grid A, all east points in grid C, the north of row 1 in all grids, and the south of row 5 in all grids. The cases which passed GTD test were (B3) looking all direction (located in center of space below the dome) since only diffused light is reaching there, and points (B2 south, B4 north) located also below the dome looking towards the center. Figure 83 illustrates the results for GTD highest and lowest points.

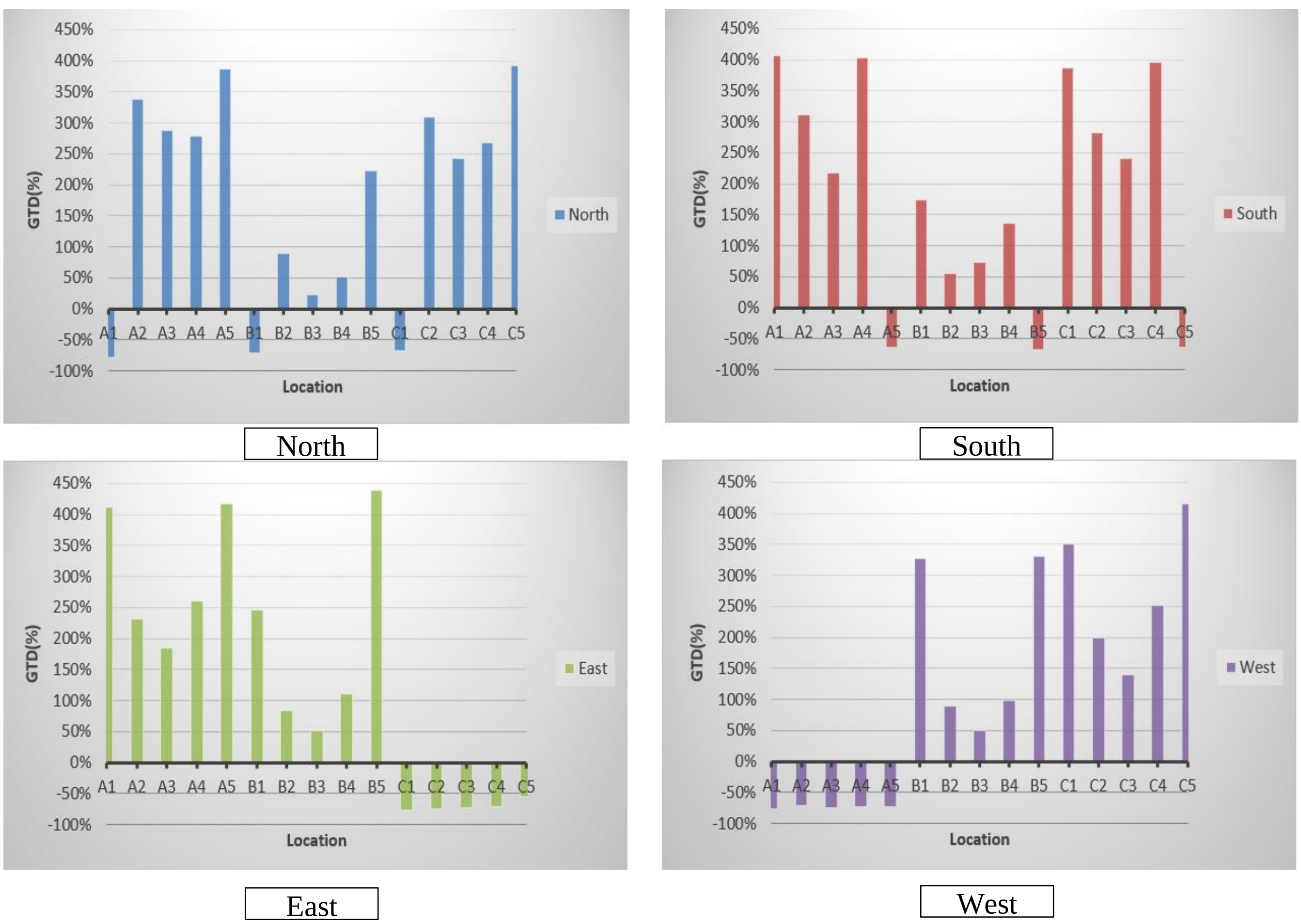


Figure 83: 21st Jun at 12:00 pm - GTD(%) results

- 21st Jun at 4:00 pm

Comparing the glare evaluation throughout the floor, glare was recorded to be either intolerable (gridC towards west) or disturbing (gridA towards east). All the cases looking towards the walls had glare to be imperceptible. Cases on grid C were all intolerable (except the cases looking to the walls) and scored the highest values looking towards west and north, this is because of the sun position at 4:00pm in 21st June "Summer Solstice", the sun sets down as far to the northwest with an angle of 40° making the east side of the room (grid C) receives most of the light. Cases on grid B showed variety in glare evaluation, the cases looking towards west and north all were either intolerable or disturbing (the case under the dome) for the same reason as grid C. The cases with precipitable where in grid B, looking towards east (B2, B4) looking away from the sun. For grid A, looking towards north and east recorded to be disturbing it's also because of the sun angle at that timing but as a value its less than grid C since grid A is located west of the dome and hence the left side of the dome receive less sun light because of the position and angle of the sun, that space is affected by diffused sun light from drum glazing and reflection from dome. An illustration for the following analysis can be seen in figure 84.

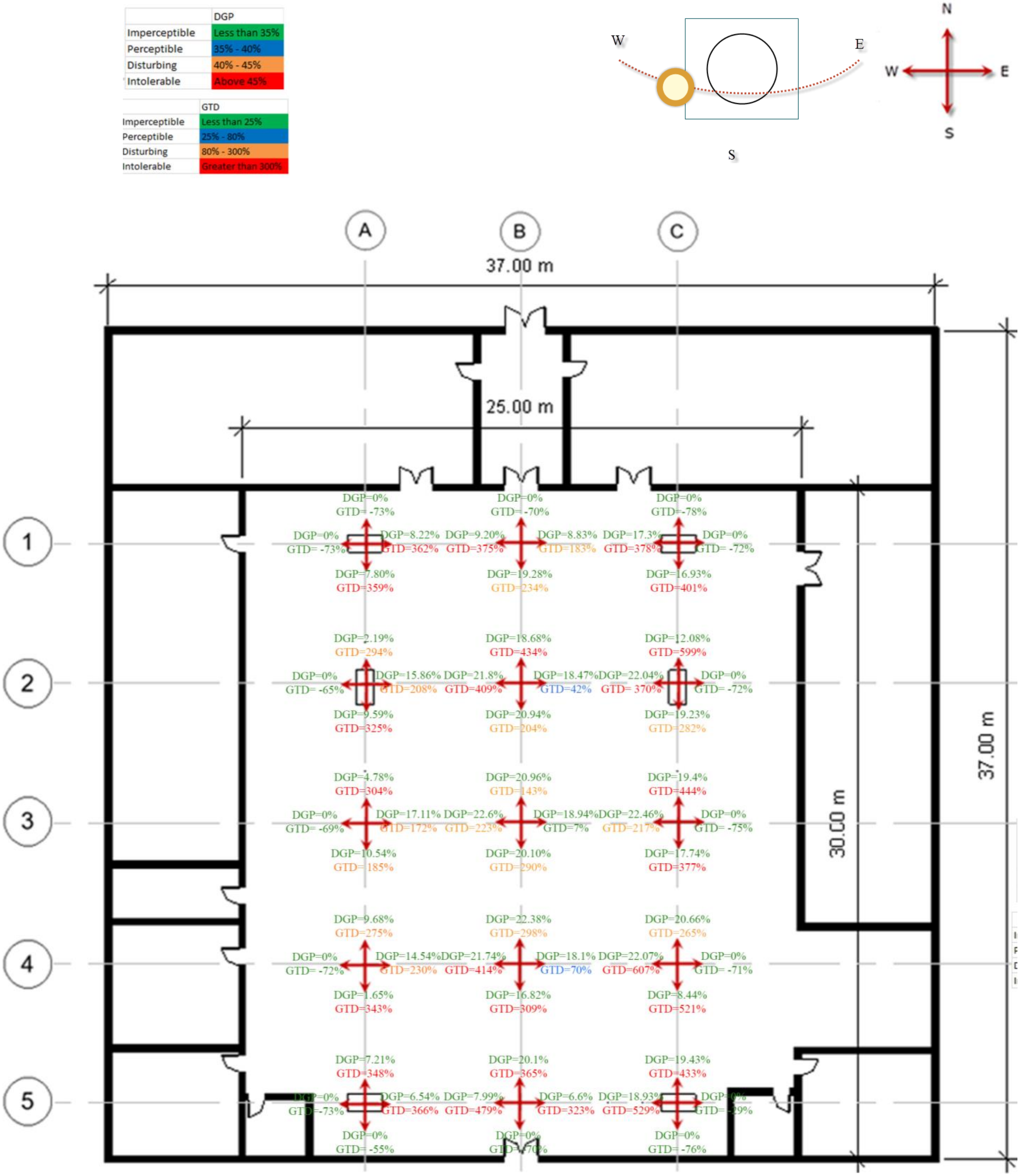


Figure 84:Glare simulation results for DGP and GTD - 21 Jun at 4 pm

Comparing DGP results, highest values as an overall were east points for B and C grids having C3 (22.46%) and B3 (23.4%) as the highest, followed by north having C4 (20.7 %) and B4 (22.3%) as the highest. This can be justified by the sun angle since at 4:00 pm on 21st June the sun sets at southeast with an angle of 40°, so the most effected points will be the points on last grid (Grid C) and row 1 in all grids. All points facing the walls (around the area perimeter) got a DGP=0% which are all west points in grid A, all east points in grid C, the north of row 1 in all grids, and the south of row 5 in all grids. Figure 85 illustrates the results for DGP highest and lowest points.

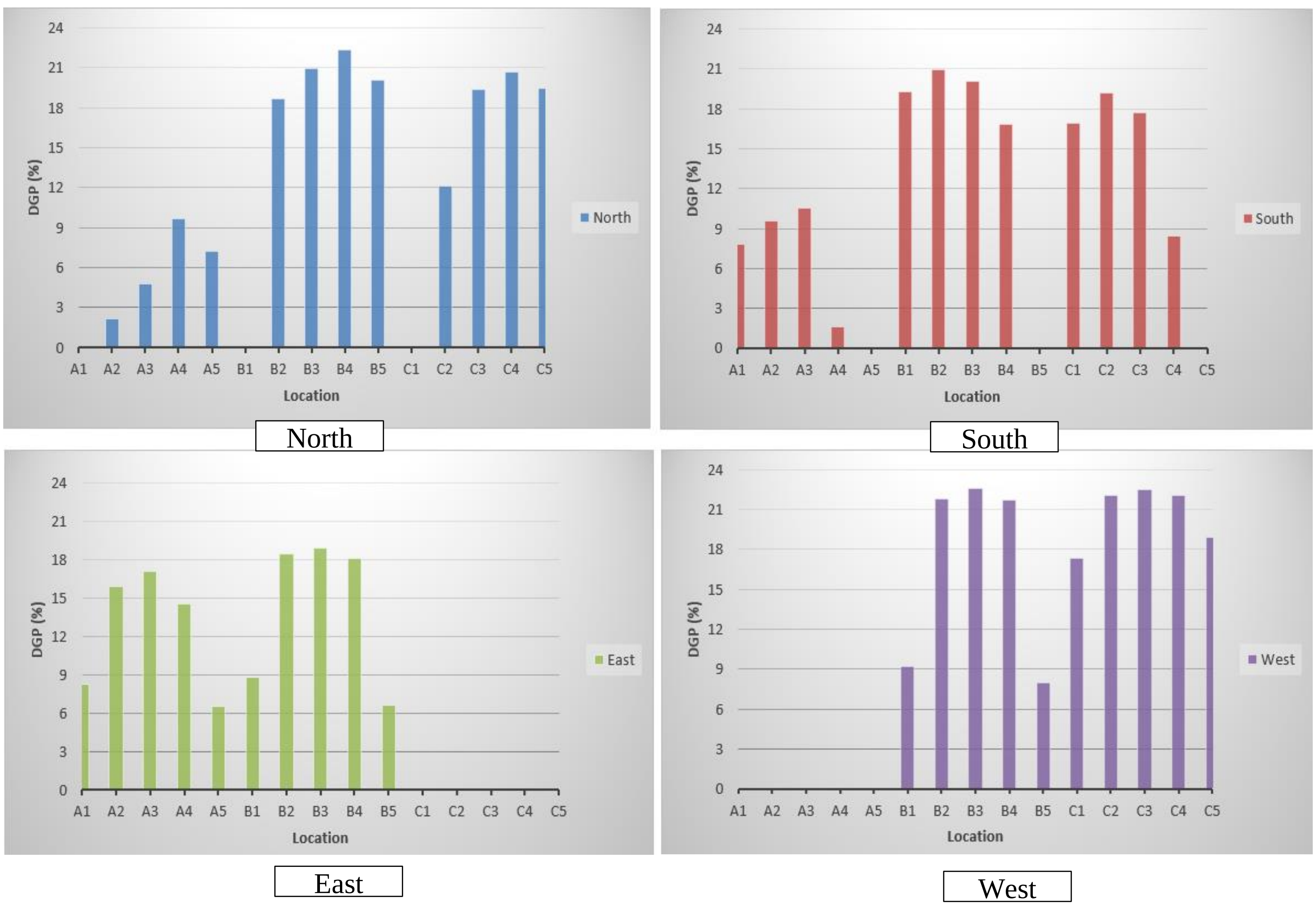


Figure 85: 21st Jun at 4:00 pm - DGP(%) results

Comparing GTD results, it showed similar results as DGP by having as on overall west points been the highest such as C4 (607%) and C5 (529%), followed by north points like C2 (599%). All points facing the walls (around the area perimeter) got a GTD=negative%. Points on grid 3 looking towards the center will less in values compared to other rows and found to be disturbing, this is probably because they are under the dome so they are less effected by the sun directly. As an overall, the points were either in disturbing range or intolerable, and the points towards space perimeter were imperceptible. The only cases which passed GTD test were (B2, B4) looking east and (B3) its because these two points are looking away from the sun direction and within the perimeter under the dome. Figure 86 illustrates the results for GTD highest and lowest points.

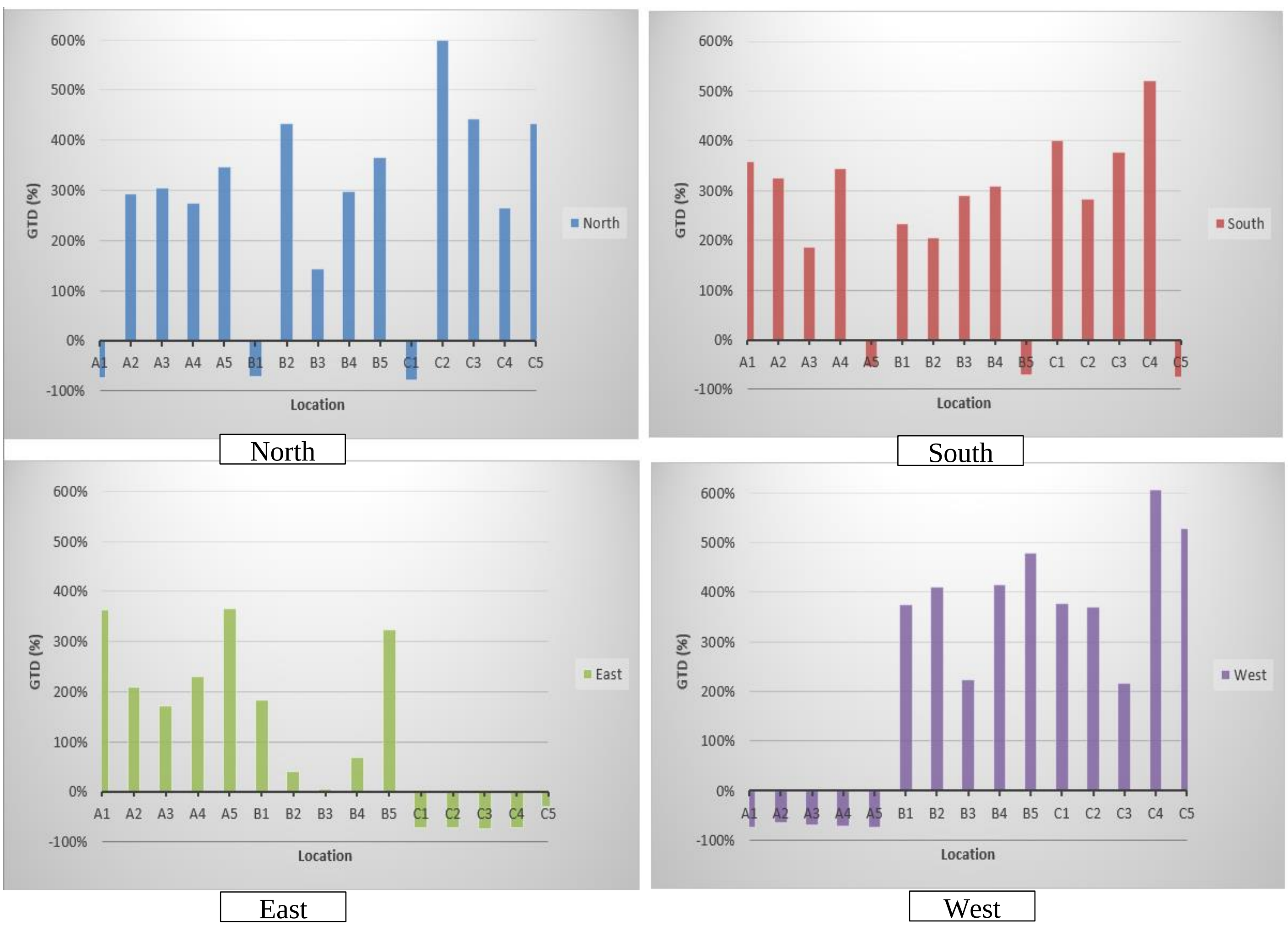


Figure 86: 21st Jun at 4:00 pm - GTD(%) results

- 21st Dec at 8:00 am

As first sight, the results on the 15 points looks similar to 8:00am Jun but with lower values (comparing DGP and GTD of both timings). Comparing the glare evaluation throughout the floor, glare was recorded to be either intolerable (grid A towards east and south) or disturbing (grid B towards east and south , grid C towards west). All the cases looking towards the walls had glare to be imperceptible. Cases on grid A were all intolerable (except the cases looking to the walls) and scored the highest values looking towards east and south, this can be justified by the sun position in sky at 8:00am in 21st Dec “winter Solstice”, the sun rises as far to the southeast lighting up the west side of the room (grid A), also as values its lower than what was recorded in Jun 21st 8:00am that’s because the angle from horizon is less (around 11° while 21st Jun was 31°). The low angle made the values lower in general for all points but in the same time raised the values looking towards south compared to 21st Jun for grid A and B, but it didn’t increase south for grid C because the angle is quite low and sharp so it didn’t hit that grid with direct sun as much as the other two grids. Cases on grid B showed variety in glare evaluation, the cases looking towards east and south all were either intolerable or disturbing. The cases with precipitable where in grid B, looking towards north (B2, B3, B4). For grid C, looking towards south and west recorded to be disturbing it’s also because of the sun angle at that timing but as a value its less than grid A since grid C is located east of the dome and though the right side of the dome is in a shaded space so it couldn’t be reached by the sun, that space is affected by diffused sun light from drum glazing and reflection from dome and very minimal direct light. An illustration for the following analysis can be seen in figure 87.

Figure 87: Glare simulation results for DGP and GTD - 21 Dec 8am

Comparing DGP results, highest values as an overall were east having A2 (22.55%) and A3 (22.38%) as the highest, followed by south having A1 (21.76%) and A2 (21.54%) as the highest and then north values to be intermediate. This can be justified by the sun angle since at 8:00 am on 21st December the sun rises from southeast with at an angle of 11°, so the most effected points will be the points on row 3 (central space) and 4 (the line facing the sun directly when its rising). All points facing the walls (around the perimeter area) got a DGP=0% which are all west points in grid A, all east points in grid C, the north of row 1 in all grids, and the south of row 5 in all grids. Figure 88 illustrates the results for DGP highest and lowest points.

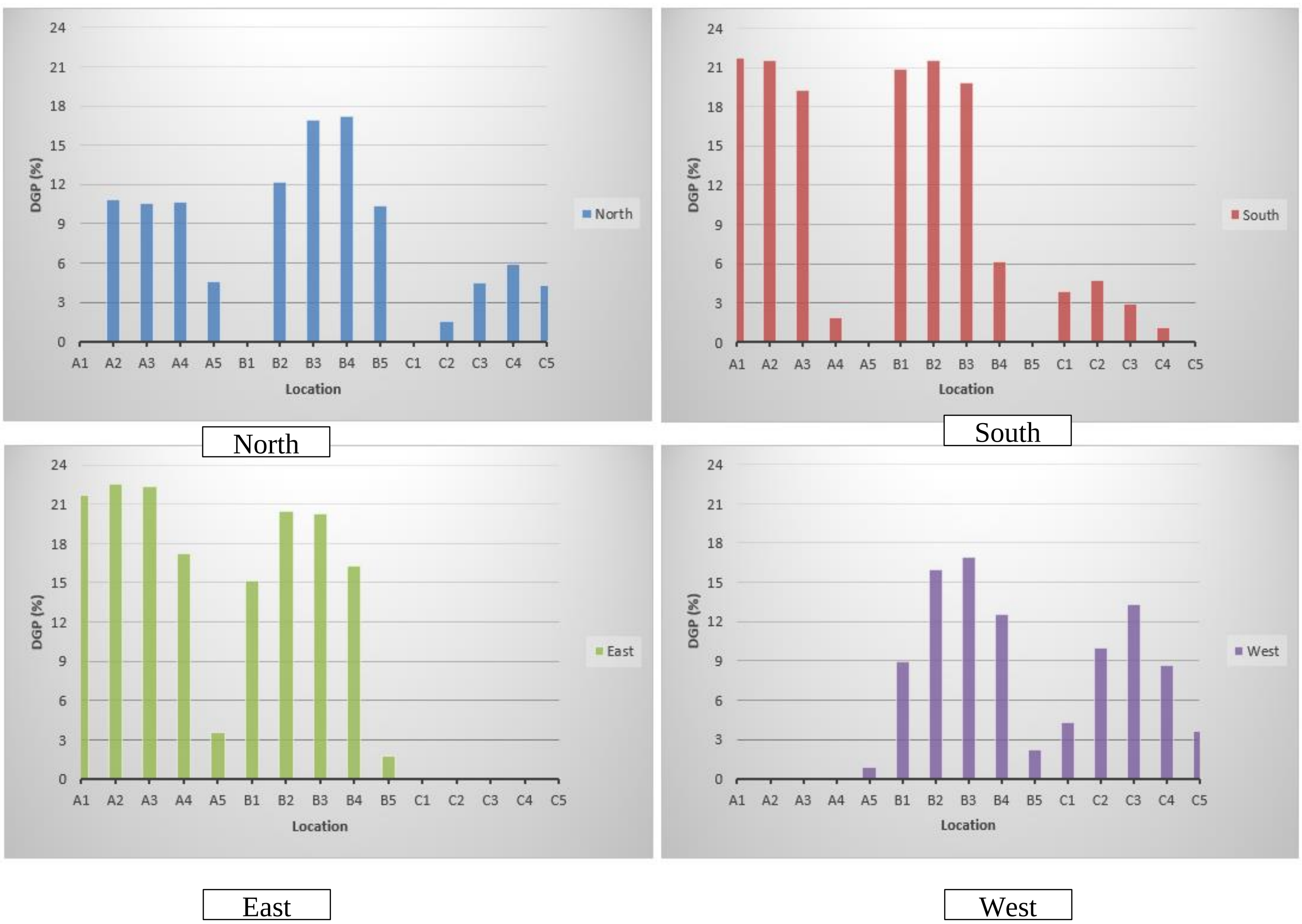


Figure 88: 21st Dec at 8:00 am - DGP(%) results

Comparing GTD results, it showed as overall south points been the highest such as A4 (791%) and A2 (769%), followed by east points such as A3 (712%). All points facing the walls (around the area perimeter) got a GTD=negative% which means they are intolerable. As an overall, the points were either in disturbing range or intolerable, and the points towards space perimeter were imperceptible. The only cases which passed GTD test were (B2, B3, B4) looking north since they are looking away from the sun direction and also located below or within edge of the dome so less direct sunlight is hitting them. Figure 89 illustrates the results for GTD highest and lowest points.

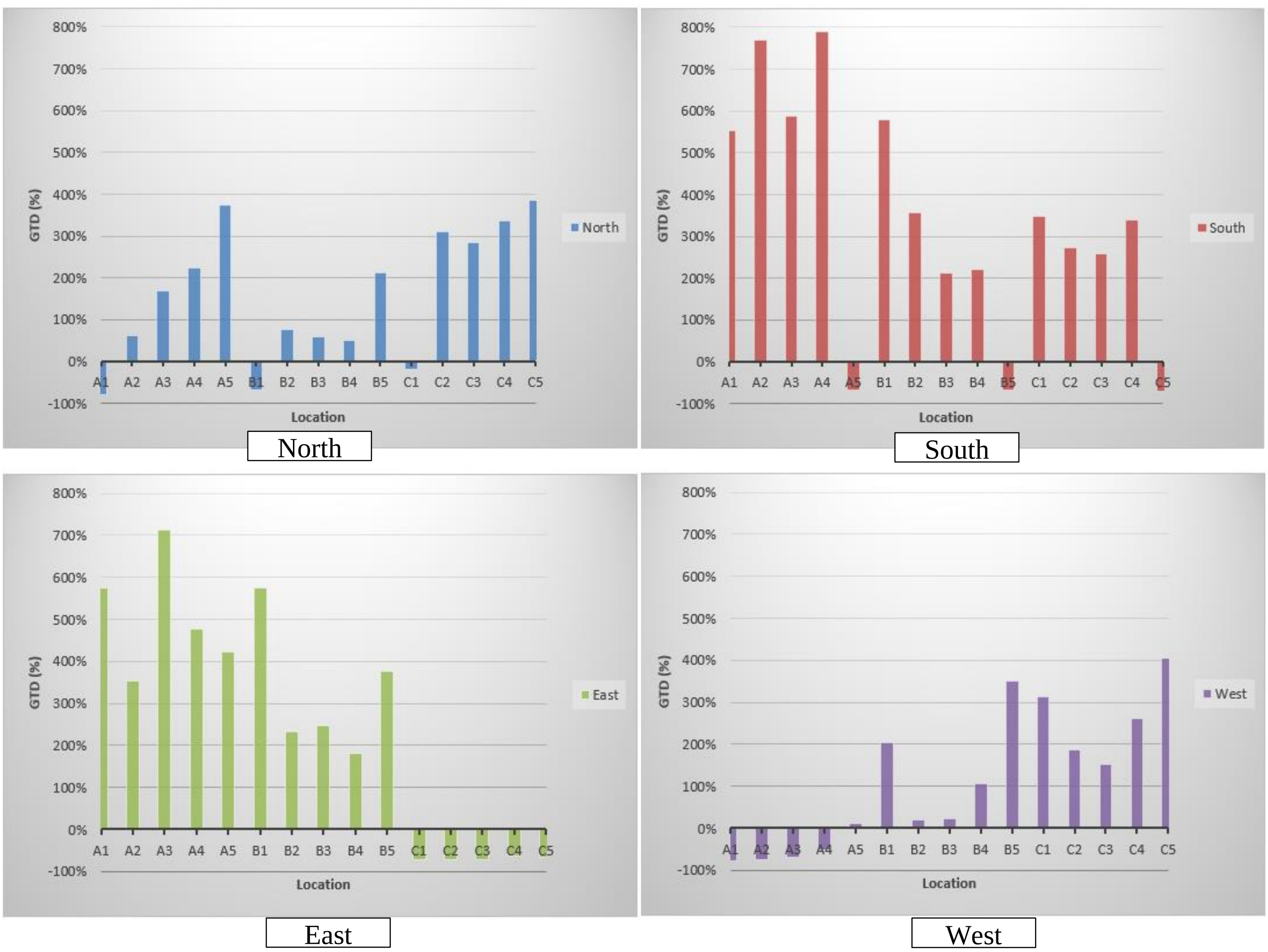


Figure 89: 21st Dec at 8:00 am - GTD(%) results

- 21st Dec at 12:00 pm

Comparing to 21st Jun and Dec at 12:00pm for both DGP and GTD values, the South , west and east values in December are much higher compared to June, but for North values it became less around the parameter (Grid A and C, ROW 1 and 2). Comparing the central space (B2,B3,B4) the December values in all direction were higher compared to June, this can be justified by the angle of the sun from horizon which is 41° (while 21st Jun was 88° almost perpendicular to the roof). The low angle introduced more space into the central space and made the values raise up to be disturbing for occupants, plus because of the sun path in the Winter solstice, the sunpath is lower in the south direction which explains why the south values were the highest compared to the rest. An illustration for the following analysis can be seen in figure 90.

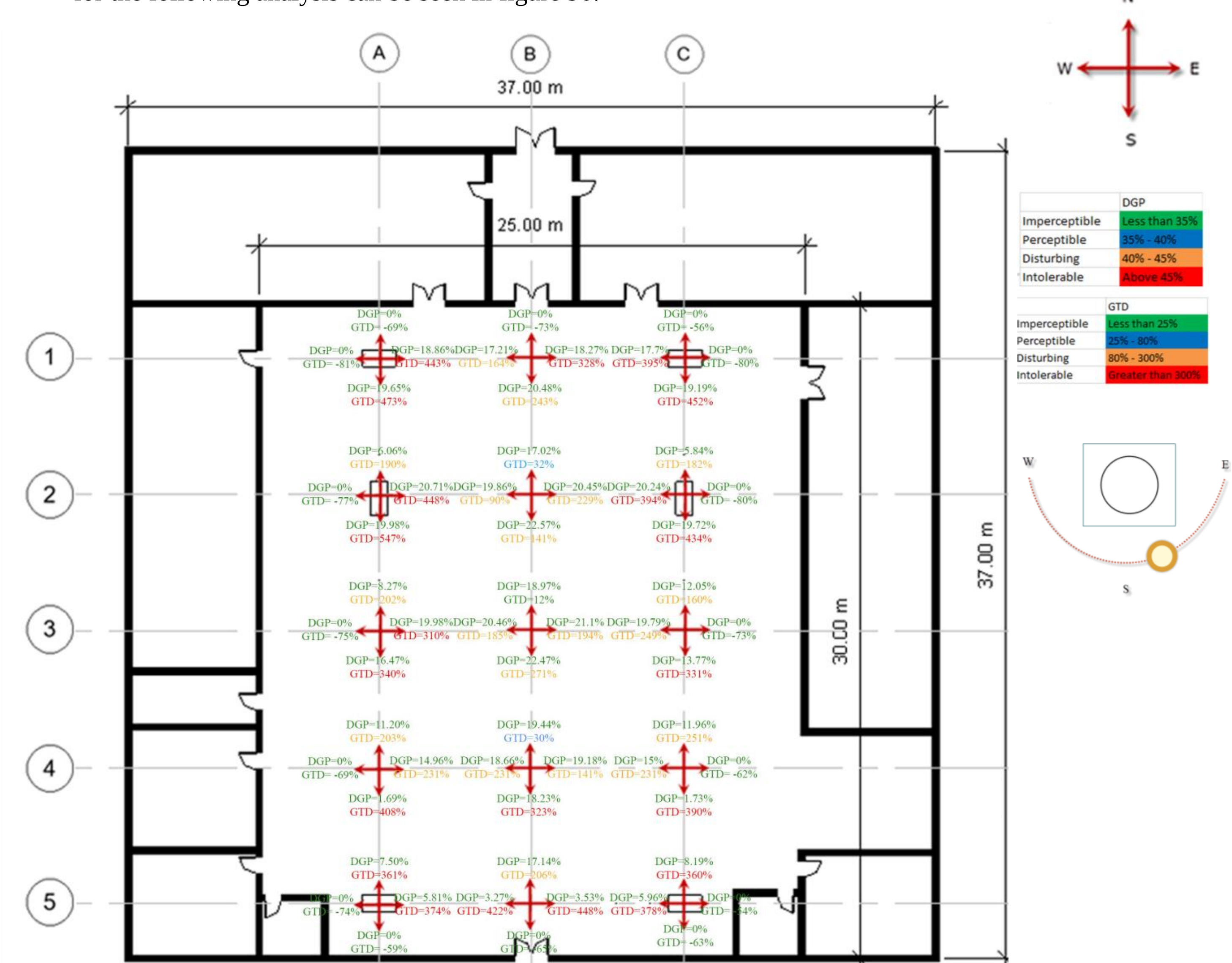


Figure 90:Glare simulation results for DGP and GTD - 21 Dec 12pm

Comparing DGP results, highest values as an overall were south direction having B1,B2 and B3 (22.5%) as the highest, followed by east direction like A2 (20.7%) and A1andA3 (20%) . the south values for the central space (ROW B 2,3,4) are the highest since the sun angle at 12:00pm in that time in the year is low around 41° so daylight is coming through the windows into that space. The sun at 12:00pm in 21st Dec is not the solar noon (solar noon is when the sun is at the highest point in the sky) and in solstices solar noon occurs few minutes later than midday, so at 12:00pm the sun is still not exactly at south, it’s still slightly towards southeast, which explains the high values on east direction. All points facing the walls (around the perimeter area) got a DGP=0% which are all west points in grid A, all east points in grid C, the north of row 1 in all grids, and the south of row 5 in all grids. Figure 91 illustrates the results for DGP highest and lowest points.

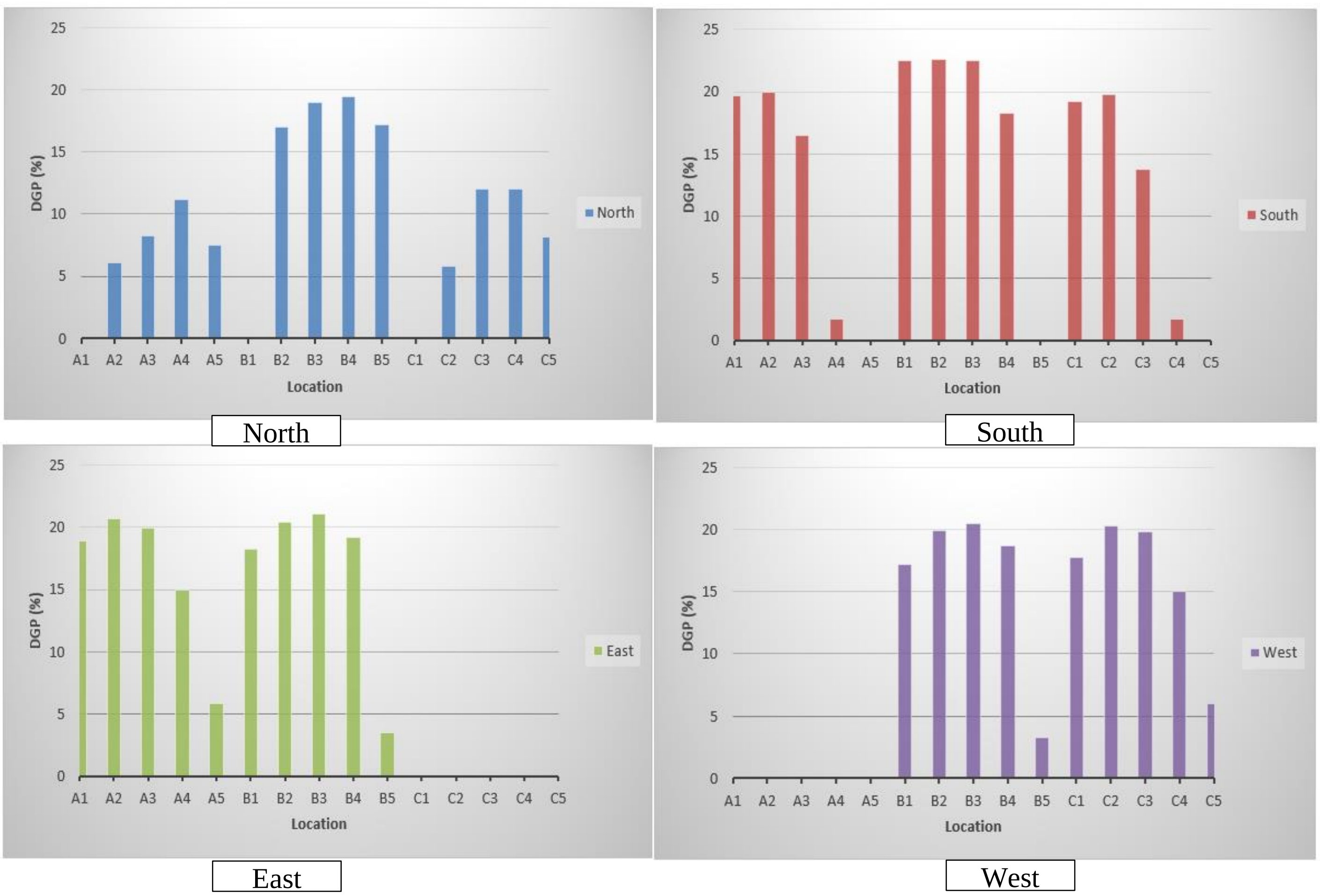


Figure 91: 21st Dec at 12:00 pm - DGP(%) results

Comparing GTD values, north direction values were less compared to 21st June, looking away from the south direction were most of the direct sunlight is hitting at that time of the year. Less points have passed the GTD evaluation, only two values looking towards north did (B2 and B4). The points in the central space (B2, B3,B4) in all direction except north were either disturbing, while the points around the perimeter (Grid A and C, ROW 1 and 2) were all intolerable, except the values looking towards the walls they were imperceptible. The south values were the highest being all imperceptible (except central points being disturbing) , as explained earlier this is due to the sun location in sky at that time of the year (Winter solstice). As overall south points been the highest such as A2 (547%) and A1 (473%), followed by east points. Figure 92 illustrates the results for GTD highest and lowest points.

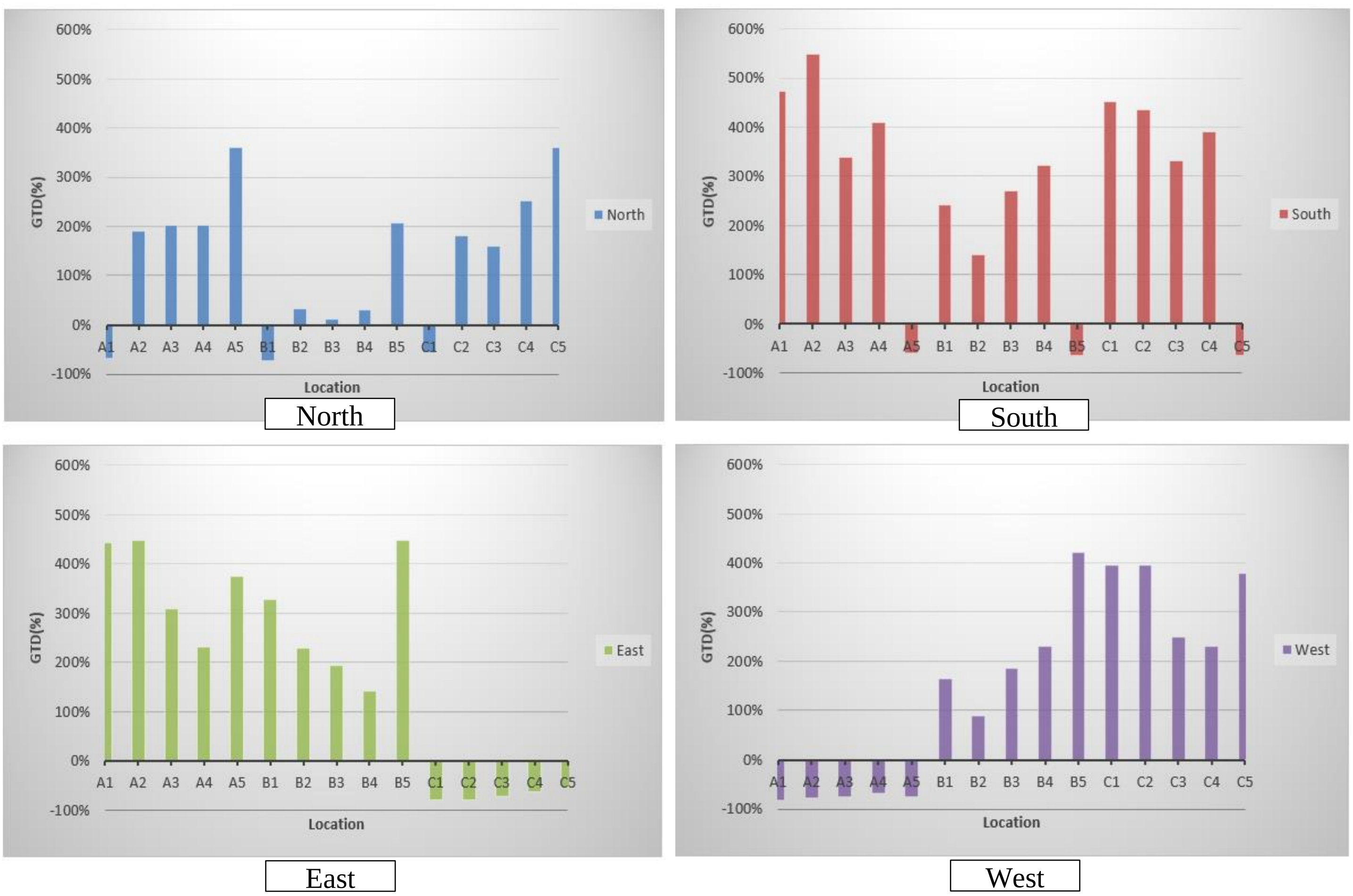


Figure 92: 21st Dec at 8:00 am - GTD(%) results

- 21st Dec at 4:00 pm

Comparing the glare evaluation throughout the floor, glare was recorded to be either intolerable (Row 1and 5 except wall side) or disturbing (rest of the points except east and north in central space B2and B3). All the cases looking towards the walls had glare to be imperceptible. For grid A, looking towards south recorded to be intolerable but not as much as grid CandB, but west recorded to be disturbing it's since grid A is located east of the dome and though the left side of the dome is in a shaded space so it couldn't be reached by the sun, that space is affected by diffused sun light from drum glazing and reflection from dome and very minimal direct light. Cases on grid B showed variety in glare evaluation, the cases looking towards west and south all were either intolerable or disturbing. The cases with precipitable where in grid B, looking towards east (B2, B4). Grid C had the highest values for both GTD and DGP especially values looking towards west and south were intolerable or highly disturbing, this can be justified by the sun position in sky at 4:00pm in 21st Dec "winter Solstice", the sun sets far to the southwest lighting up the east side of the room (grid C), also as values its lower than what was recorded in Jun 21st 8:00am that's because the angle from horizon is less (around 17° while 21st Jun was 40°). The low angle made the values lower in general for all points but in the same time raised the values looking towards south and west compared to 21st Jun for grid C and B since the sun is hitting them directly. An illustration for the following analysis can be seen in figure 93.

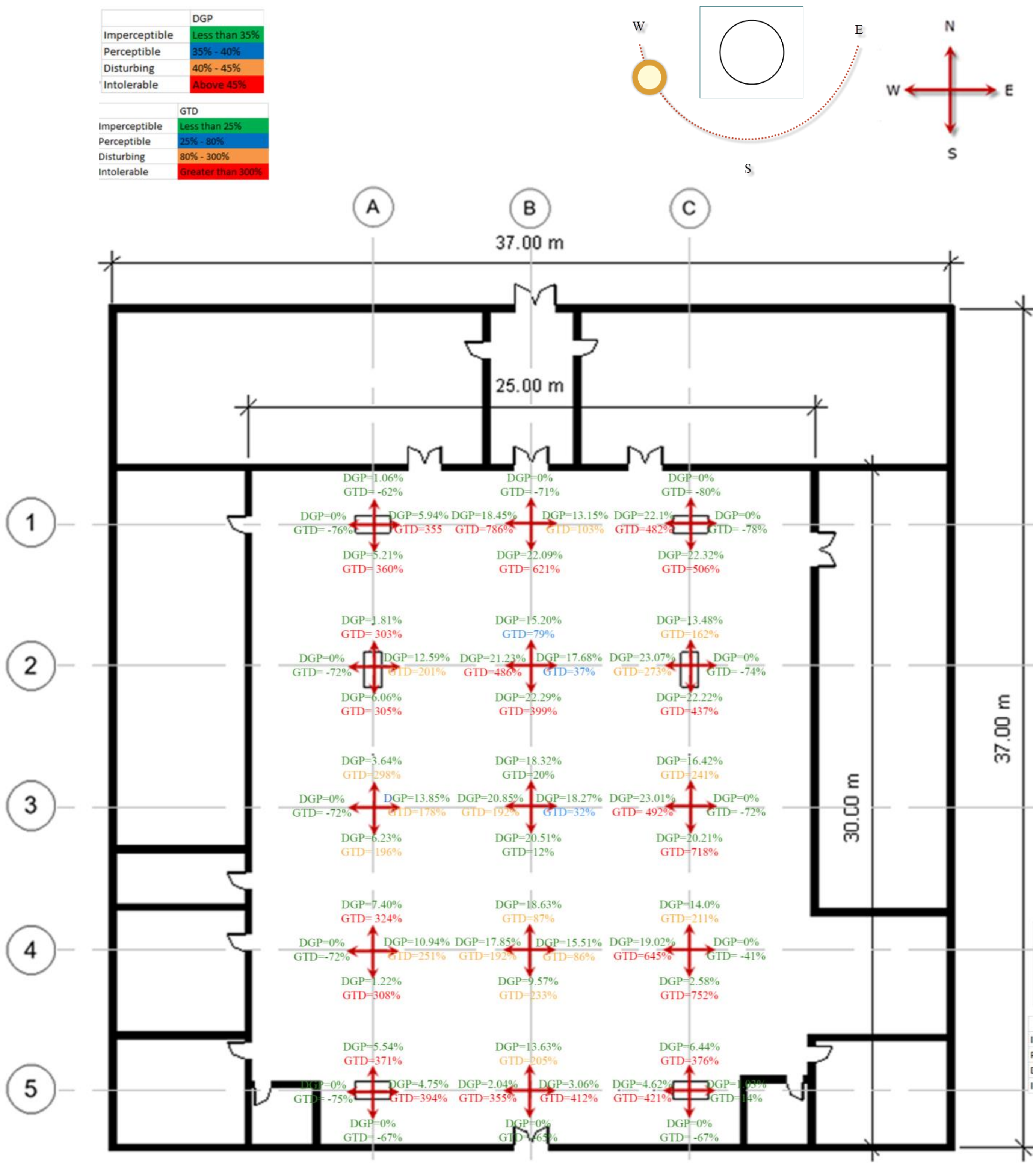


Figure 93: Glare simulation results for DGP and GTD - 21 Dec 4pm

DGP results show similar line graph to 21st June but with lower values compared to the values recorded in 21st June. The graph recorded west direction being the highest DGP% with C1,C2 and C3 (23%) followed by south point B1,B2,C1 and C2 (22%). In this case (4:00 pm) had higher values towards west then south that's because the sun at that time is at southwest and since it is close towards sunset with an angle of 17° the sunlight components towards west is much higher than south component. All points facing the walls (around the perimeter area) got a DGP=0% which are all west points in grid A, all east points in grid C, the north of row 1 in all grids, and the south of row 5 in all grids. Figure 94 illustrates the results for DGP highest and lowest points.

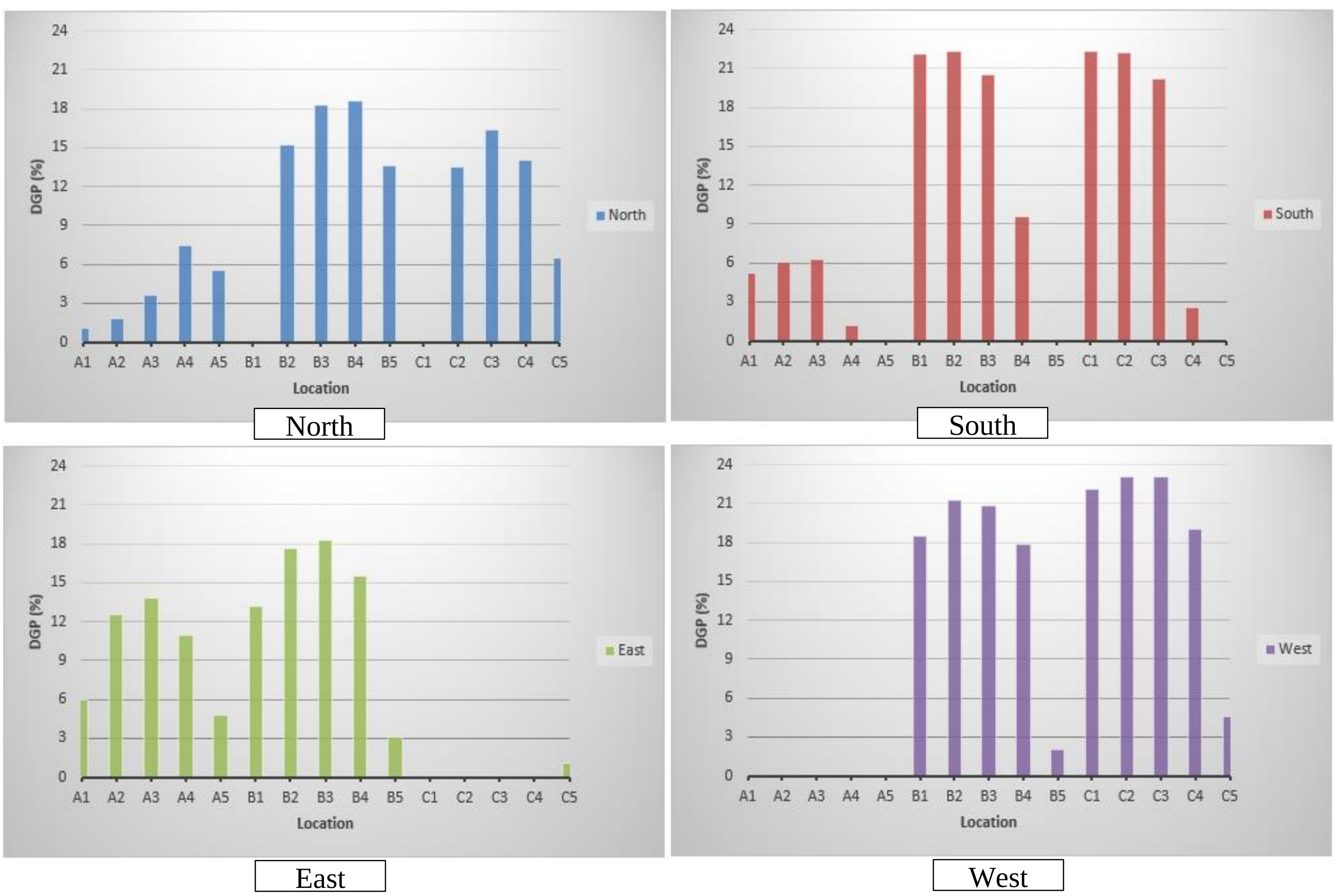


Figure 94: 21st Dec at 4:00 pm - DGP(%) results

Comparing GTD results, it showed as overall west and south points been the highest such as B1 west (786%) and C4, C5 (752,720%).All points facing the walls (around the area perimeter) got a GTD=negative% which means they are intolerable. As an overall, the points were either in disturbing range or intolerable, and the points towards space perimeter were imperceptible. Grid C values as an average showed the highest values in each direction. The only cases which passed GTD test were (B2, B4) looking east and B2 north since they are looking away from the sun direction and also because its located below or within edge of the dome so less direct sunlight is hitting them. Figure 95 illustrates the results for GTD highest and lowest points.

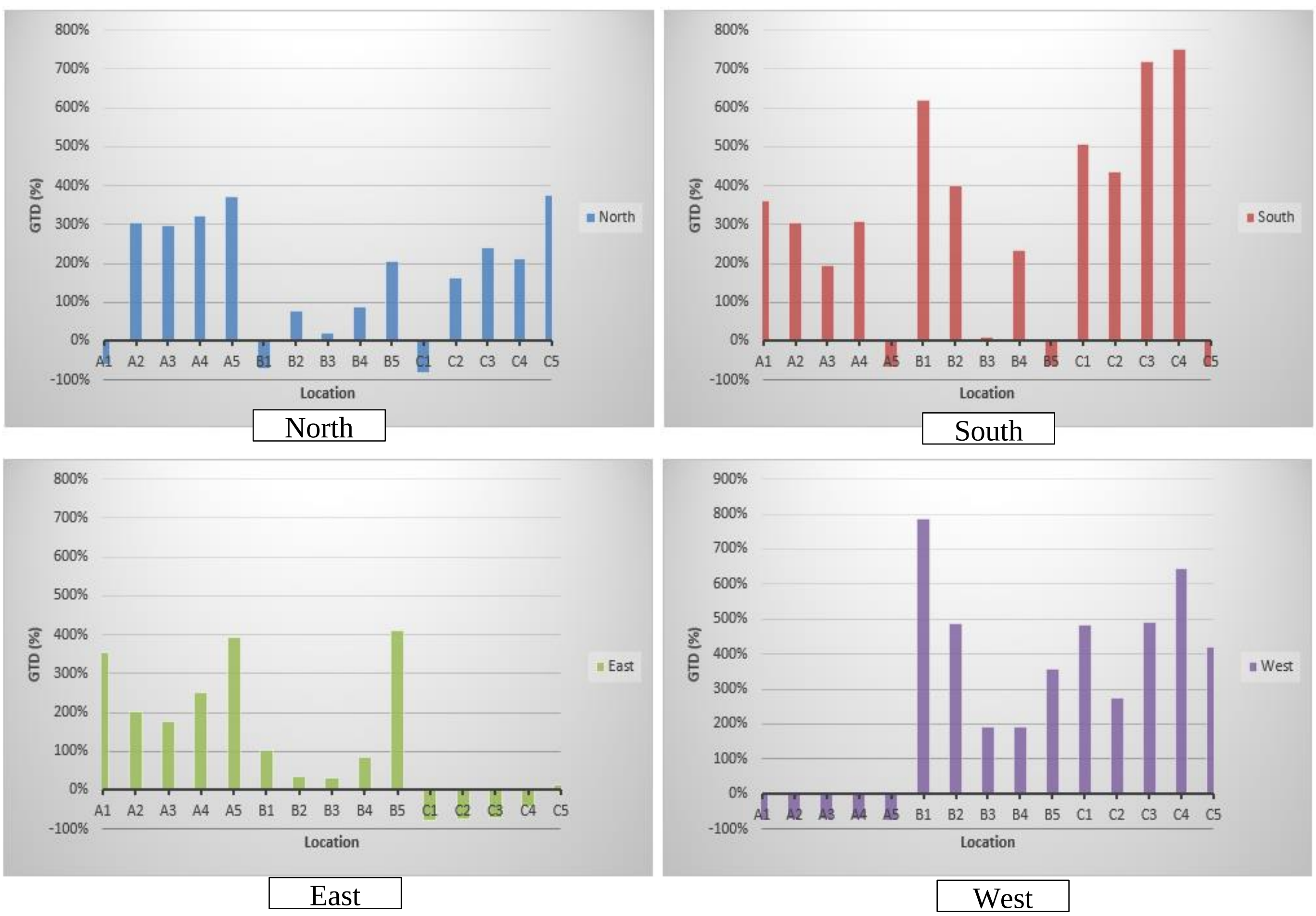


Figure 95:21st Dec at 4:00 pm - GTD(%) results

After the previous deep analysis and comparison between DGP and GTD results, in the following figure96 which shows best orientation recorded per date and time in order to prevent disturbing/intolerable glare.

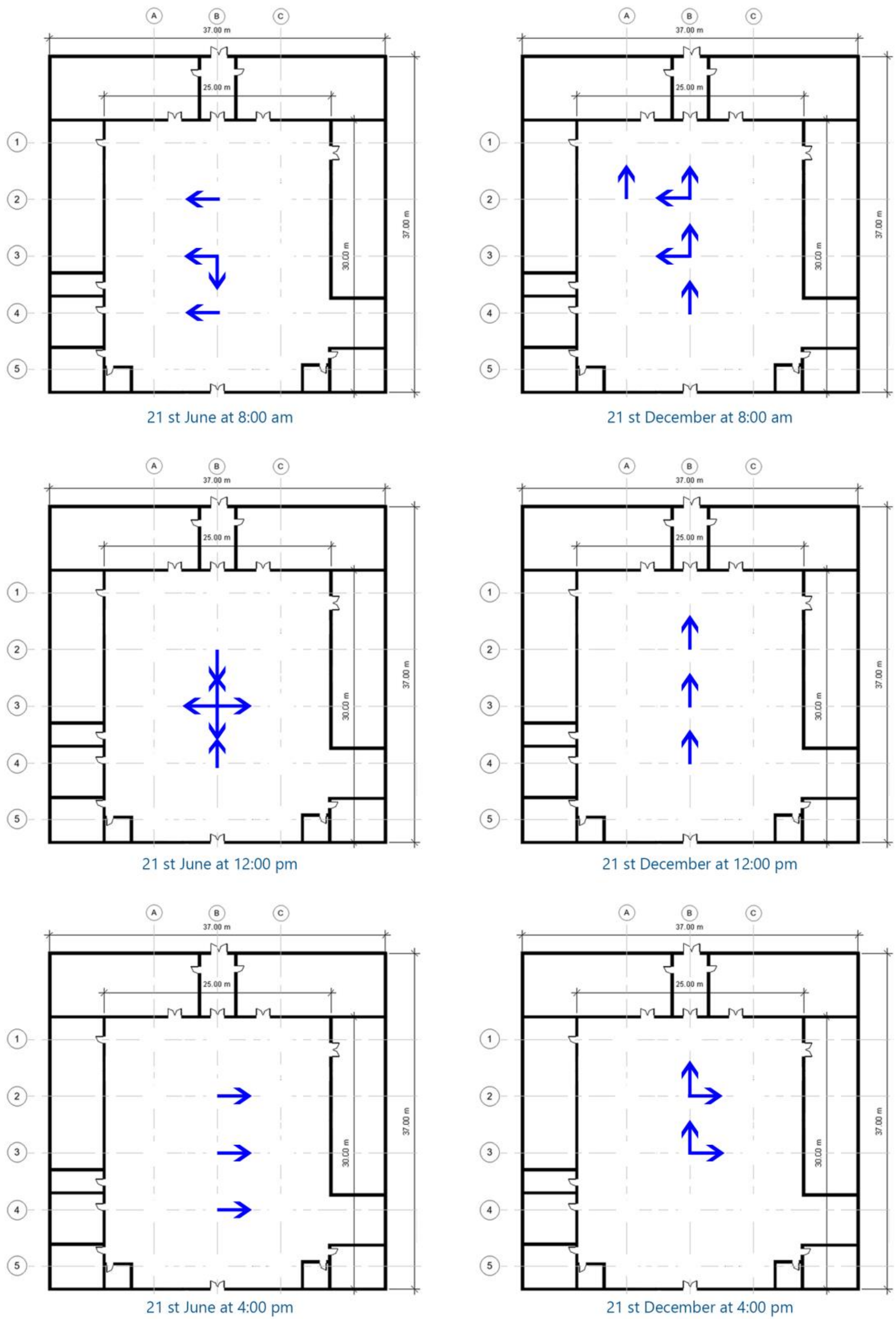


Figure 96: Best orientation per date and time in order to prevent disturbing/intolerable glare

CHAPTER 5: Conclusion and Recommendations

CHAPTER 5: Conclusion and Recommendations

5.1 Conclusion from simulation results

This research has investigated the visual discomfort using simulation and divided them into three cases Case1: Annual variables ($sDA_{300/50\%}$ and $ASE_{1000/250}$), Case2: Light Properties (Illuminance level), Case3: Glare (DGP, GTD).

5.1.1. Case1: Annual Variables

Comparing the three variables (Diameter, Drum's Height, Percentage of Glazing), it seems that percentage of glazing has a larger impact, followed by drum's height and then the diameter. A range around 14m diameter is the best for sDA values, having bigger diameters or smaller than that range won't help in improving the sDA values. Whenever the diameter is smaller, better ASE value occurred, but with less sDA values. The ideal diameter was 14.0m in order to have the recommended values for ASE and sDA values. Increasing the height showed more impact on both metrics compared to diameter. It's not as much as the glazing percentage impact but still it had some moderate changes in the sDA and ASE values. It's true that increasing the percentage enhanced the sDA values but it made the ASE value become worse compared to diameter and height impact and though increase the potential of having glare.

Diameter change would help in distributing the light more to the space when it's in the right diameter range (as mentioned before diameters of 7m and 18m didn't reach the recommended values for both metrics in most of their cases but diameter of 14m had better results) , but percentage of glazing is the main contributor for getting sufficient sDA value. Increasing the height of the drum had an effect of increasing the sDA value while maintain the ASE value in the acceptable range, which means increasing drum height helps to satisfy both aspects (less ASE, higher sDA). Glazing percentage

=100% is more likely to not reach the recommended value for the ASE metric compared to smaller height or percentage.

Increasing the height makes it possible to keep ASE in the adequate and preferred level and in the same time increase sDA levels yet not to the extent that makes sDA level higher enough to reach recommended values. So increasing drum height, did affect more sDA values, but it had minimal to no effect on ASE. Compared to diameter, increasing the height showed more impact on the values compared to diameter. It’s not as much as the glazing percentage impact but still it had some moderate impact in the sDA and ASE values.

The cases with glazing percentage of 25% are more likely to reach recommended values for both ASE and sDA. When having a small diameter of low height (D=7m, H=2m), it’s better to increase the percentage into 100%. For other heights and diameters (D=14,18m,H=3,4m) having glazing percentage of 25% is enough to get sufficient daylight and ensure no glare is going to occur.

It is true that increasing the glazing percentage enhanced the sDA values but it made the ASE value become worse compared to diameter and height.

For the small diameter 7m, the preferred glazing percentage would be 100% for H=2m, 87.5% for H=3m, 70% for H=4m to reach recommended values for both metrics, for the medium diameter 14m its more preferable to have glazing percentage up to 60% for H=2m, 48.5% for H=3m, 37.5% for H=4m, and for the big diameter18m a glazing percentage of 40% for H=2m , 36% for H=3m , 27.5% for H=4m.

Investigating the glazing area, equations were concluded that relates the glazing area with sDA and ASE values, the equations were as following:

1) $\mathbf{ASE = -0.000001A^5 + 0.0003A^4 - 0.0116A^3 + 0.1657A^2 - 0.7891A + 1.0098}$
whereby A is the glazing area (m^2) , $ASE = ASE_{(1000/250)}(\%)$, $R^2 = 0.976$

2) $\mathbf{sDA = 0.000004A^6 - 0.0004A^5 + 0.0159A^4 - 0.2786A^3 + 2.3417A^2 - 7.4824A + 6.7135}$
whereby A= glazing area $(m2)$, $sDA = sDA_{(300/50\%)}(\%)$, $R^2 = 0.9658$

5.1.2. Case2: Light Properties

- Since irradiance is directly proportional with illuminance values as per "National Bureau of Standards" (figure 70), irradiance solar data generated by Revit+Insight using EnergyPlus weather database were used to explain the illumination behavior in the simulated timings, this included Direct Normal Irradiance (DNI) Diffuse Horizontal Irradiance (DHI) and Global Horizontal Irradiance (GHI). The simulation results founded:
    1. Within all cases, it has been noticed that the results at 8:00am is brighter than 4:00 pm. GHI DNI DHI values are higher at 8:00am in all cases compared to 4:00 pm especially direct sunlight which means more illuminance is coming directly into the area. (check section 4.2.2.2. for further details).
    2. Comparing any case with the results it had in different months, it has been noticed that 21st June had always the highest illuminance level compared to 21st September and 21st December of the same case. As illuminance distribution within floor area, 21st December had bigger area with illuminance level being around 2,000 lux, on the other hand 21st June had smaller spot with high illuminance but the illuminance level in it was reaching up to 5,500 lux.

- Sun path are the main reasons of the variety in illuminance level in the tested months:

1. From the comparison between the cases, it has been noticed that the average lux in 21st December at 12:00pm is higher followed by 21st September then last 21st June. the daylight coming into the space at 21st December at 12:00pm is entering with an angle due to the sun path at that timing of the year with an angle of 41° above horizon, while the sun in 21st June at 12pm is perpendicular. (check section 4.2.2.1. for further details).
2. At 8:00am, in 21st June the bright center oriented towards west “slightly tilted to south”, in 21st September the bright center towards north-west, in 21st December the size of the bright circle is smaller which means less illuminance lux reaching the 2000lux and oriented north-west but in a higher angle compared to September.

3. At 12:00pm, in 21st June the bright center is exactly in the mid of the space shaping almost a perfect circle, that space has the highest illuminance level reaching up to 5,500 lux, in 21st September the bright center is shifted towards north with an illuminance level reaching 3,500 lux, in 21st December the bright center is shifted the highest towards north and its spread from center towards the north façade but with an illuminance level of 2,000lux.

4. At 4:00 pm, in 21st June the bright center is oriented towards east “slightly tilted to south”, in 21st September the bright center is oriented towards north-east, in 21st December the size of the bright circle is smaller and has much lower illuminance level oriented north-west but in a higher angle compared to September. (check section 4.2.2.1. for further details).

- Comparing modification done in each variable, it has been noticed that: for diameter, using diameter of 18m gave better results and much brighter (higher illuminance level and better distribution), followed by 14m and last 7.0m. For drum’s height, a 4.0m height was giving the highest illuminance in followed by 3.0m and last 2.0m. For glazing percentage, the highest illuminance was having 100%

of drum as glazing, it even had higher impact and more brightness compared to largest diameter and height, followed by having drum as 25% glazed, then 15% and last with 10%.

- D14m and D18m have almost equal illuminance average when several cases were tested but the bigger diameter helped in distributing the light in bigger area (better spreading of illuminance) but in lower illuminance value. (check section 4.2.2.3. for further details).
- Increasing the height from 2m to 3m enhances the illuminance throughout all months in all cases, however increasing it even higher up to 4m doesn't show any significant difference in illuminance levels except for the case of December. (check section 4.2.2.4. for further details).
- The parameter that had the highest effect in enhancing the illuminance level among the three variables is the glazing percentage. Increasing the percentage of glazing enhanced the illuminance level for all cases throughout the months.
- Ranking their effect on enhancing illuminance level, highest effect is the glazing percentage =100%, followed by glazing percentage=25%, then height =4m, glazing percentage=15% and height=3m are almost the same, followed by diameter of 18m and last diameter of 14m. (check section 4.2.2.7. for further details).
- In 21st June and 21st September, the effect of D14m and D18m is almost equal, while in 21st December the effectiveness of diameter 18 is significantly higher.
- Increase the height up to 3m showed significant increase. Increasing it higher, up to 4m showed not much difference for September and June compared to December which had high impact on average lux.
- The degree of impact of drum's height =3m is equal to the effect of glazing percentage =15%.
- Having a 100% glazing percentage, can increase the illuminance level up to 11-13 times its original (10% glazing).

5.1.3. Case3: Glare

After deep analysis in section “4.2.3. Case 3: Glare”, and comparison between DGP and GTD results, the conclusion can be summarized in the following figure 96 which shows best orientation recorded per date and time in order to prevent disturbing/intolerable glare.

At 21st June, for 8:00am best orientation is the central spaces looking towards west, at 12:00 pm the best orientation is the area directly under the dome looking any direction towards and outwards the center, and at 4:00 pm its more preferable are the central spaces to look towards east. (Check figure 78,81,84).

At 21st December, for 8:00am several spots within the plan are considered acceptable including central space looking towards north and west and the upper row looking towards north, at 12:00pm the best area was the central space looking towards north, and at 4:00 pm the upper spaces of the center are more preferable looking towards north and east. (Check figure 87,90,93).

Because of the sun position at 8:00am in 21st June “Summer Solstice”, the sun rises as far to the northeast with an angle of 31°, lighting up the west side of the room, and the sun sets down as far to the northwest with an angle of 40° making the east side of the room.

The sun is at its highest position in sky at 12 pm with an angle of 88° (almost prepdicular 90° on roof top), so whatever is below the dome is hiding and only receive minimal daylight from reflections of daylight on dome, walls or floors, while the points below diameter directly recieves more diffused light because they are closer to the walls and some of sunlight from windows at very sharp angle, while the other points around the dome are receiving most of the direct sunlight and though have the highest values in GTD and DGP.

For December “winter Solstice”, at 8:00am the sun is at position as far to the southeast lighting up the west side of the room, and as values its lower than what was recorded in Jun 21st 8:00am that’s because the angle from horizon is less (around 11° while 21st Jun was 31°). The low angle made the values lower in general for all space but in the same time raised the values looking towards south compared to 21st Jun. (check section 4.2.3. for further details).

At 12:00 pm, the December values in all direction were higher compared to June, this can be justified by the angle of the sun from horizon which is 41° (while 21st Jun was 88° almost perpendicular to the roof). The low angle introduced more space into the central space and made the values raise up to be disturbing for occupants, plus because of the sun condition in the Winter solstice, the sunpath is lower in the south direction which explains why the south values were the highest compared to the rest.

The sun position in sky at 4:00pm in 21st Dec the sun sets far to the southwest lighting up the east side of the room (also as values its lower than what was recorded in Jun 21st 8:00am that's because the angle from horizon is less (around 17° while 21st Jun was 40°). (check section 4.2.3. for further details).

In summer (June) using the space for reading or to have a lecture the preferable space would be central area looking towards west at 8:00am, looking towards east at 4:00pm, and by mid of the day there is no glare or discomfort throughout all directions in central space. Using the space with laptops or PC screens, its more preferable to use the spaces within the perimeter (looking towards walls). In winter (December), if the space was used for reading or lecturing, it's better to use central space looking towards north throughout the day, it's possible also to look towards west at 8:00am and towards west at 4:00pm but only in the upper space. Also like summer, when using laptops or PC it would be better to use the spaces around the perimeter. (Explained in details in section 5.2. Recommendations, point4).

5.2 Recommendations

Do classical architectural elements such as domes have the ability to actually affect amount of sufficient daylight necessary for adequate visual comfort?

- Yes, through the analysis that was made in this thesis, changing parameters of the dome such as its height of the drum, diameter and glazing percentage have affected the amount of daylight and visual comfort of people using the space. As well as the interior configuration like desks distribution and preferred sitting places depending on amount of daylight coming from the dome. Further research on other architectural elements (atrium, flying buttresses, oculus, lightwell,..) should be investigated in future researches.

What are the correct techniques or methods that should be considered whenever a symbolic or classical element is presented to avoid visual discomfort and glare?

- For places such as educational spaces it's better to use horizontal architectural elements such as atriums or sky lights distributed linearly, have a circular shape as a dome cause inequality and more as radial distribution of daylight through the space which could be more preferable in a space like a museum where the focus is on the things within the perimeter of the space (radial distribution of things within space). It's better to have linear distribution of desks in educational buildings, it gives more control to the amount of daylight desired within the space, and also give more options for interior distribution of the desk especially that it's an educational space so students would be more likely to sit in a linear distribution to focus on lecturer or to even for individual work. In the end of the day the architect/designer who designs the building should run an analysis for the designed architectural features to test if its providing the desired amount of daylight and visual comfort or not.

Within working hours, is the amount of daylight provided in the space is sufficient or artificial light should be presented to enhance the space visual comfort quality?

- From simulations, illuminance level was at its best for whenever the glazing percentage of the drum was 100% providing adequate amount of daylight fully over the space, but in the same time it was causing intolerable glare for occupants. The option were it had a balance of illuminance level and visual comfort was D=14 , H=4 , S=25% (sDA = 88% , ASE=3%). It will need some artificial light to help within the space perimeter, as found from the glare analysis the points looking towards walls were imperceptible and though would need artificial light to use that space for reading purposes or drawing.

What is the best occupants' orientation and the best locations to be considered for furniture distribution to avoid glare during the day?

- It depends on the task and time of the year, in summer (June) if the person wants to use the space for reading or to have a lecture the preferable space would be central area looking towards west at 8:00am, looking towards east at 4:00pm, and by mid of the day there is no glare or discomfort throughout all directions in central space. For future studies, researchers can test the glare if a person wants to use their laptops or PC screens where the user looks at one direction (PC screen) and sun coming from the back causing glare, also can test recommended PC brightness with different daylight configuration. As per that statement, a preliminary recommendation/suggestion, its more preferable to use the spaces within the perimeter (looking towards walls) since the light coming from the laptops needs a space/location that have minimal daylight in order not to create glare on screens while working. In winter (December), if the space was used for reading, drawing or lecturing, it's better to use central space looking towards north throughout the day, it's possible also to look towards west at 8:00am and towards west at 4:00pm but only in the upper space. Also like summer, when using laptops or PC it would be better to use the spaces around the perimeter.

What are the optimal dimensions of the dome?

- The best combination from the cases tested were found to be the following:

- D= 7m , H=2m , S=100% , glazing area = 22.94 m^2
- D=14m , H=3m , S=25% , glazing area = 16.25 m^2
- D=14m , H=4m , S=25% , glazing area = 21.68 m^2
- D=18m , H=3m , S=25% , glazing area = 21.56 m^2
- D=18m , H=4m , S=25% , glazing area = 28.75 m^2

This proves that the best and recommended glazing area to wall area percentage is 25%, as founded in previous research papers in literature review (2.4.1. Window Size) which indicated that best percentage of glazing area to wall area to be a range of 25-30%.

Architects and designers should target to reach sDA values of 75% or more in regular used places, like an open plan office or classrooms, and should get it minimum of 55% of area in which daylight is essential. They should aim to get high sDA values while maintaining to lower ASE values by implementing the correct strategies, and ensure to lower ASE values without sacrificing sDA.

Adding a window typically increases both sDA and ASE. The best way to address both metrics has to do with fundamental design elements such as:

- The diameter of the dome (or the element the glazing is shaped accordingly)
- The sill height in drum (or the element) that the window is placed at
- The maximum amount of glazing to be applied without causing excessive glare
- Sun path around the year within the area of the designed building

If the architect/designer decides to use the dome as a part of the building design he should consider a radial distribution of furniture within space. The location of the student's desk inside the class has a great impacton the visualcomfort of the student. For drawing/lecturing purposes in summer, it's better to have the focus in the center of the space and the desks to be distributed radially around the center. In winter, it's better to have linear distribution looking towards north. For individual work on laptop or PC, the places around the perimeter would be better since low daylight presented in those areas and though balance between the light coming from the PC and prevent glare from screens.

If the dome is already constructed and needed enhancement its more preferable to increase the amount of glazing within the dome since it makes the highest impact compared to other variables, with taking into consideration the values of sDA and ASE by testing them in simulations since increasing the glazing percentage increases the possibility of glare to occur. If the architect/designer wants better, uniform and equal daylight distribution bigger diameter can provide it although it doesn't increase the illuminance levels that much, but if he is looking for higher illuminance level and ensure the glare won't occur the designer should go with higher height.

5.2.1. Future Studies

The research has brought questions that need to be solved through further research :

- Future studies can investigate the impact of the following on visual comfort:
  - Several building geometry and interior specifications (reflectance) : Design improvements include increased ceiling and window head height and upper glazed area, shallower room depth from glazed wall top lighting, light shelves, and lighter interior material colors.
  - Glazing specification: Glazing transparency may be too low, and glazed areas should be located toward ceilings for ideal daylight performance but have in consideration to address the negative impact of higher direct sun levels.
  - The shape and orientation of the room,
  - The amount of glass on different elevations (like North vs. South facades),
  - The design of shading devices (designed to stop direct daylight while allowing indirect light).
  - Shading: Exterior shading and/or deep window insets may be negatively affecting daylight levels. Equator-facing glazing admits daylight while avoiding direct sun.

- Glazing percentage of 15% has similar effect of having drum height of 3m, further researches can investigate the relation between heights and glazing percentage and if they are related with an equation, this would give more possibilities for the architect/designer to choose the preferred parameter depending on their targeted design.

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Appendix A – Illumination Results

Table 26: 21st June Illuminance level for (D=7 , H=2 , S=10,15,25,100)

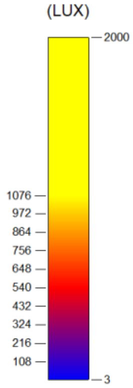
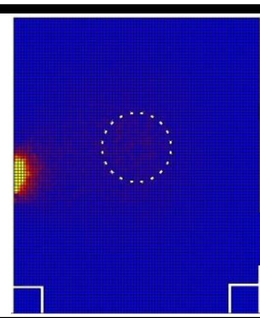
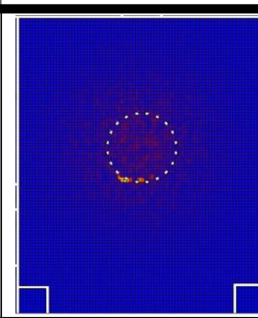
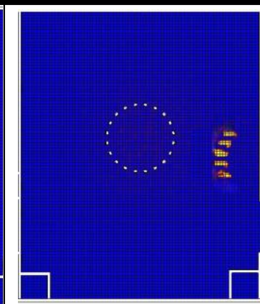
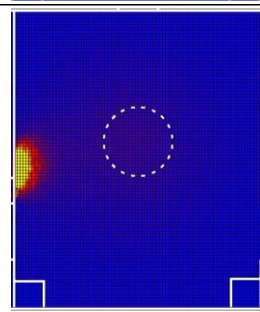
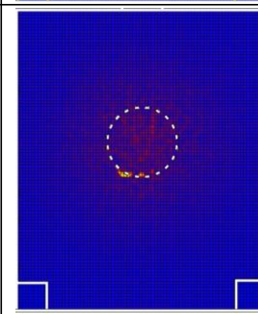
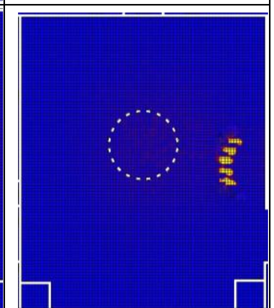
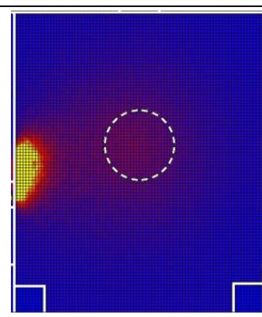
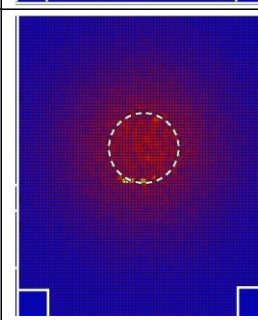
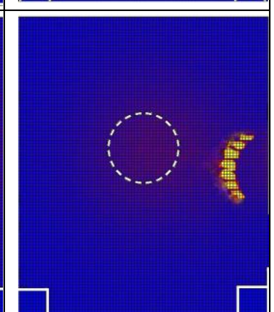
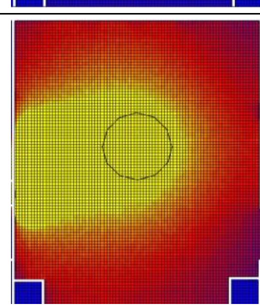
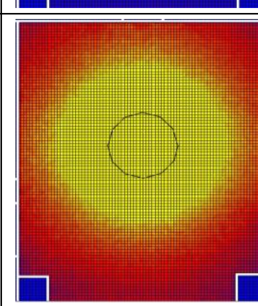
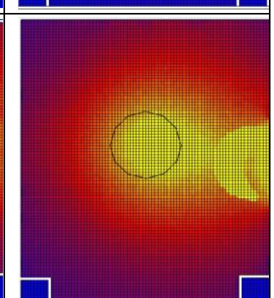
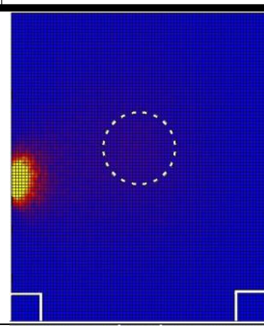
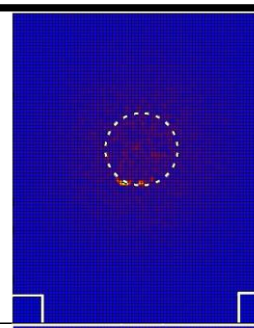
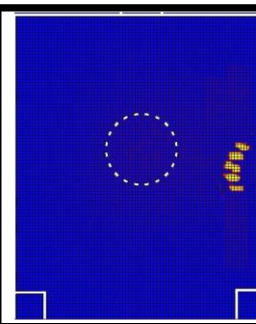
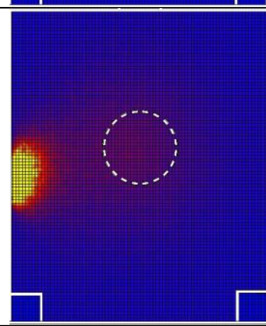
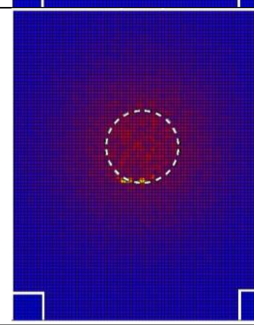
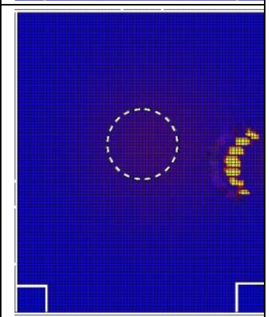
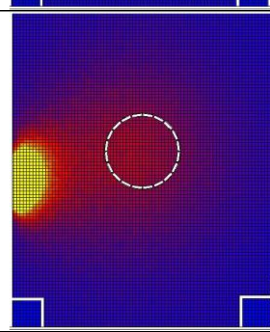
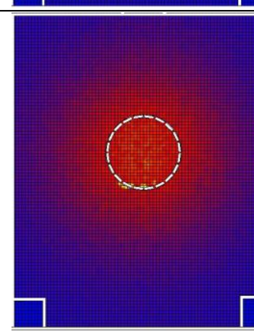
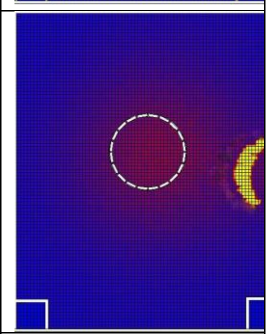
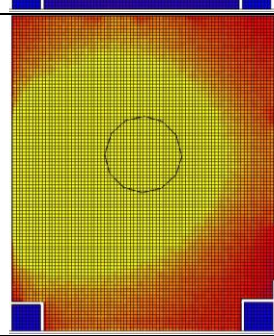
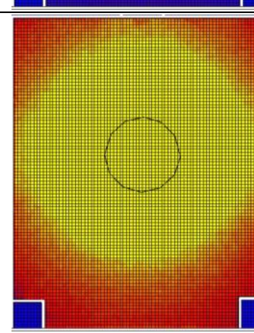
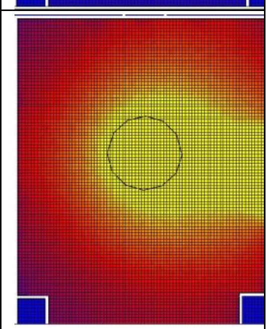
Date: 21st June					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
7.0 	2.0 m (sill height = 0.3 m)	10%			
		15%			
		25%			
		100%			

Table 27: 21st June Illuminance level for (D=7 , H=3 , S=10,15,25,100)

Date: 21st June					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
7.0	3.0 m (sill height = 0.8 m)	10%			
		15%			
		25%			
		100%			

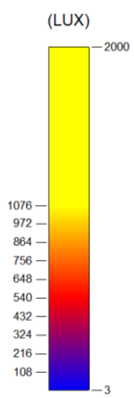


Table 28: 21st June Illuminance level for (D=7 , H=4 , S=10,15,25,100)

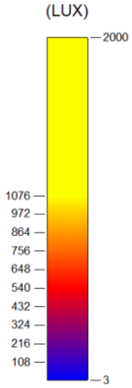
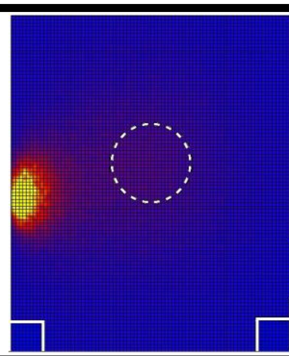
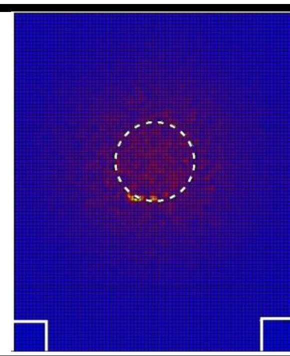
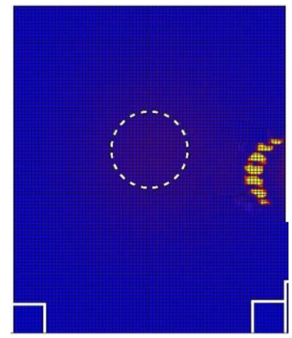
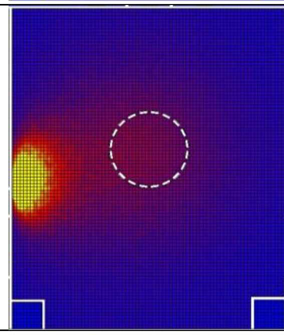
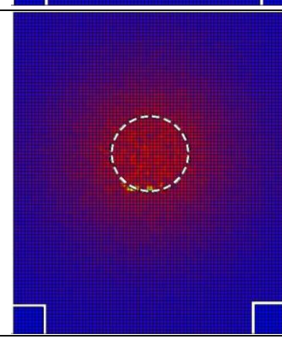
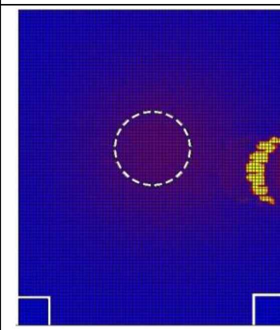
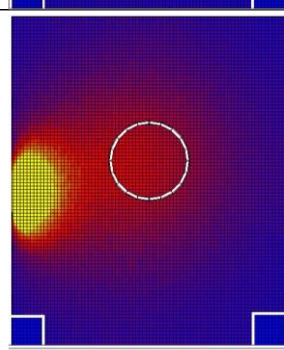
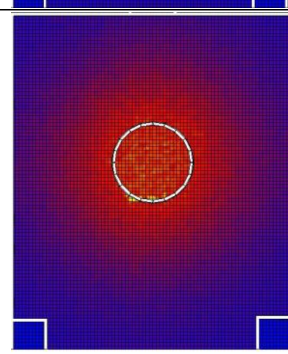
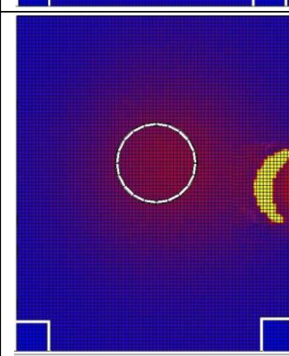
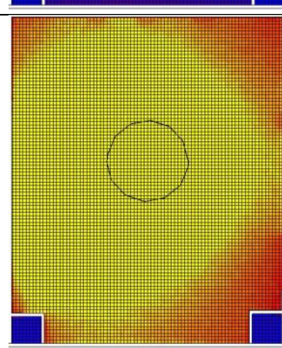
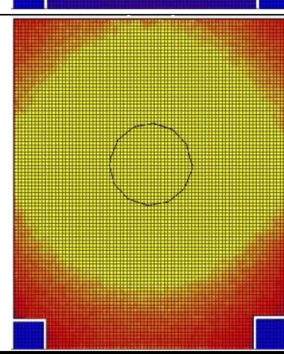
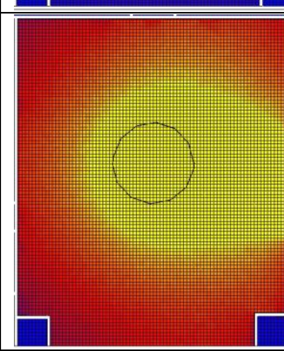
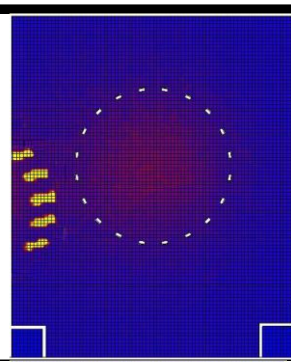
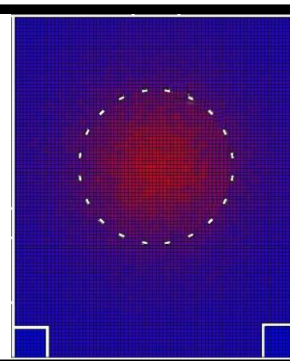
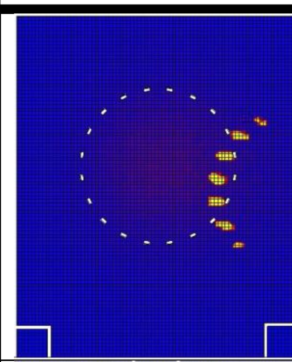
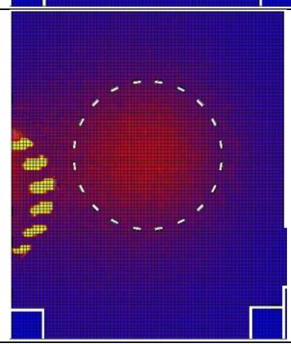
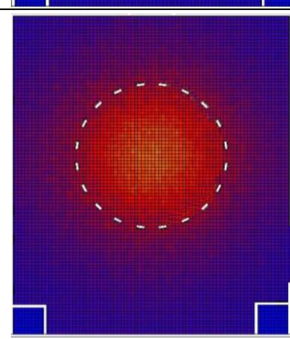
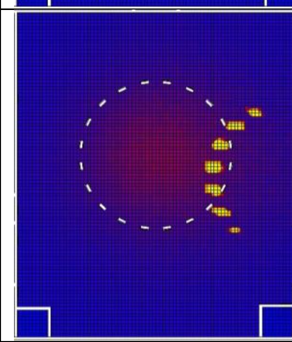
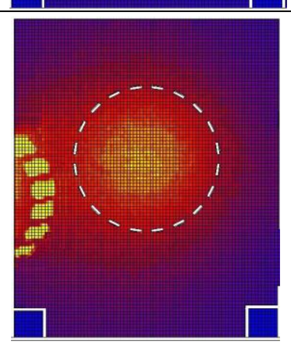
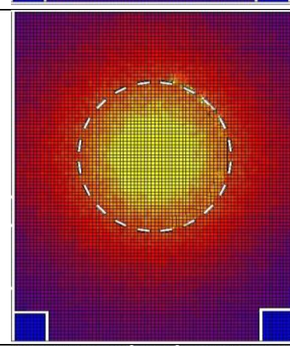
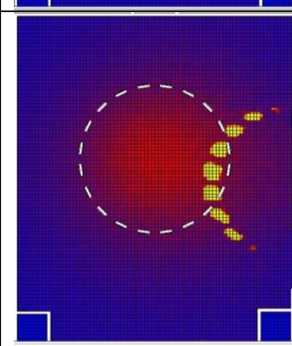
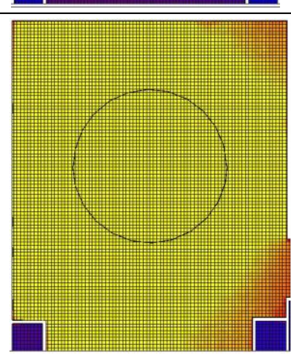
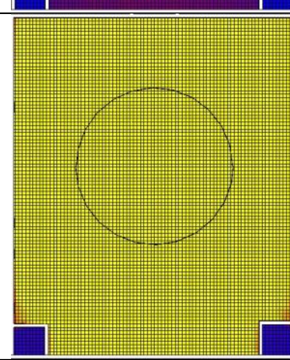
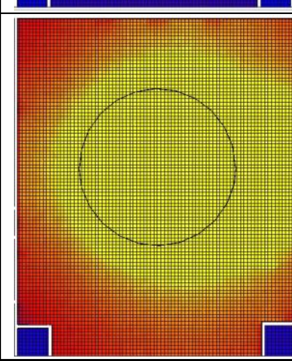
Date: 21st June					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
7.0 (LUX) 	4.0 m (sill height = 1.3 m)	10%			
		15%			
		25%			
		100%			

Table 29: 21st June Illuminance level for (D=14, H=2 , S=10,15,25,100)

Date: 21st June					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
14.0	2.0 m (sill height = 0.3 m)	10%			
		15%			
		25%			
		100%			

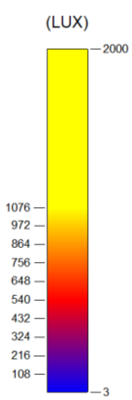


Table 30: 21st June Illuminance level for (D=14, H=3 , S=10,15,25,100)

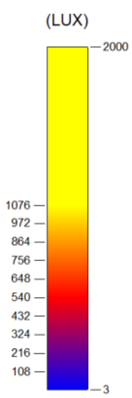
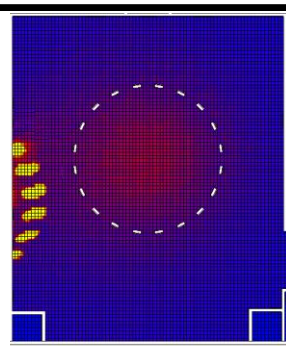
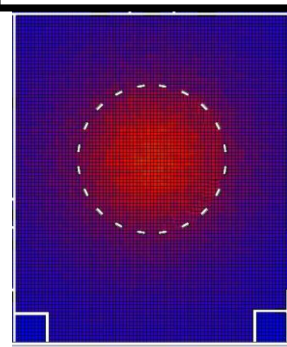
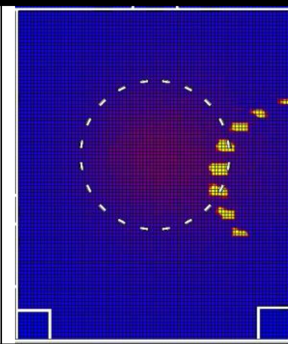
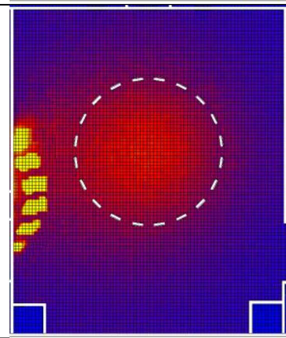
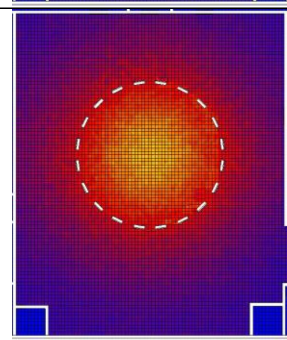
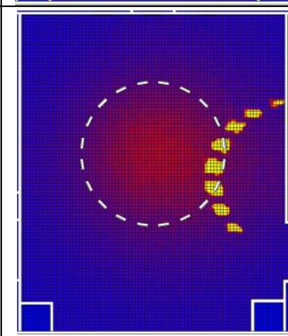
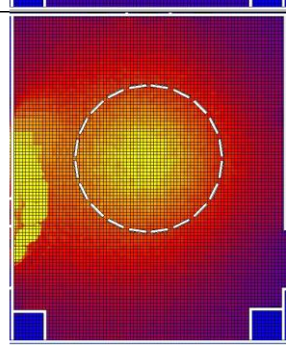
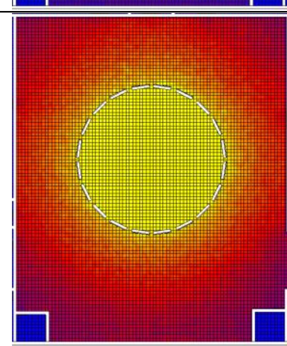
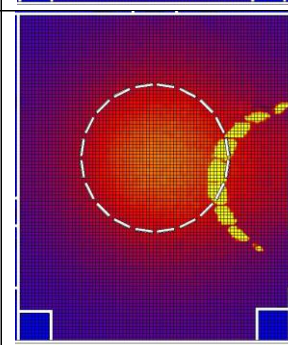
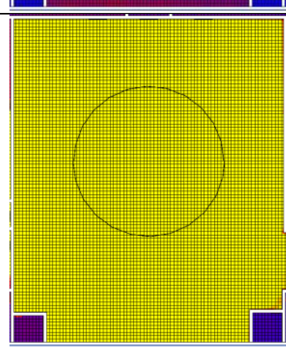
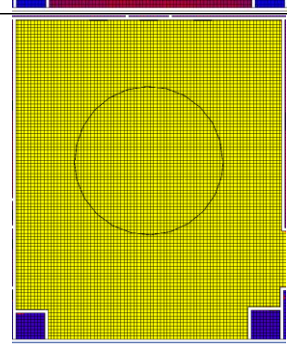
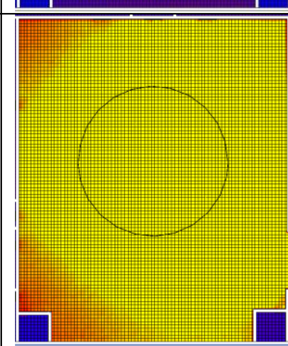
Date: 21st June					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
14.0 	3.0 m (sill height = 0.8 m)	10%			
		15%			
		25%			
		100%			

Table 31: 21st June Illuminance level for (D=14, H=4 , S=10,15,25,100)

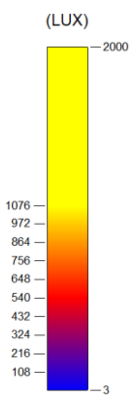
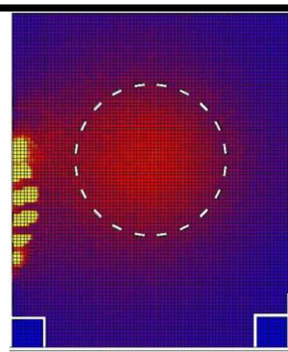
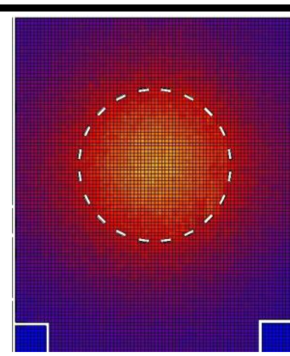
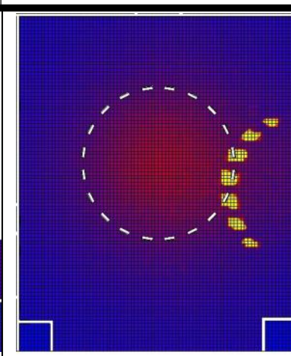
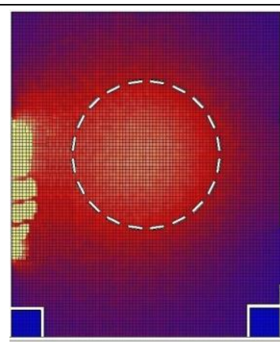
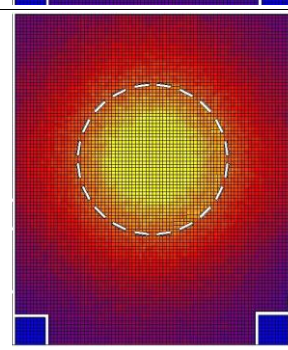
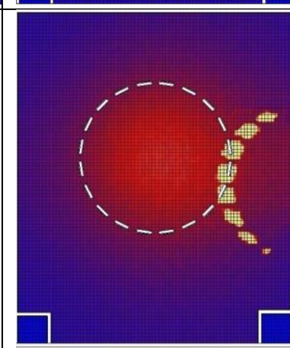
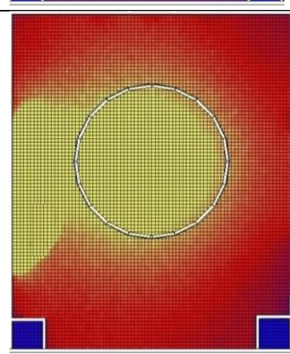
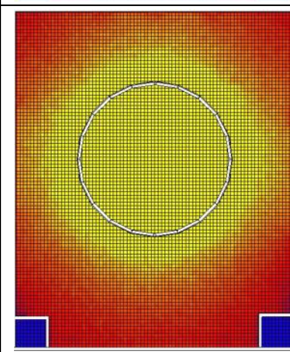
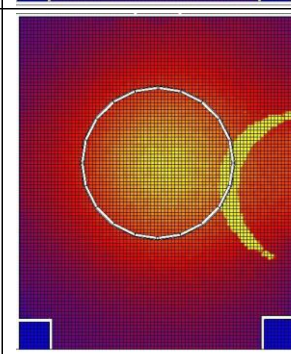
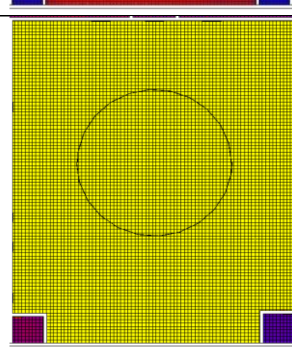
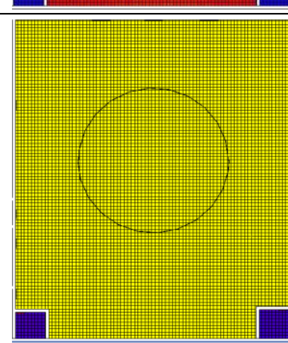
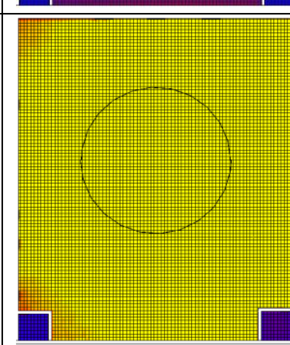
Date: 21st June					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
14.0 	4.0 m (sill height = 1.3 m)	10%			
		15%			
		25%			
		100%			

Table 32: 21st June Illuminance level for (D=18, H=2 , S=10,15,25,100)

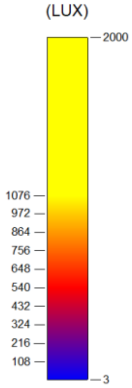
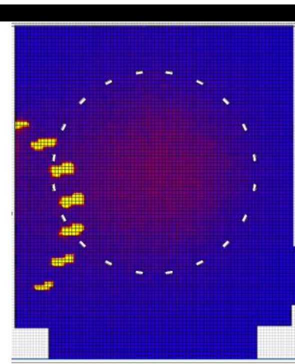
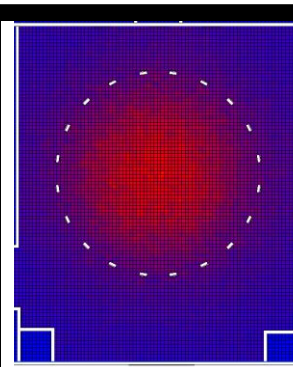
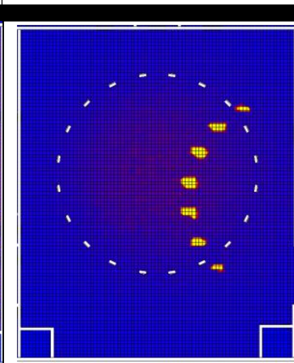
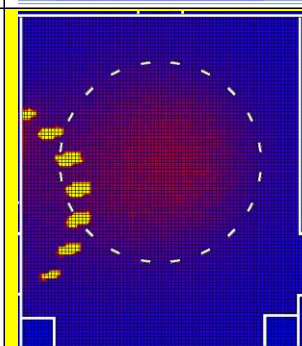
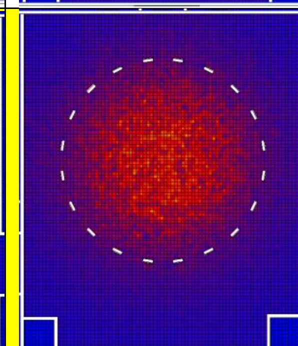
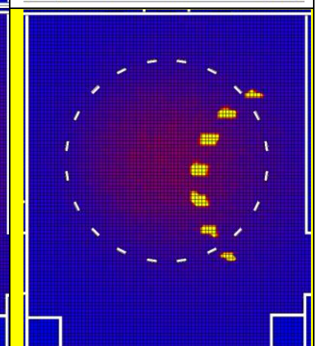
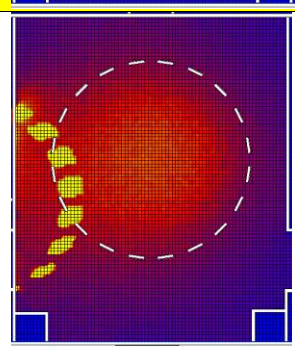
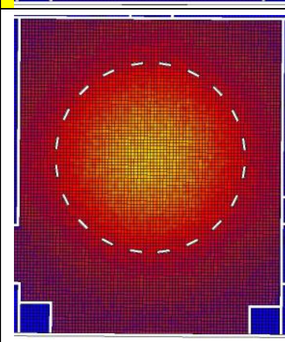
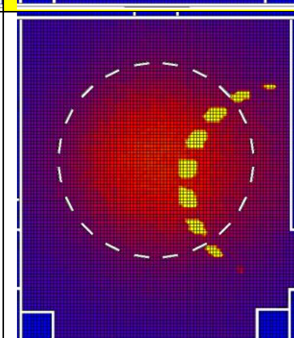
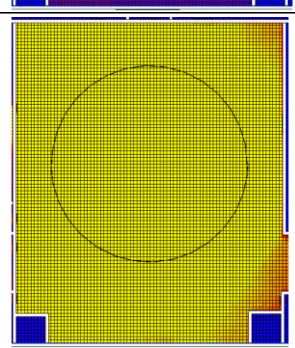
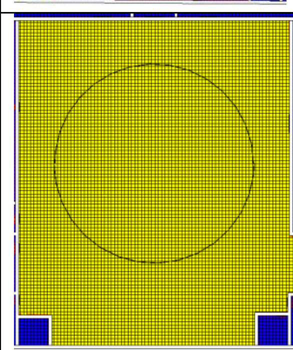
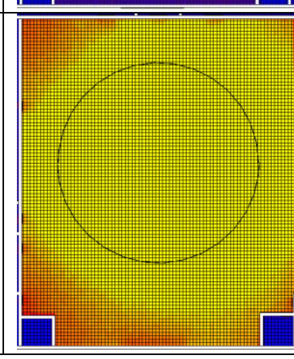
Date: 21st June					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
18.0 (LUX) 	2.0 m (sill height = 0.3 m)	10%			
		15%			
		25%			
		100%			

Table 33: 21st June Illuminance level for (D=18, H=3 , S=10,15,25,100)

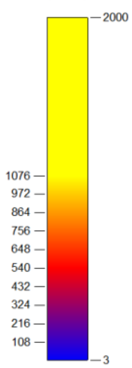
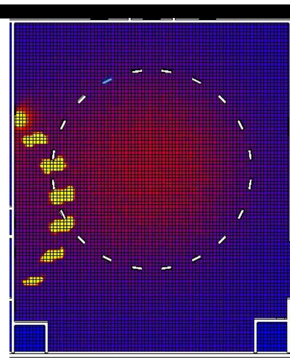
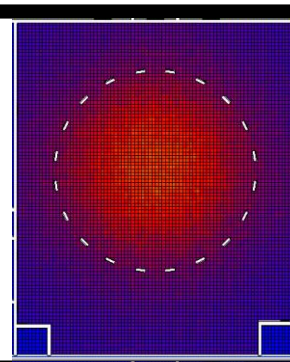
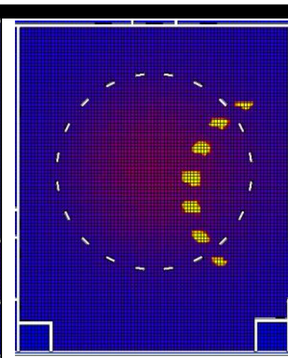
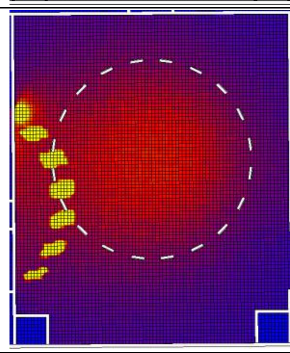
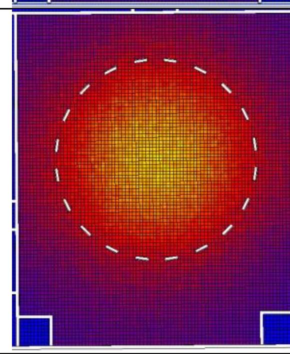
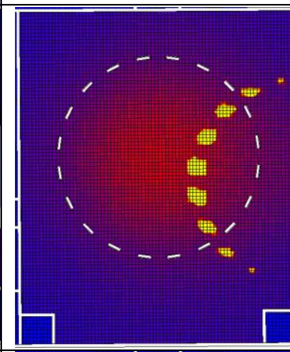
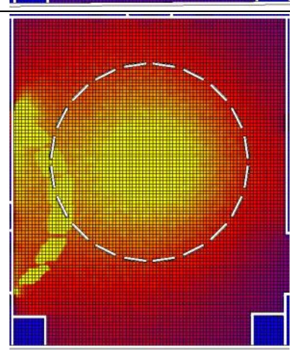
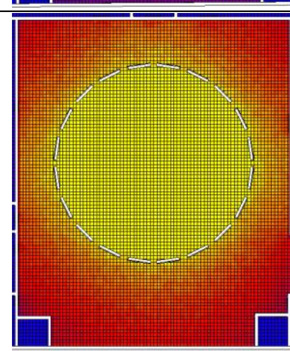
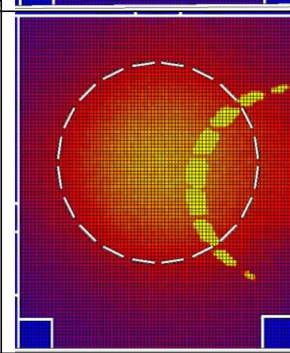
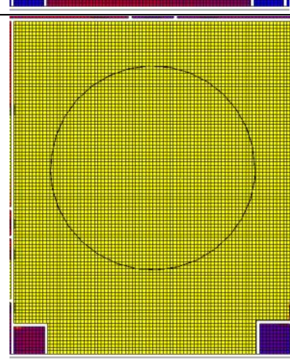
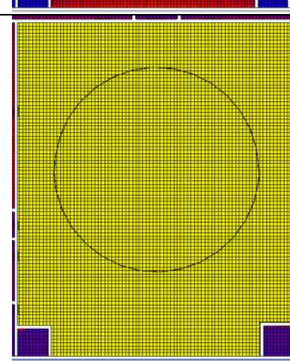
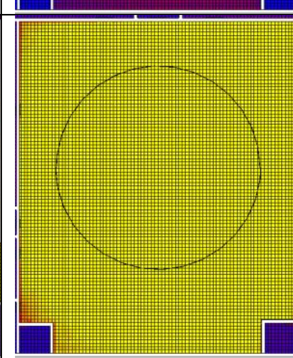
<table>
<tr><th colspan="6">Date: 21st June</th></tr>
<tr><th rowspan="2">Dome Diameter</th><th rowspan="2">Height of Drum</th><th rowspan="2">S windows in drum
(W area/ D area)</th><th colspan="3">Illuminance</th></tr>
<tr><th>8:00 AM</th><th>12:00 PM</th><th>4:00 PM</th></tr>
<tr><td rowspan="4">18.0
(LUX)

</td><td rowspan="4">3.0 m
(sill height = 0.8 m)</td><td>10%</td><td></td><td></td><td></td></tr>
<tr><td>15%</td><td></td><td></td><td></td></tr>
<tr><td>25%</td><td></td><td></td><td></td></tr>
<tr><td>100%</td><td></td><td></td><td></td></tr>
</table>

Table 34: 21st June Illuminance level for (D=18, H=4 , S=10,15,25,100)

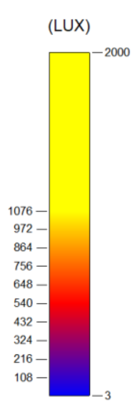
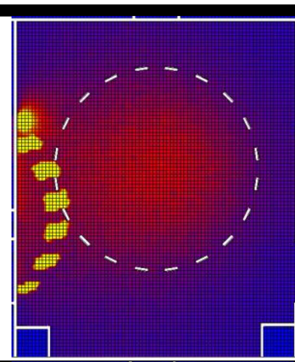
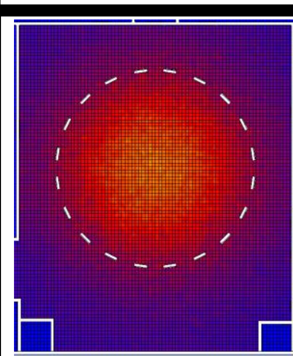
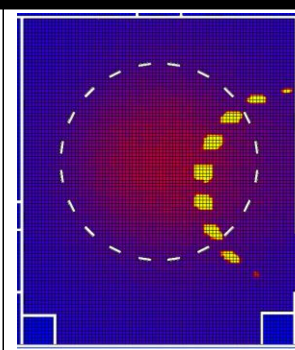
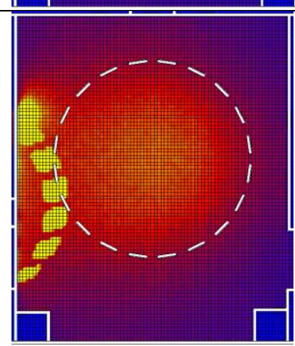
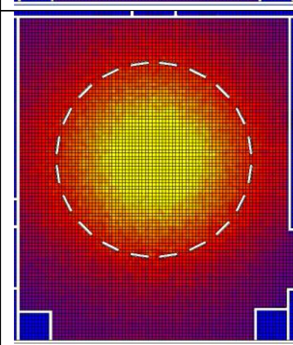
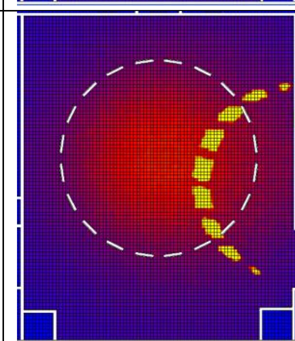
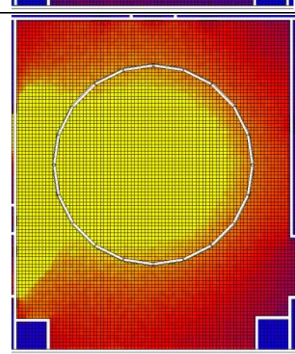
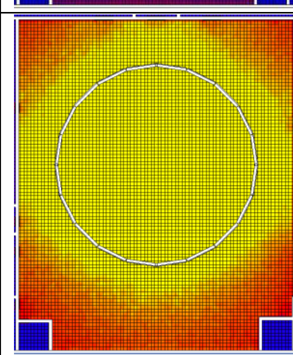
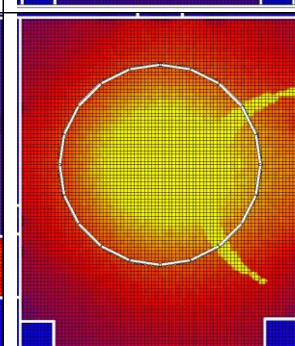
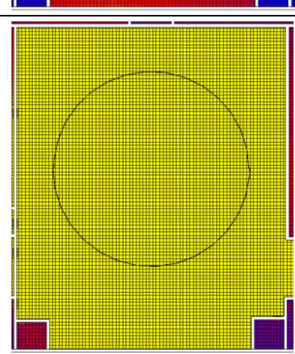
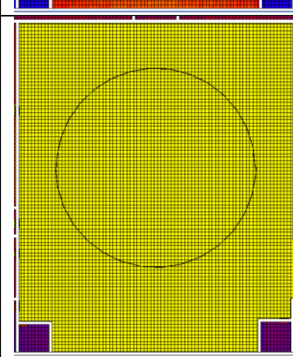
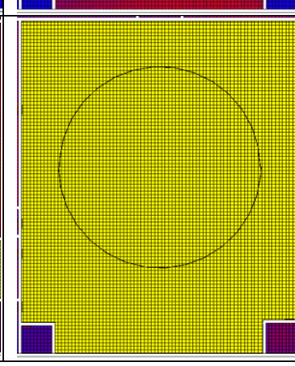
Date: 21st June					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
18.0 	4.0 m (sill height = 1.3 m)	10%			
		15%			
		25%			
		100%			

Table 35: 21st September Illuminance level for (D=7, H=2 , S=10,15,25,100)

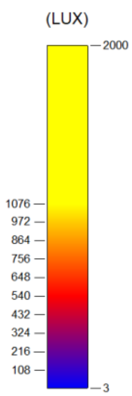
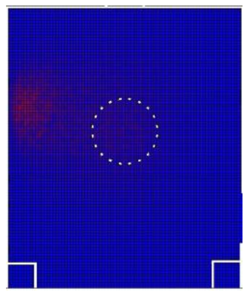
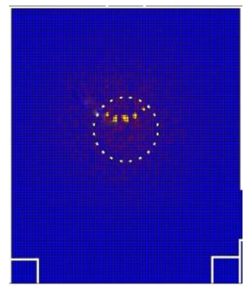
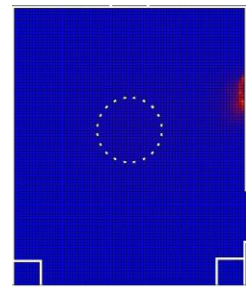
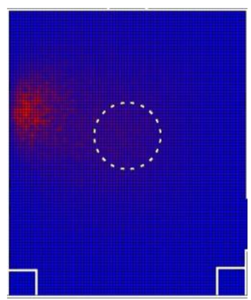
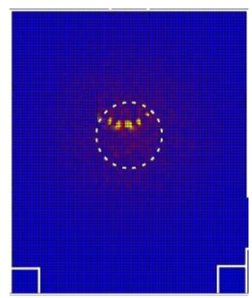
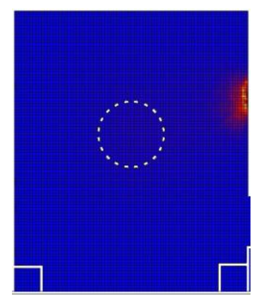
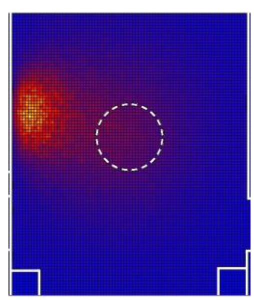
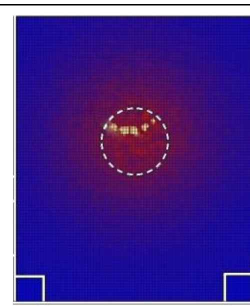
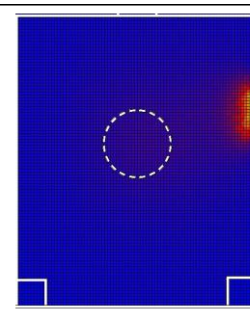
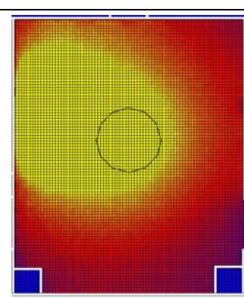
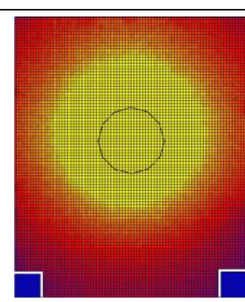
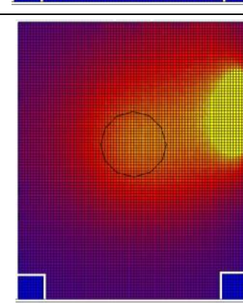
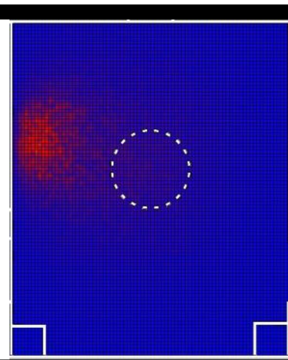
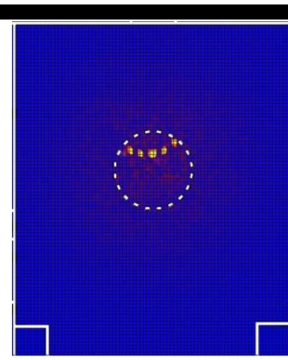
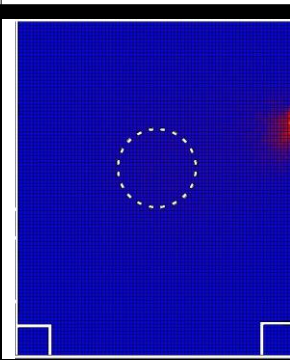
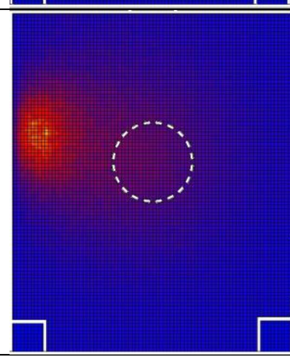
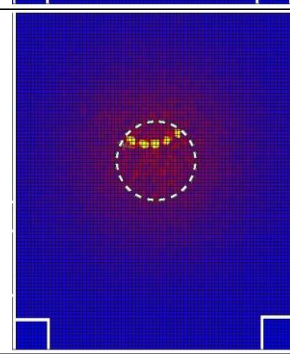
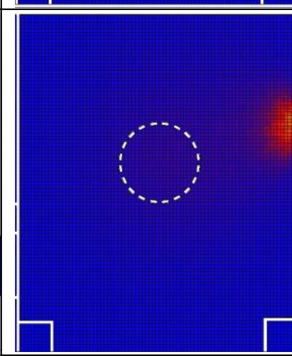
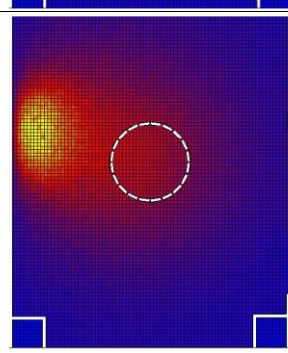
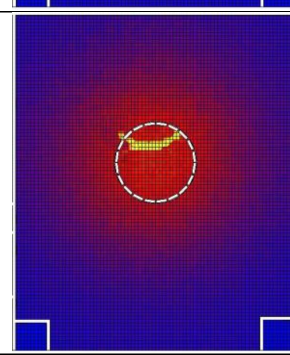
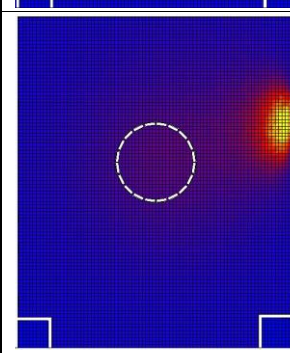
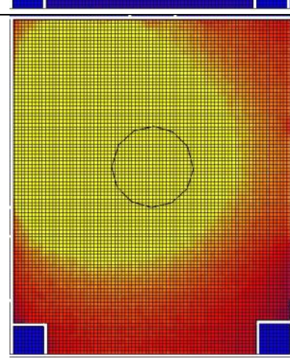
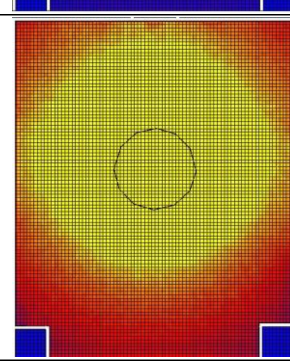
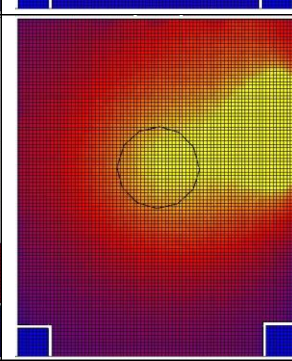
<table>
<tr><th colspan="6">Date: 21st September</th></tr>
<tr><th rowspan="2">Dome Diameter</th><th rowspan="2">Height of Drum</th><th rowspan="2">S windows in drum (W area/ D area)</th><th colspan="3">Illuminance</th></tr>
<tr><th>8:00 AM</th><th>12:00 PM</th><th>4:00 PM</th></tr>
<tr><td rowspan="4">7.0
</td><td rowspan="4">2.0 m
(sill height = 0.3 m)</td><td>10%</td><td></td><td></td><td></td></tr>
<tr><td>15%</td><td></td><td></td><td></td></tr>
<tr><td>25%</td><td></td><td></td><td></td></tr>
<tr><td>100%</td><td></td><td></td><td></td></tr>
</table>

Table 36: 21st September Illuminance level for (D=7, H=3 , S=10,15,25,100)

Date: 21st September					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
7.0	3.0 m (sill height = 0.8 m)	10%			
		15%			
		25%			
		100%			

(LUX)

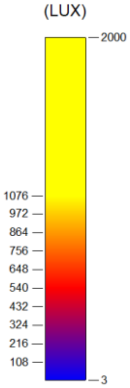


Table 37: 21st September Illuminance level for (D=7, H=4 , S=10,15,25,100)

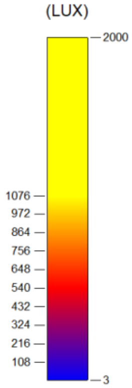
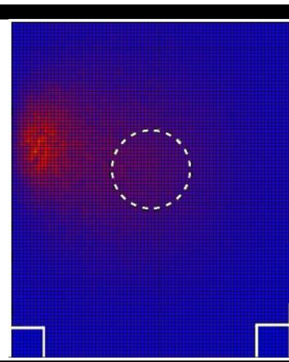
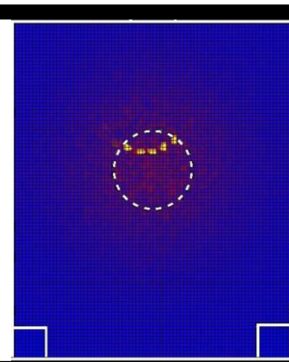
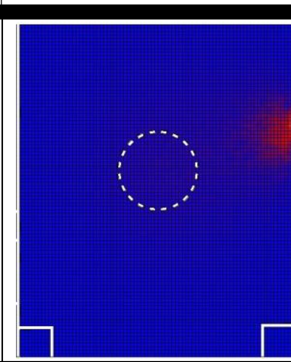
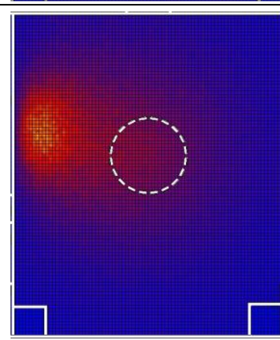
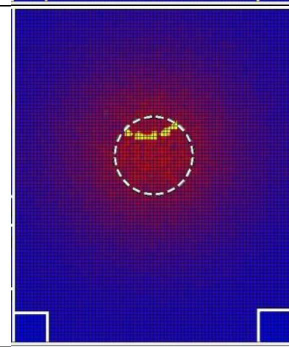
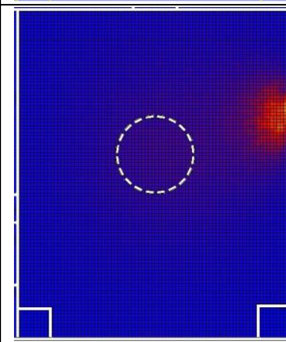
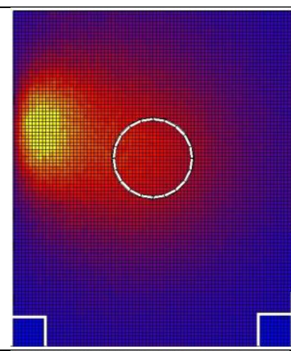
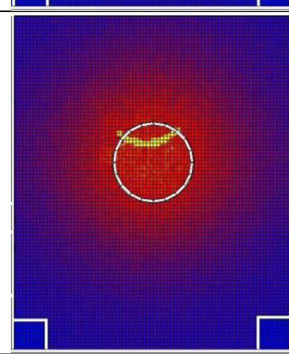
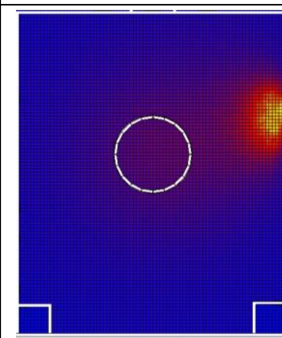
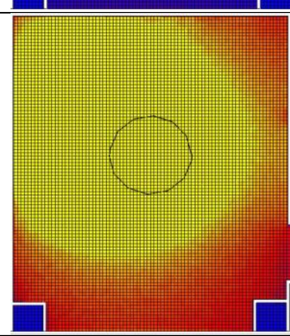
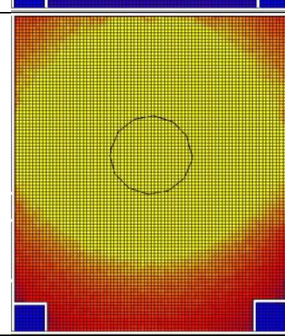
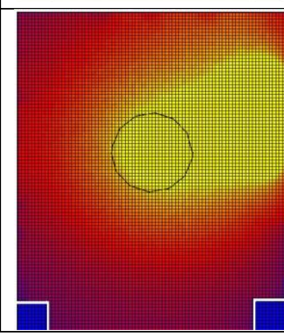
Date: 21st September					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
7.0 (LUX) 	4.0 m (sill height = 1.3 m)	10%			
		15%			
		25%			
		100%			

Table 38: 21st September Illuminance level for (D=14, H=2 , S=10,15,25,100)

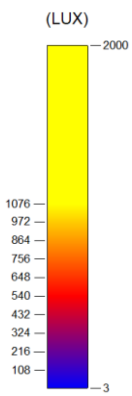
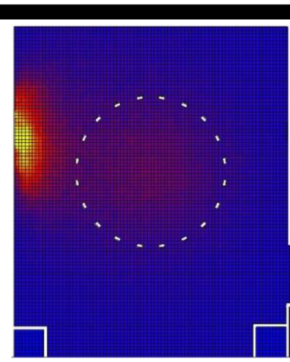
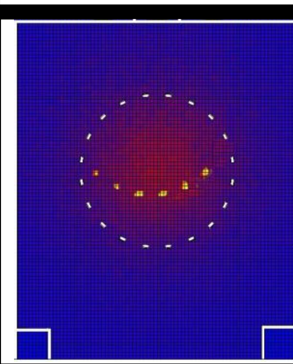
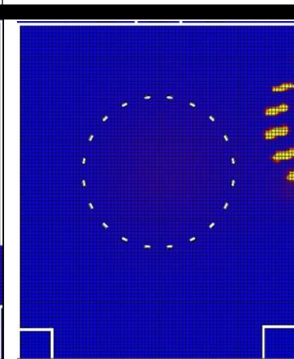
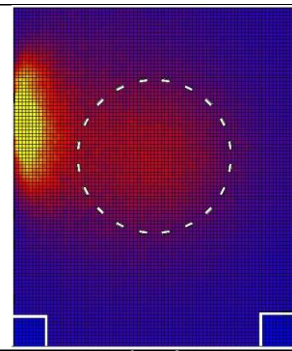
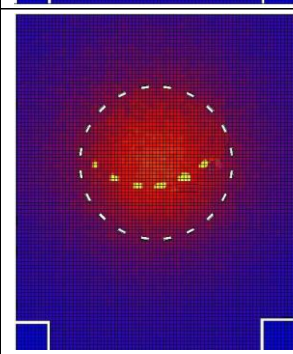
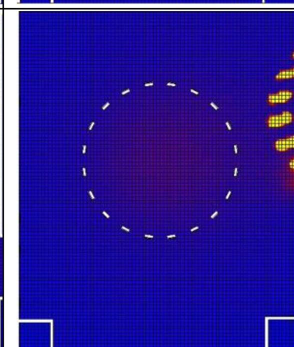
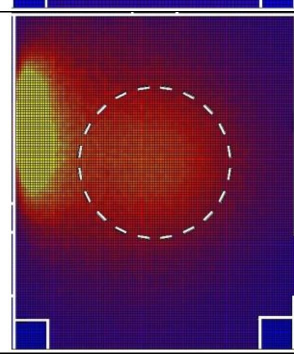
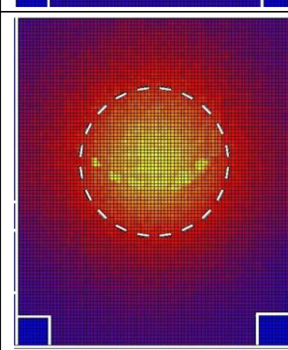
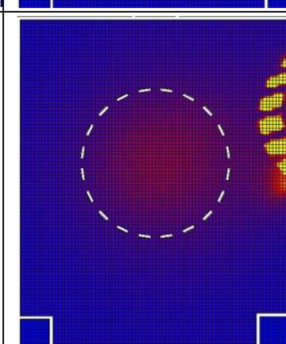
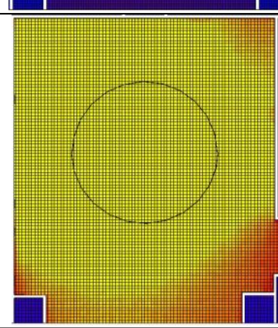
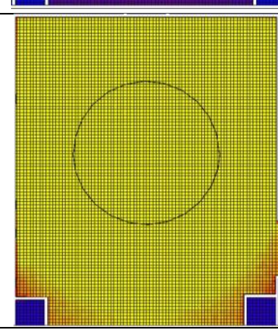
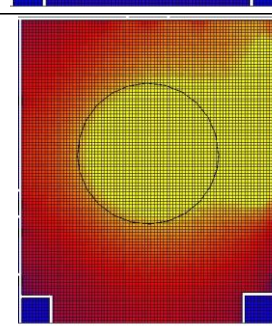
Date: 21st September					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
14.0 	2.0 m (sill height = 0.3 m)	10%			
		15%			
		25%			
		100%			

Table 39: 21st September Illuminance level for (D=14, H=3 , S=10,15,25,100)

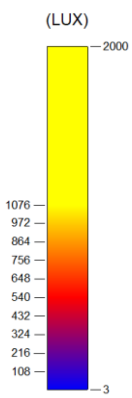
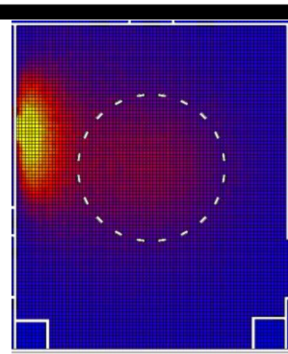
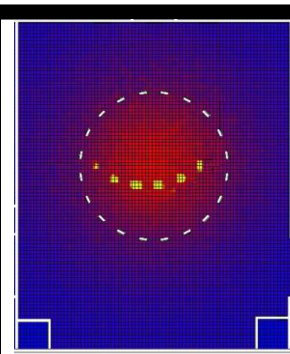
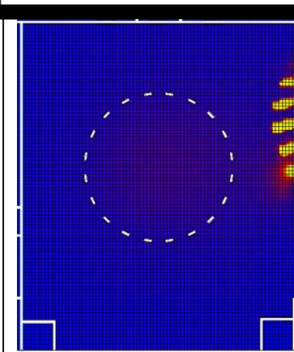
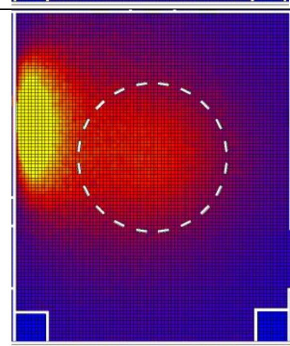
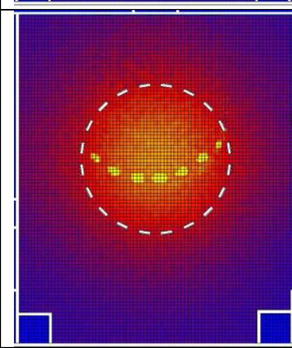
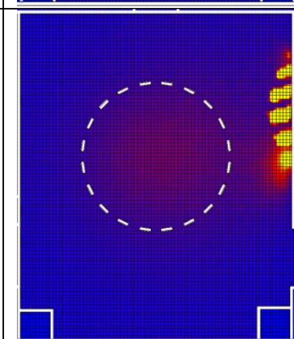
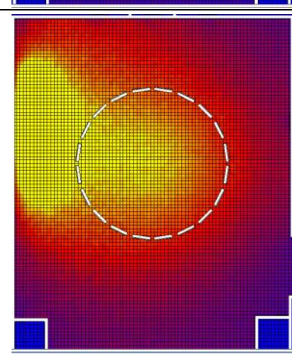
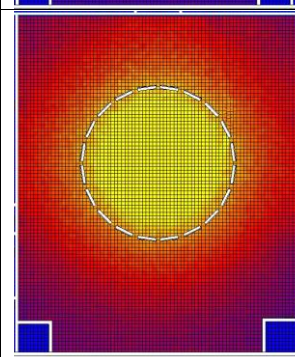
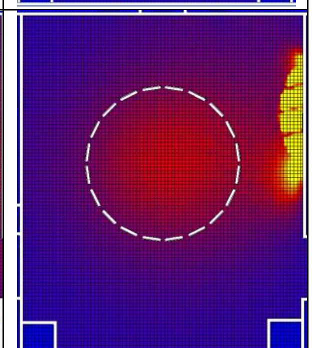
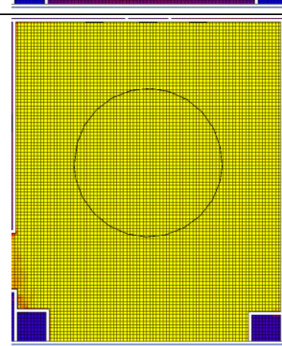
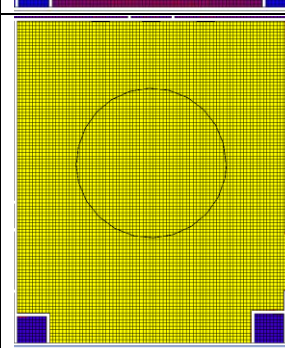
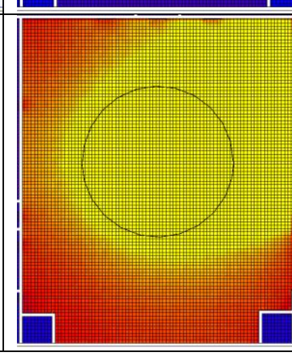
Date: 21st September					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
14.0 	3.0 m (sill height = 0.8 m)	10%			
		15%			
		25%			
		100%			

Table 40: 21st September Illuminance level for (D=14, H=4 , S=10,15,25,100)

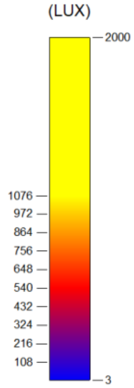
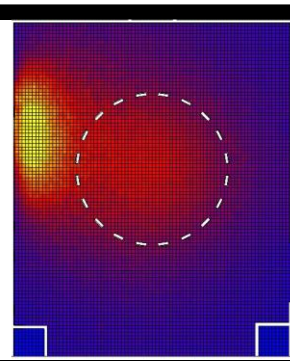
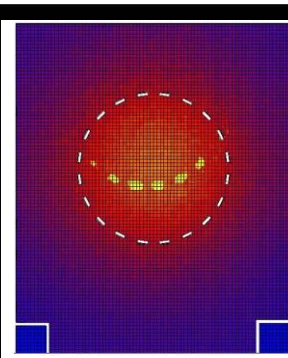
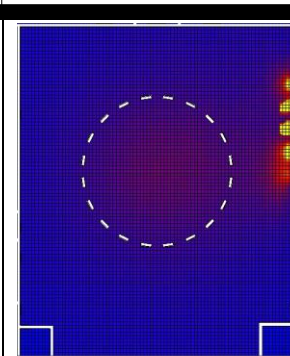
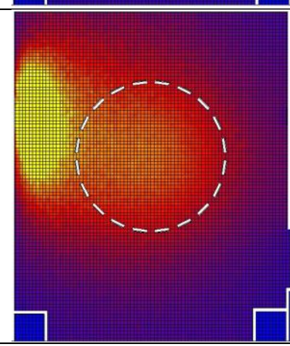
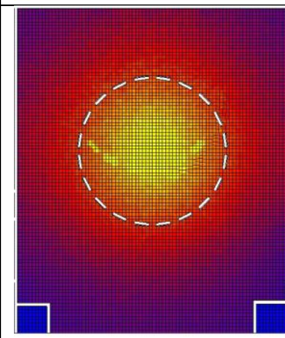
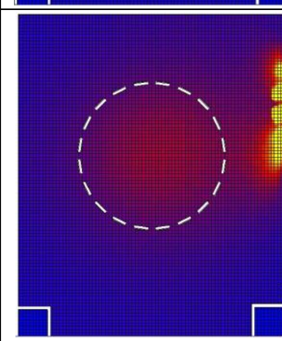
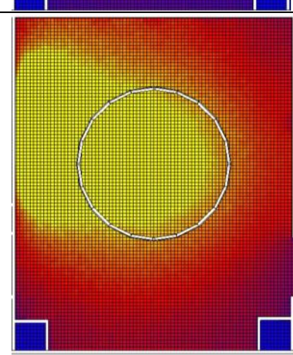
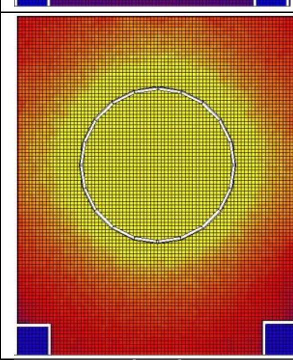
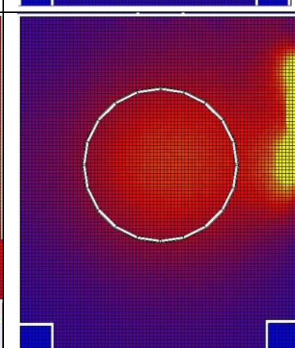
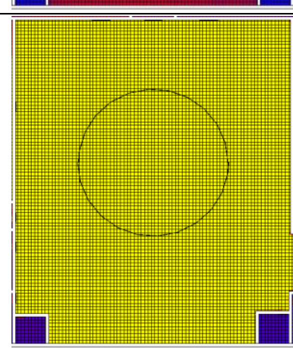
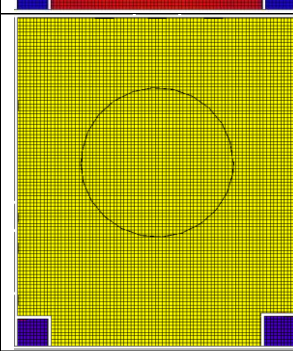
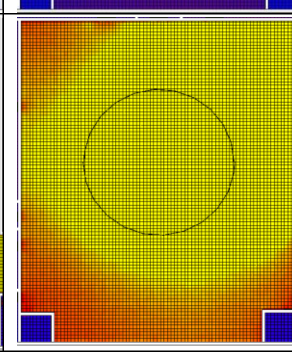
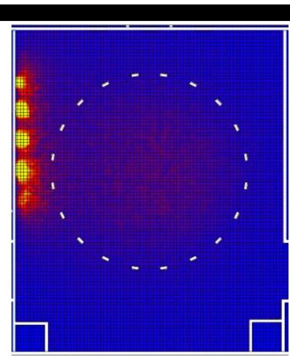
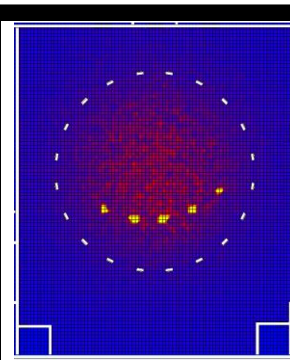
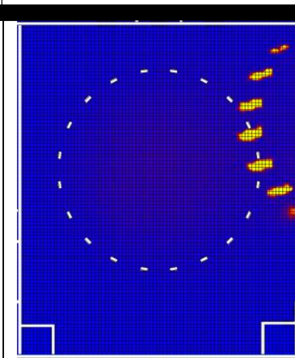
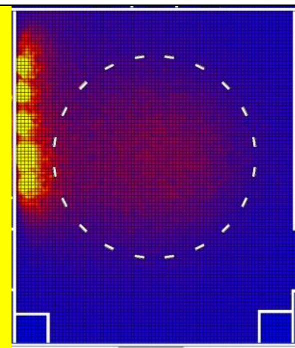
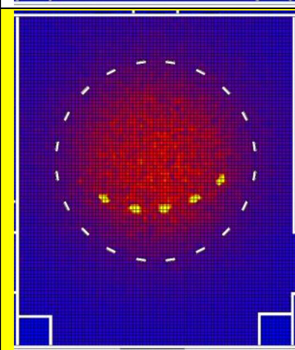
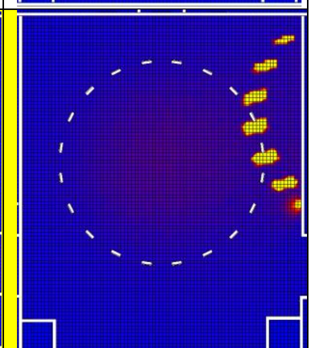
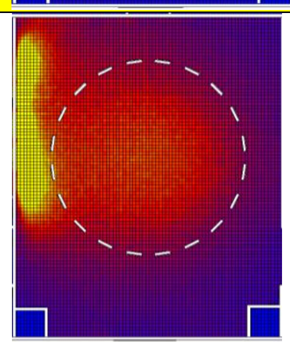
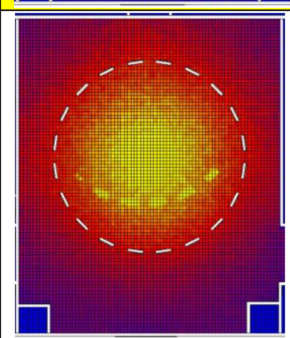
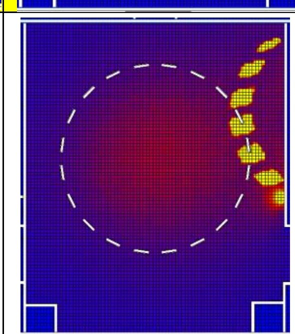
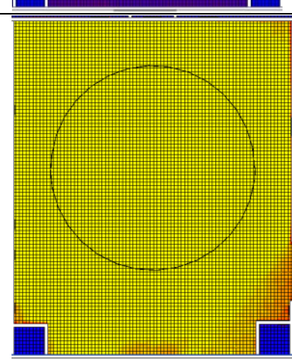
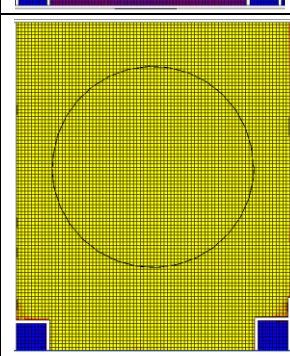
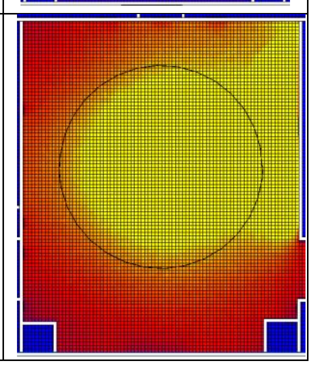
Date: 21st September					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
14.0 (LUX) 	4.0 m (sill height = 1.3 m)	10%			
		15%			
		25%			
		100%			

Table 41: 21st September Illuminance level for (D=18, H=2 , S=10,15,25,100)

Date: 21st September					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
18.0	2.0 m (sill height = 0.3 m)	10%			
		15%			
		25%			
		100%			

(LUX)

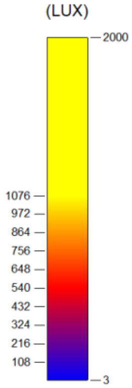


Table 42: 21st September Illuminance level for (D=18, H=3 , S=10,15,25,100)

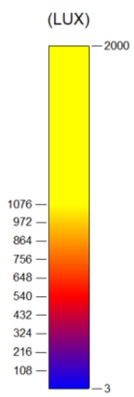
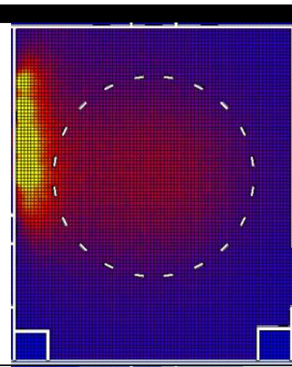
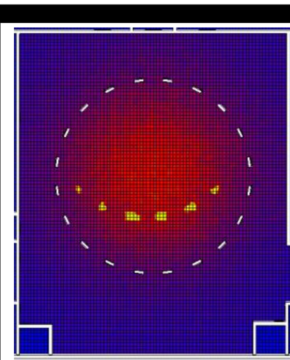
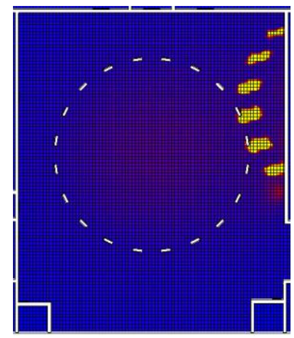
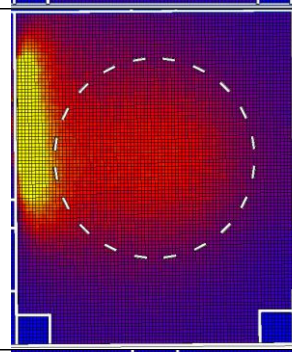
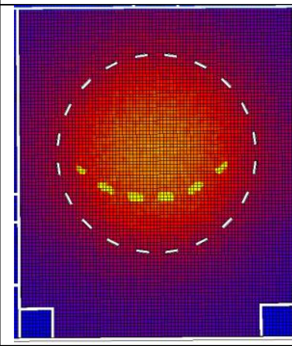
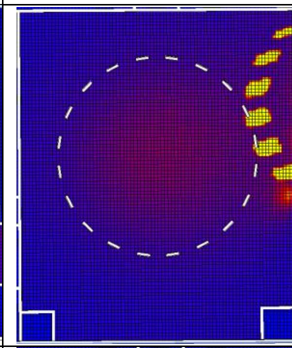
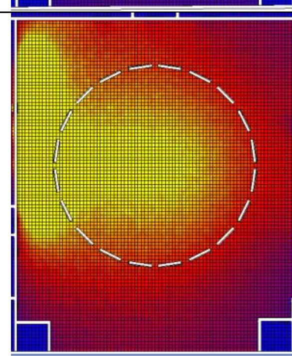
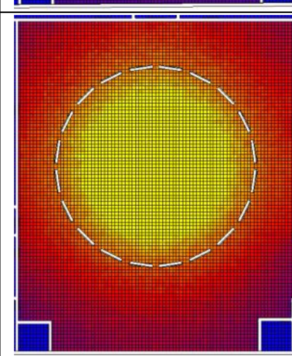
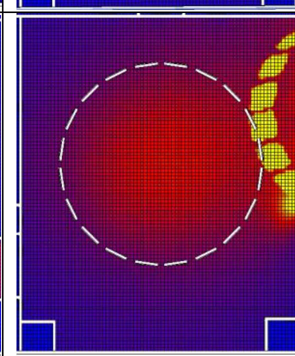
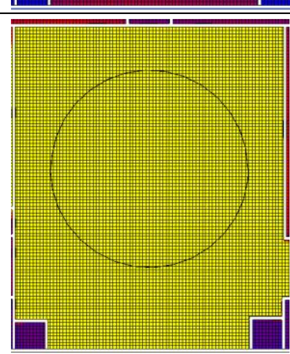
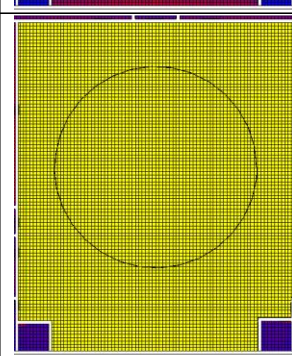
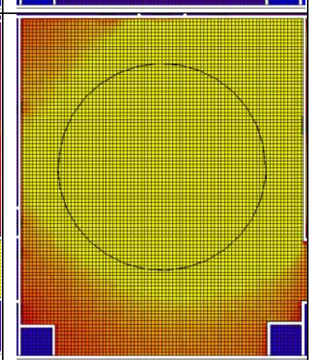
Date: 21st September					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
18.0  	3.0 m (sill height = 0.8 m)	10%			
		15%			
		25%			
		100%			

Table 43: 21st September Illuminance level for (D=18, H=4 , S=10,15,25,100)

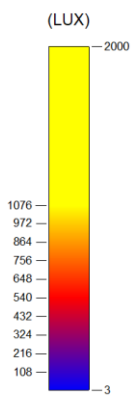
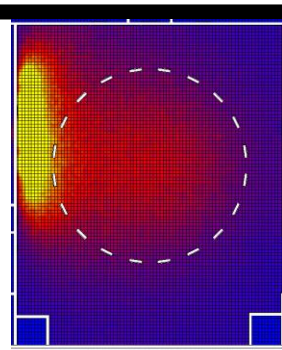
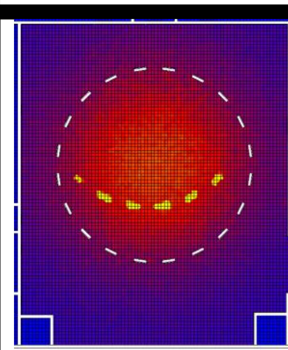
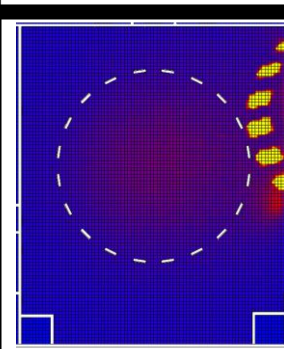
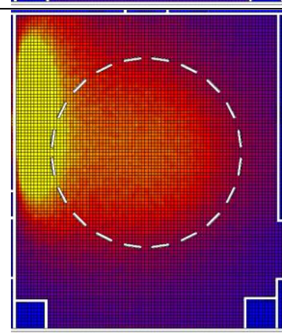
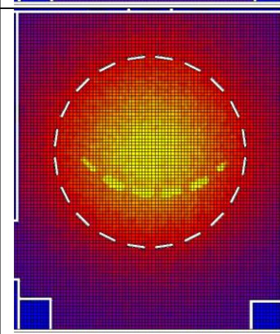
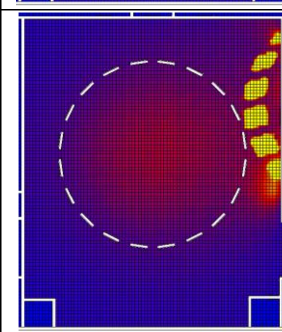
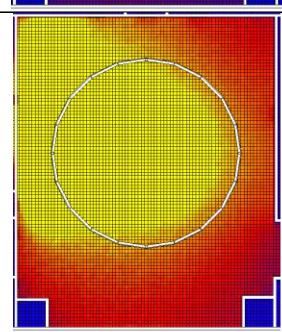
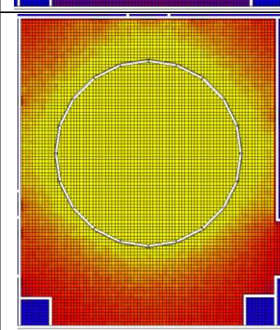
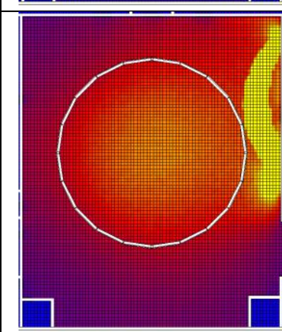
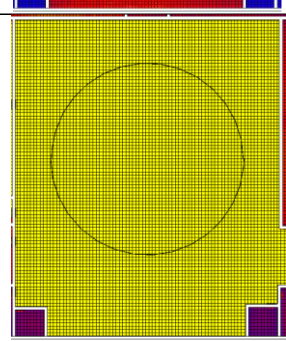
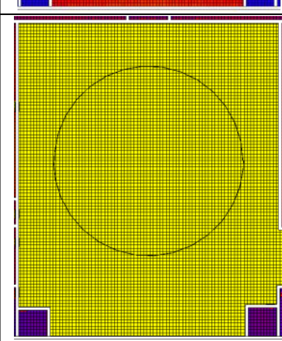
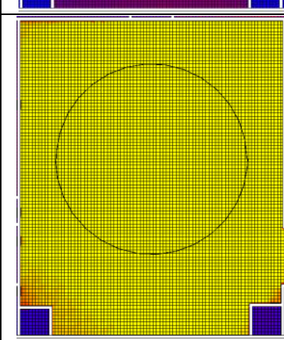
Date: 21st September					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
18.0 	4.0 m (sill height = 1.3 m)	10%			
		15%			
		25%			
		100%			

Table 44: 21st December Illuminance level for (D=7, H=2 , S=10,15,25,100)

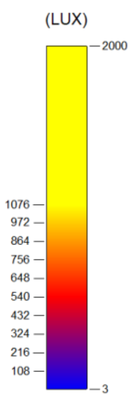
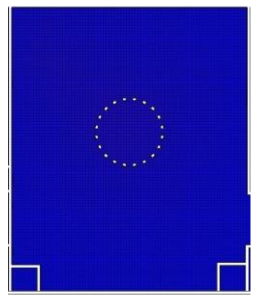
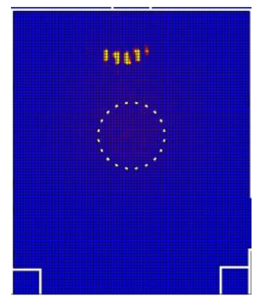
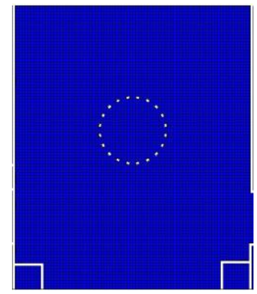
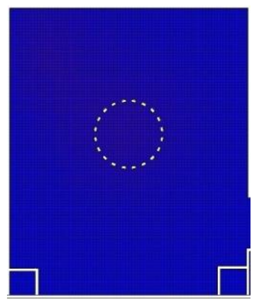
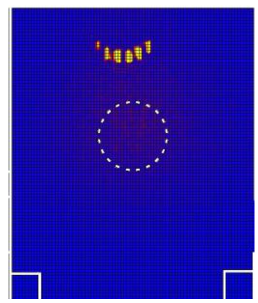
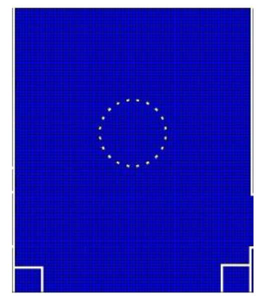
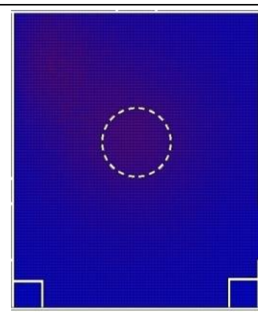
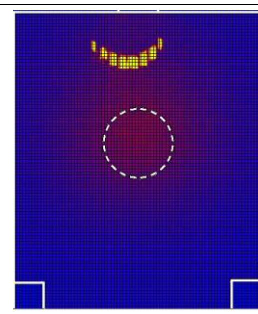
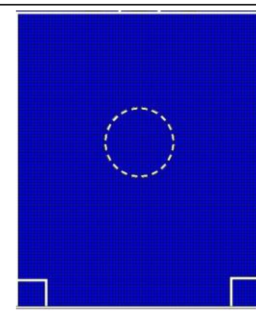
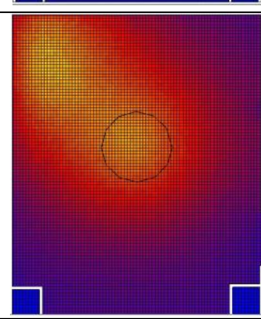
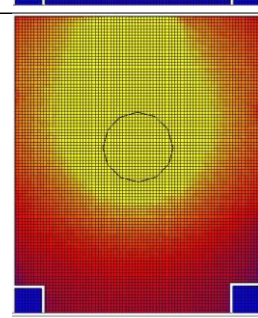
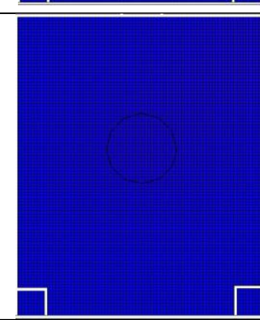
Date: 21st December					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
7.0 	2.0 m (sill height = 0.3 m)	10%			
		15%			
		25%			
		100%			

Table 45: 21st December Illuminance level for (D=7, H=3 , S=10,15,25,100)

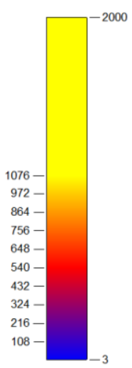
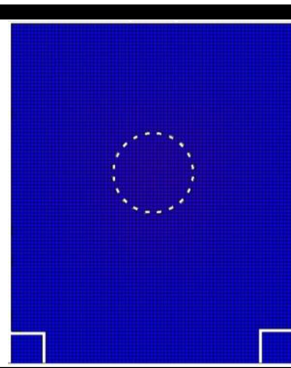
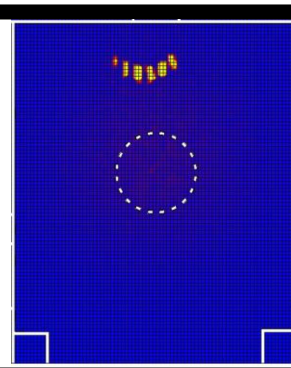
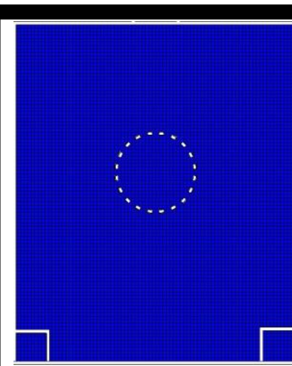
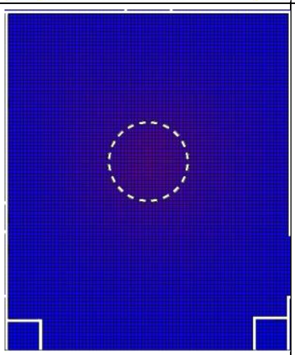
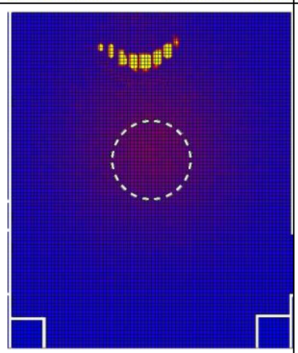
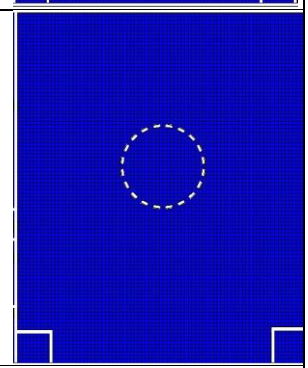
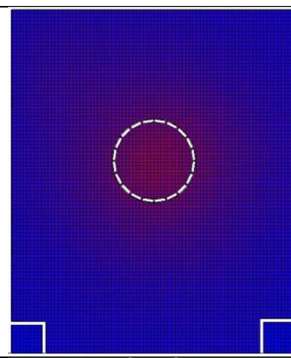
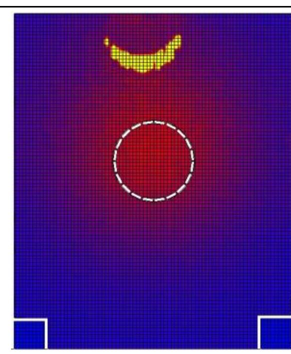
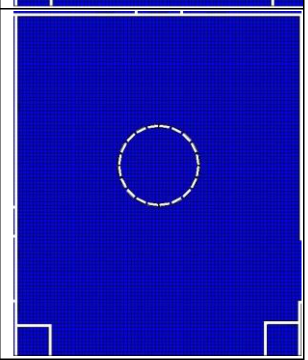
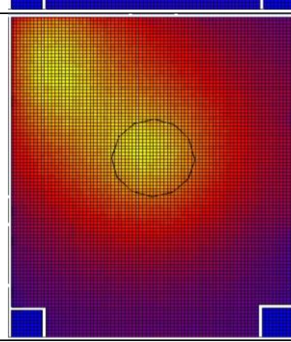
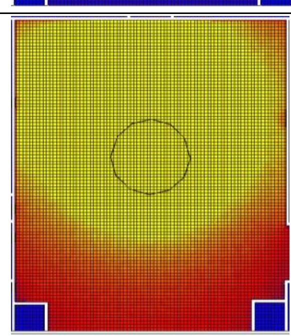
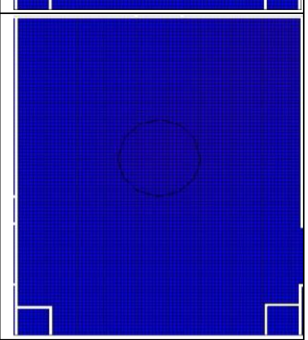
Date: 21st December					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
7.0 (LUX) 	3.0 m (sill height = 0.8 m)	10%			
		15%			
		25%			
		100%			

Table 46: 21st December Illuminance level for (D=7, H=4 , S=10,15,25,100)

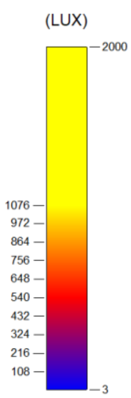
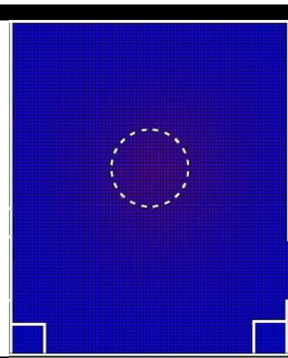
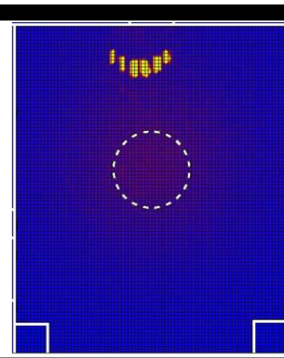
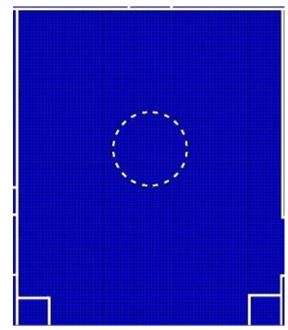
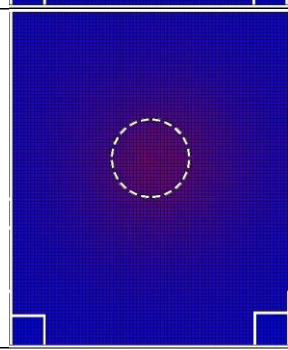
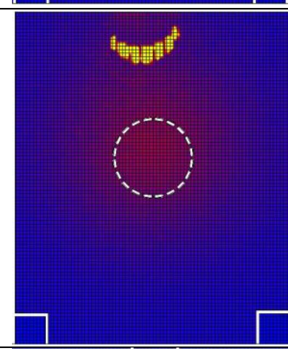
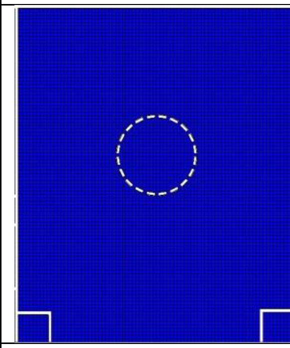
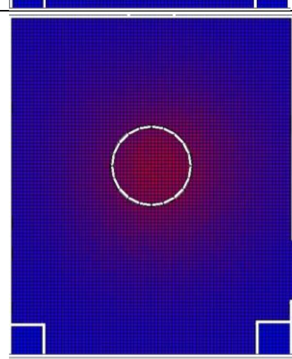
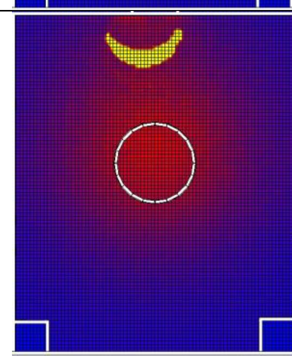
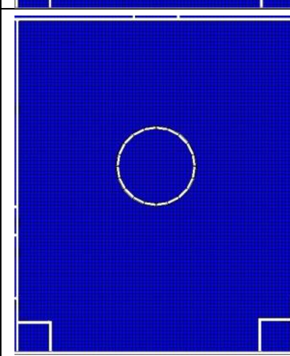
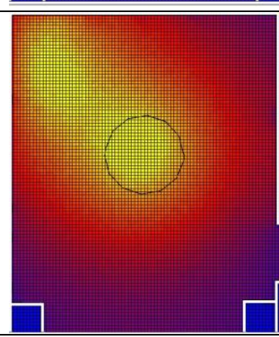
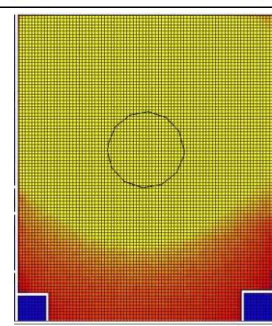
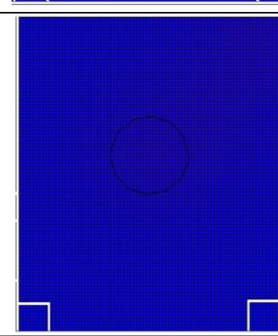
Date: 21st December					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
7.0 	4.0 m (sill height = 1.3 m)	10%			
		15%			
		25%			
		100%			

Table 47: 21st December Illuminance level for (D=14, H=2 , S=10,15,25,100)

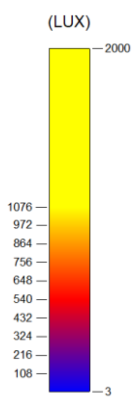
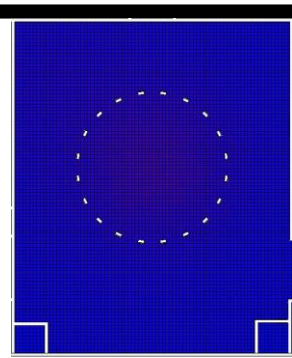
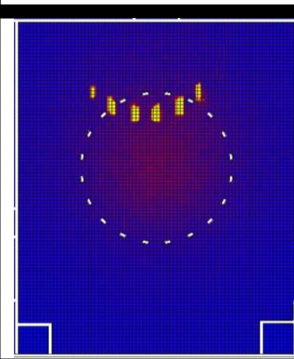
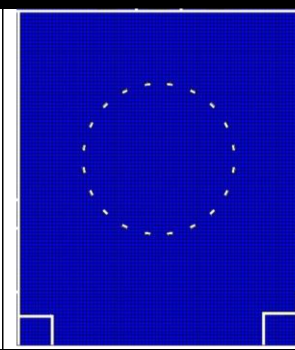
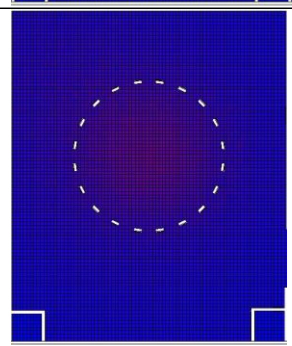
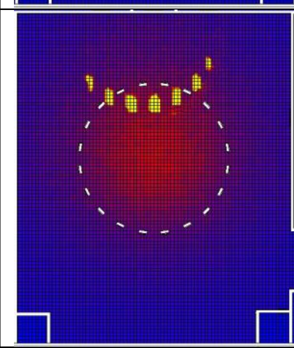
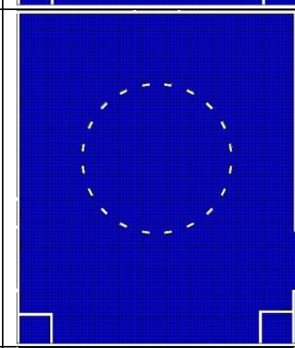
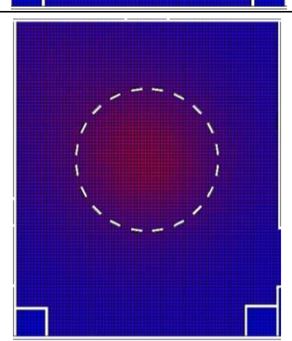
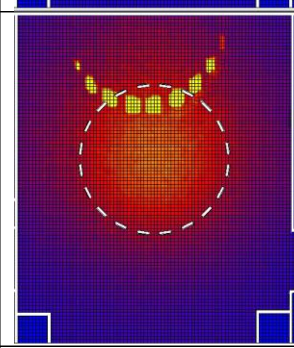
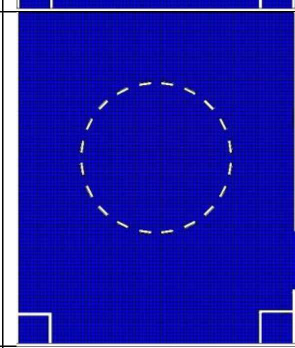
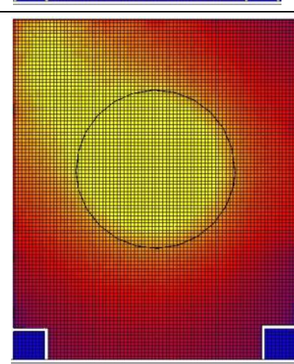
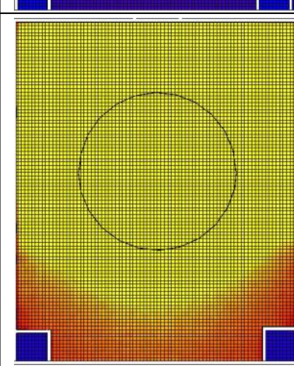
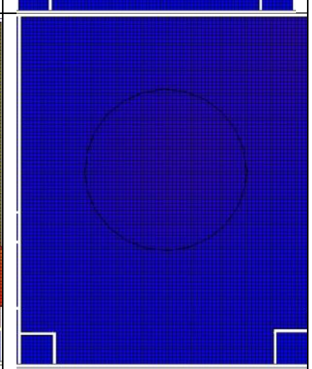
<table>
<tr><td colspan="6">Date: 21st December</td></tr>
<tr><td rowspan="2">Dome Diameter</td><td rowspan="2">Height of Drum</td><td rowspan="2">S windows in drum (W area/ D area)</td><td colspan="3">Illuminance</td></tr>
<tr><td>8:00 AM</td><td>12:00 PM</td><td>4:00 PM</td></tr>
<tr><td rowspan="4">14.0
</td><td rowspan="4">2.0 m
(sill height = 0.3 m)</td><td>10%</td><td></td><td></td><td></td></tr>
<tr><td>15%</td><td></td><td></td><td></td></tr>
<tr><td>25%</td><td></td><td></td><td></td></tr>
<tr><td>100%</td><td></td><td></td><td></td></tr>
</table>

Table 48: 21st December Illuminance level for (D=14, H=3 , S=10,15,25,100)

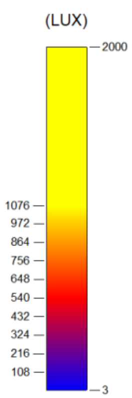
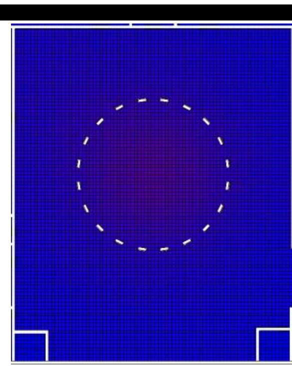
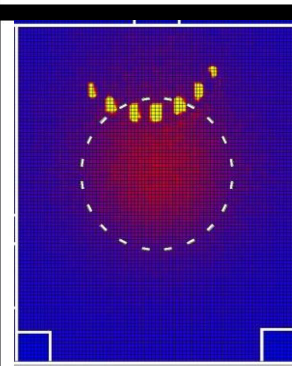
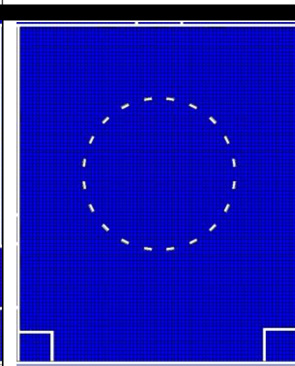
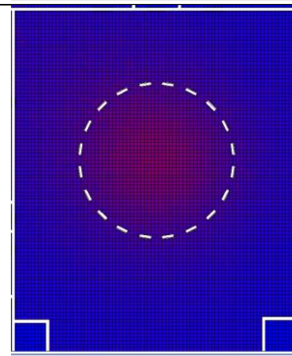
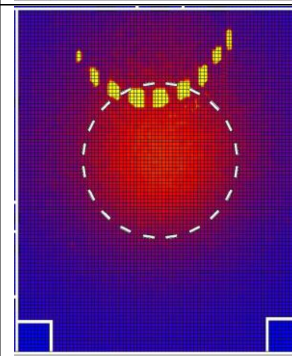
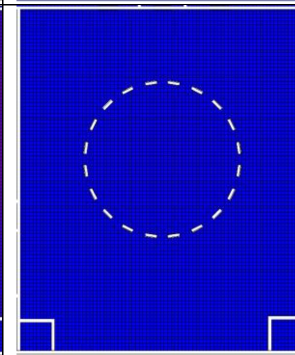
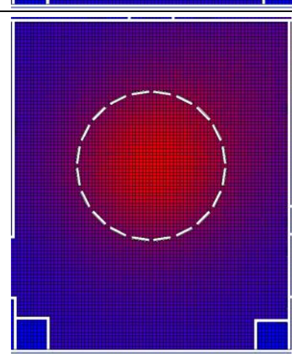
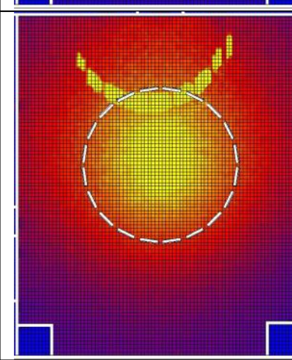
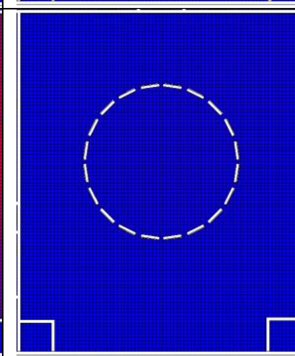
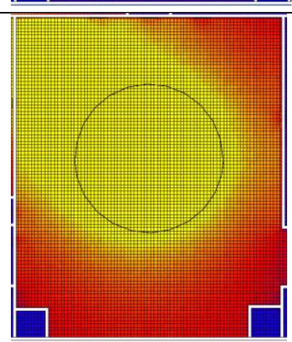
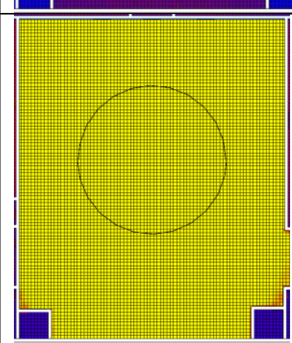
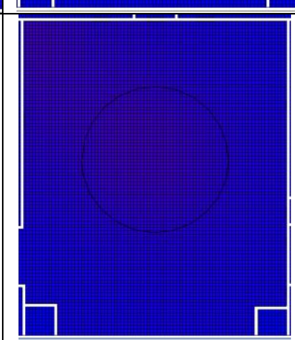
Date: 21st December					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
14.0  	3.0 m (sill height = 0.8 m)	10%			
		15%			
		25%			
		100%			

Table 49: 21st December Illuminance level for (D=14, H=4 , S=10,15,25,100)

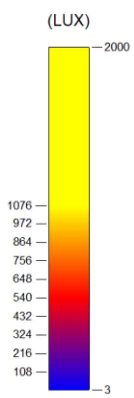
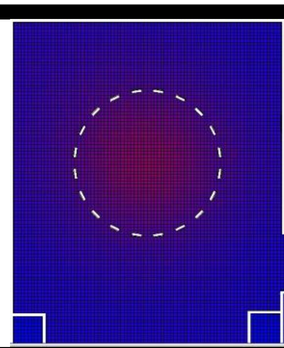
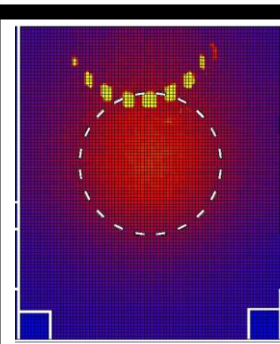
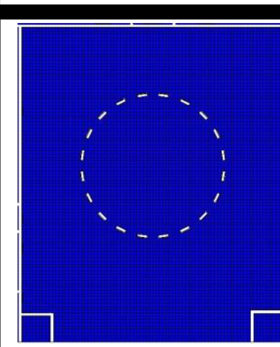
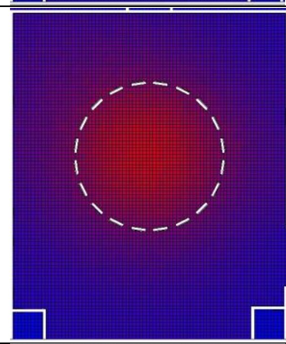
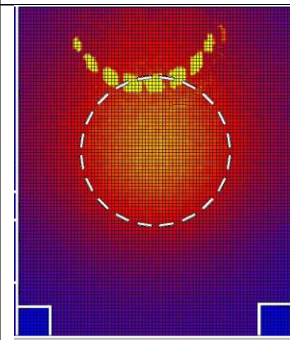
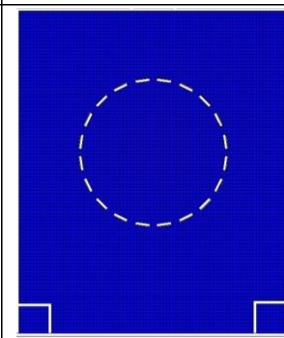
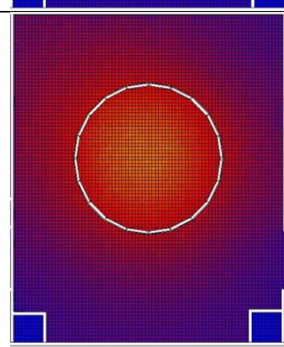
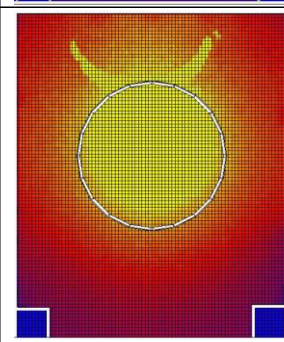
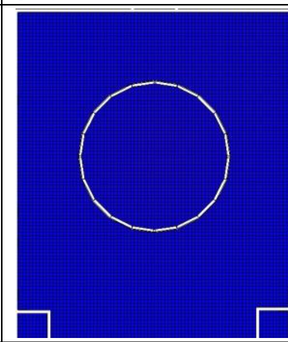
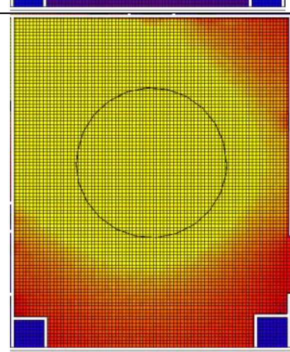
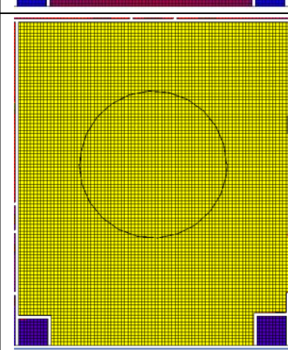
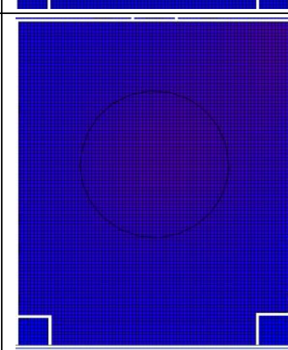
Date: 21st December					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
14.0 	4.0 m (sill height = 1.3 m)	10%			
		15%			
		25%			
		100%			

Table 50: 21st December Illuminance level for (D=18, H=2 , S=10,15,25,100)

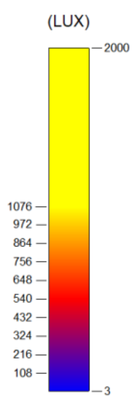
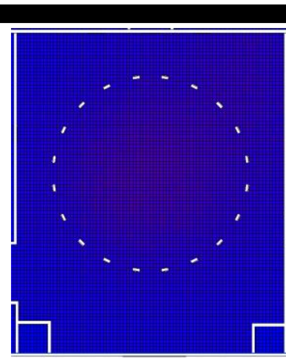
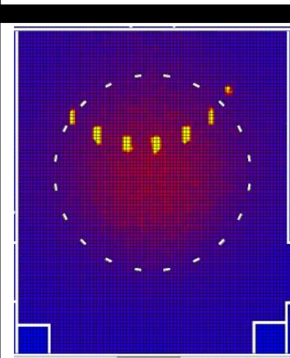
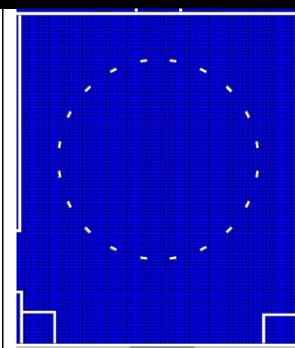
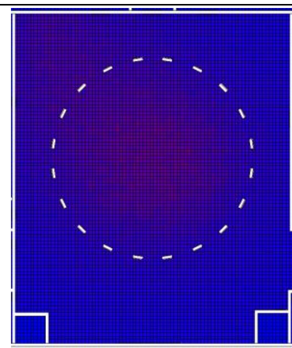
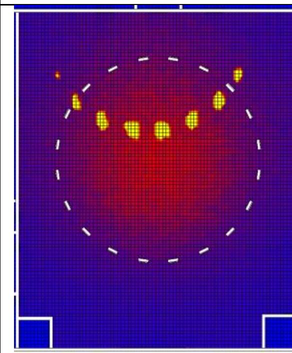
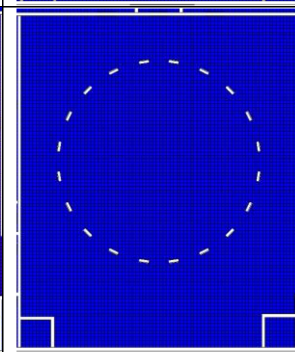
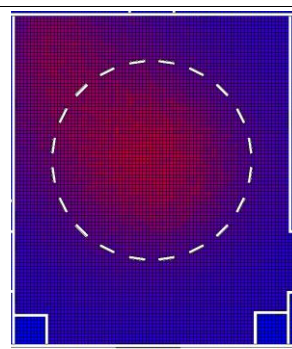
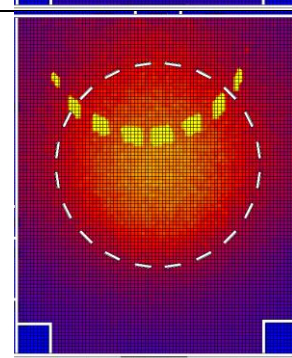
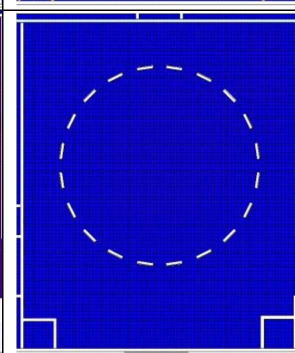
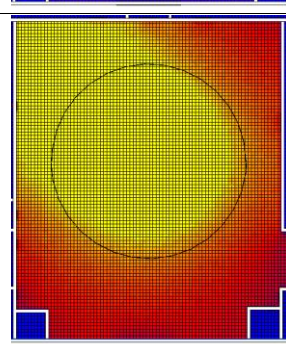
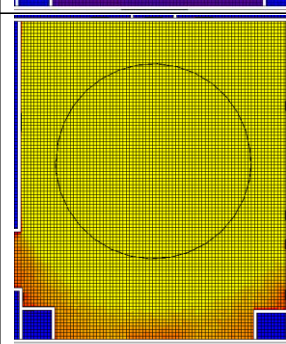
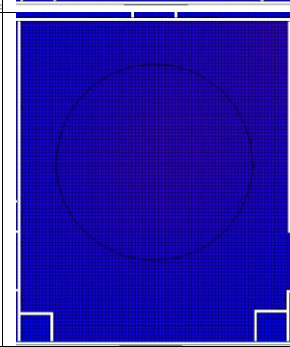
Date: 21st December					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
18.0 	2.0 m (sill height = 0.3 m)	10%			
		15%			
		25%			
		100%			

Table 51: 21st December Illuminance level for (D=18, H=3 , S=10,15,25,100)

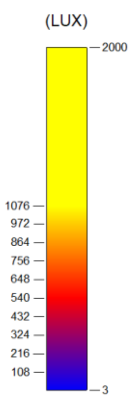
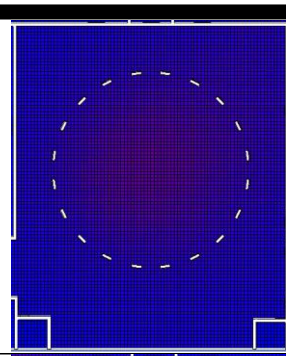
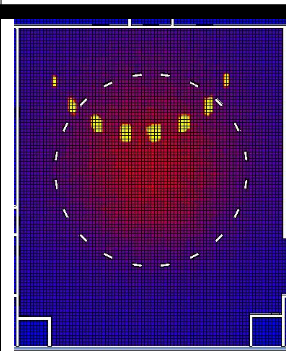
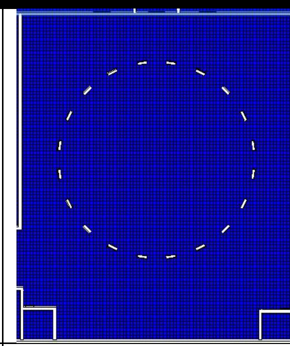
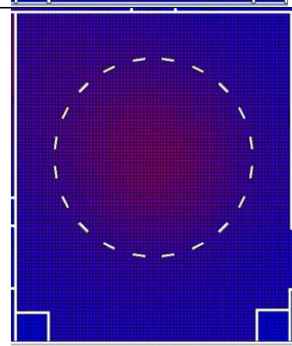
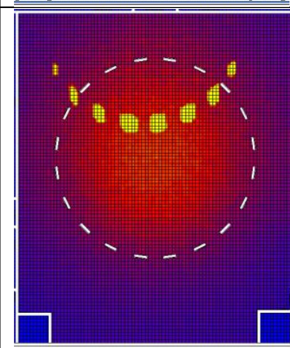
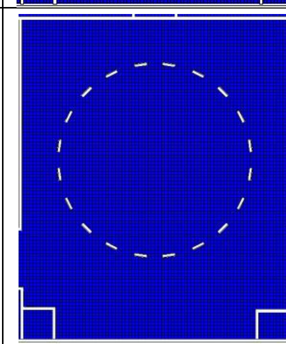
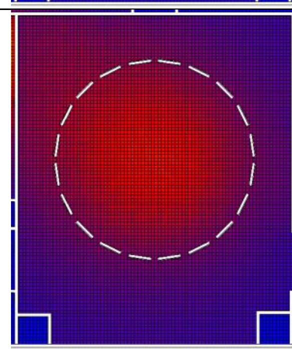
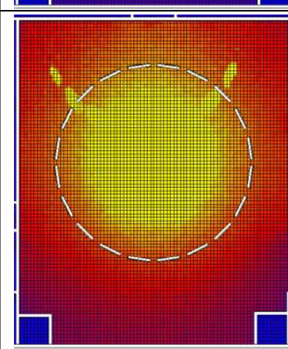
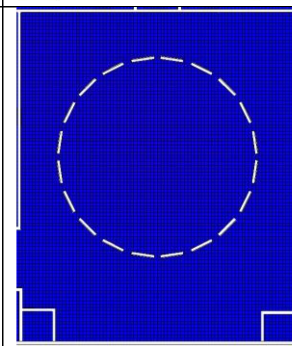
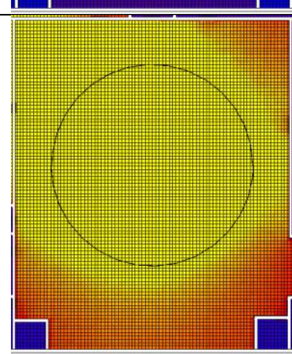
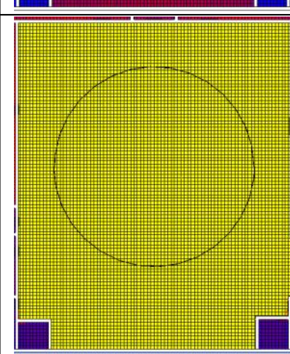
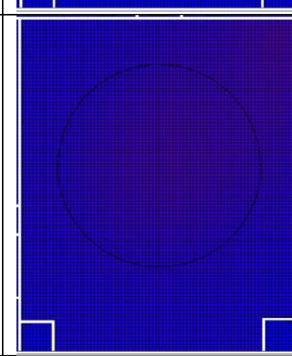
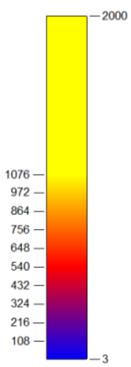
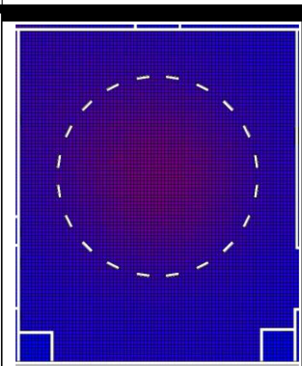
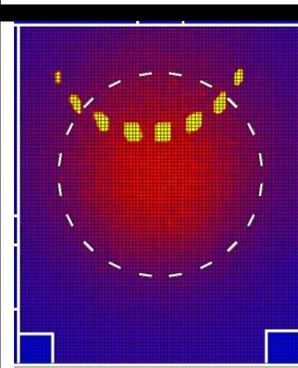
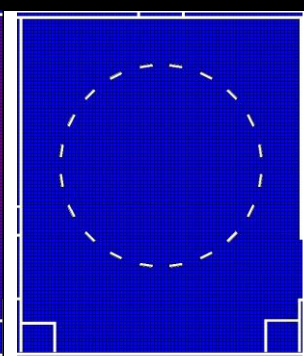
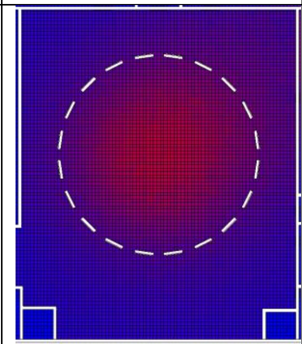
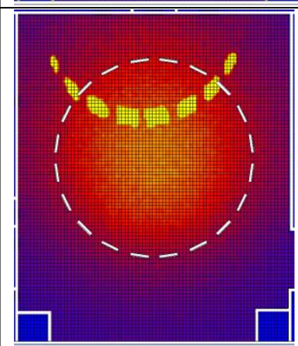
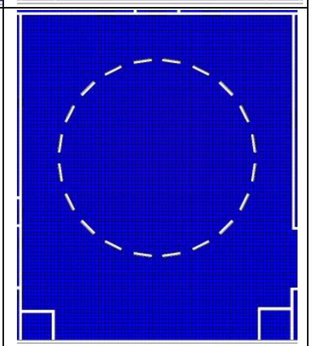
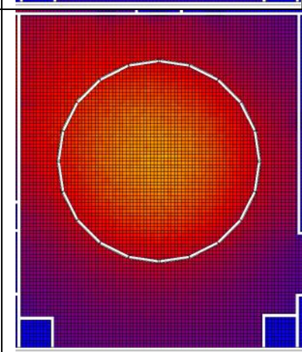
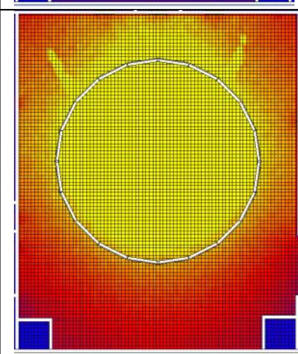
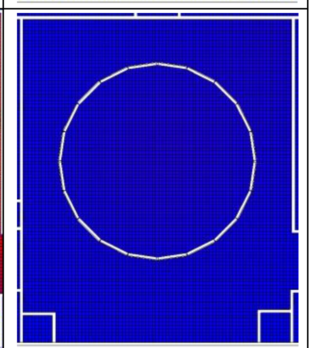
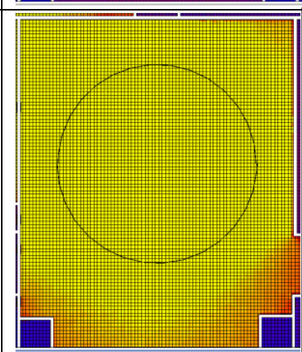
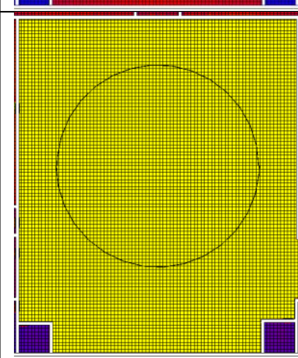
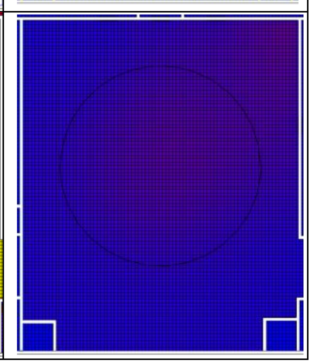
Date: 21st December					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
18.0 	3.0 m (sill height = 0.8 m)	10%			
		15%			
		25%			
		100%			

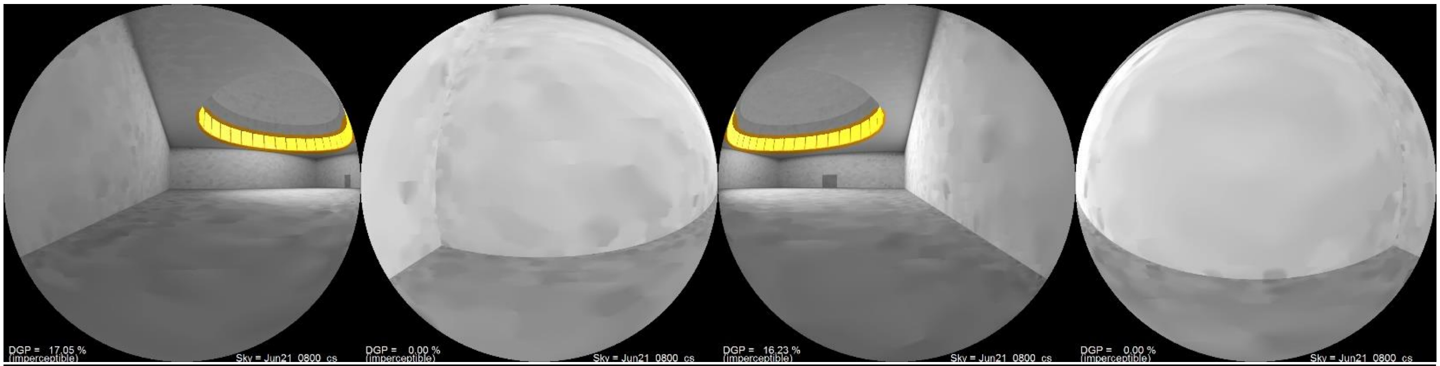
Table 52: 21st December Illuminance level for (D=18, H=4 , S=10,15,25,100)

Date: 21st December					
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	Illuminance		
			8:00 AM	12:00 PM	4:00 PM
18.0 (LUX) 	4.0 m (sill height = 1.3 m)	10%			
		15%			
		25%			
		100%			

Appendix B – DGP simulation results

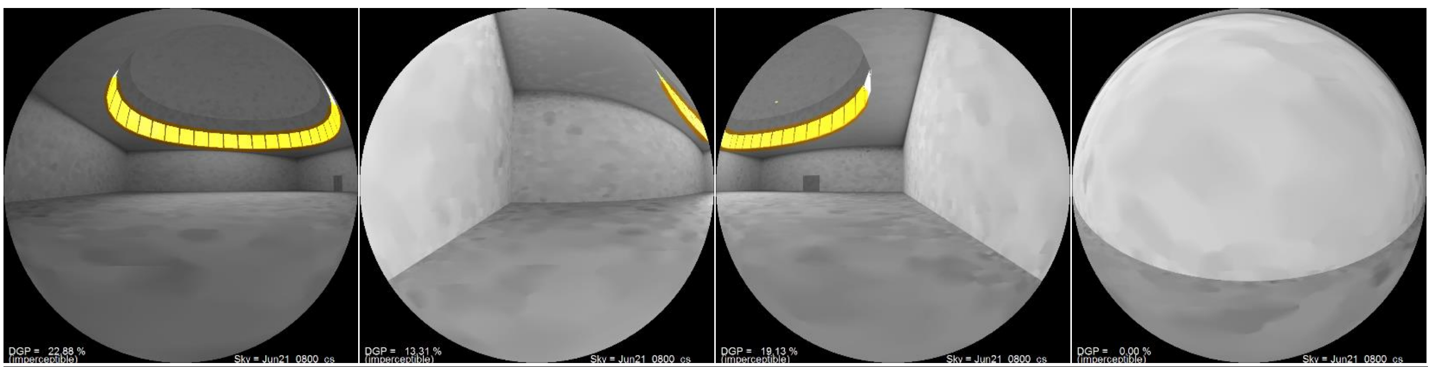
1. **<u>21 Jun 8:00 am</u>**

<u>Point A1:</u>



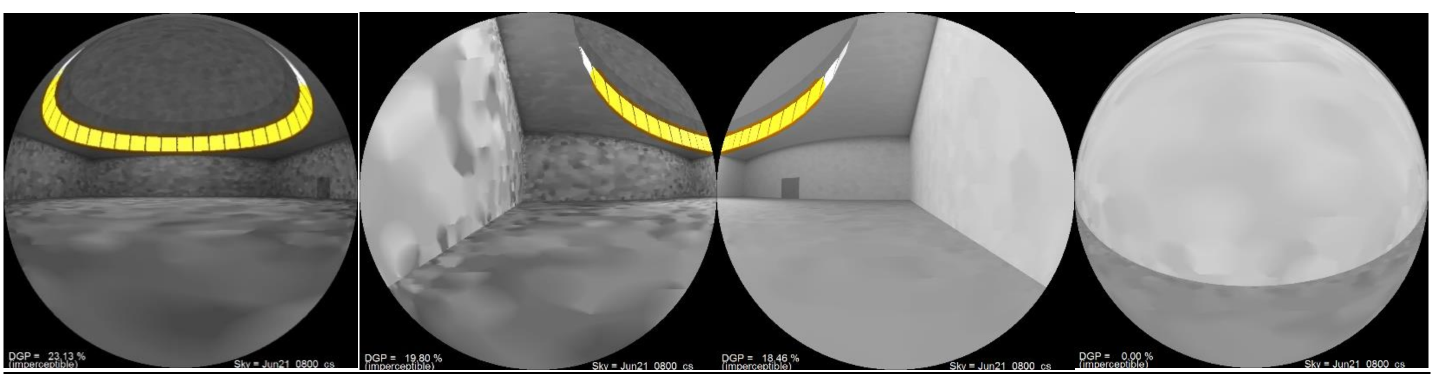
East **North** **South** **West**

<u>Point A2:</u>



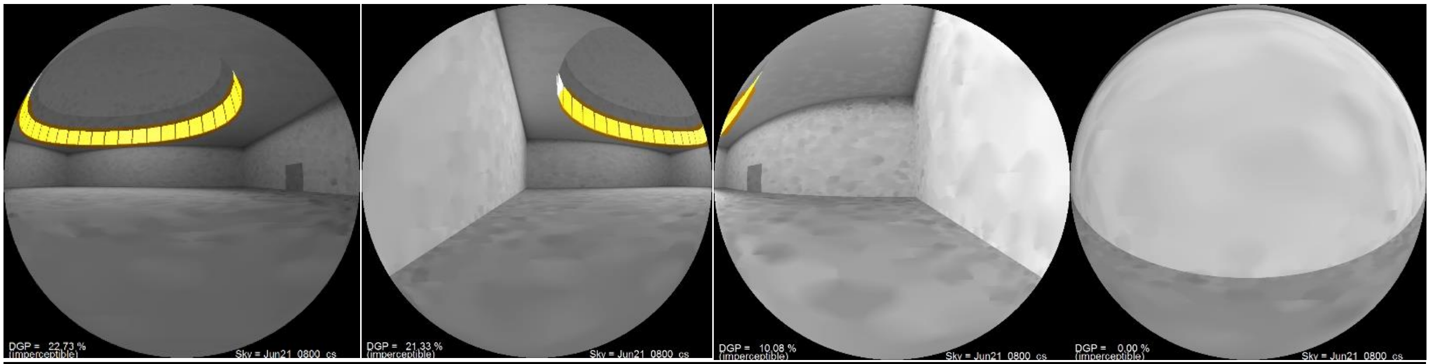
East **North** **South** **West**

<u>Point A3:</u>



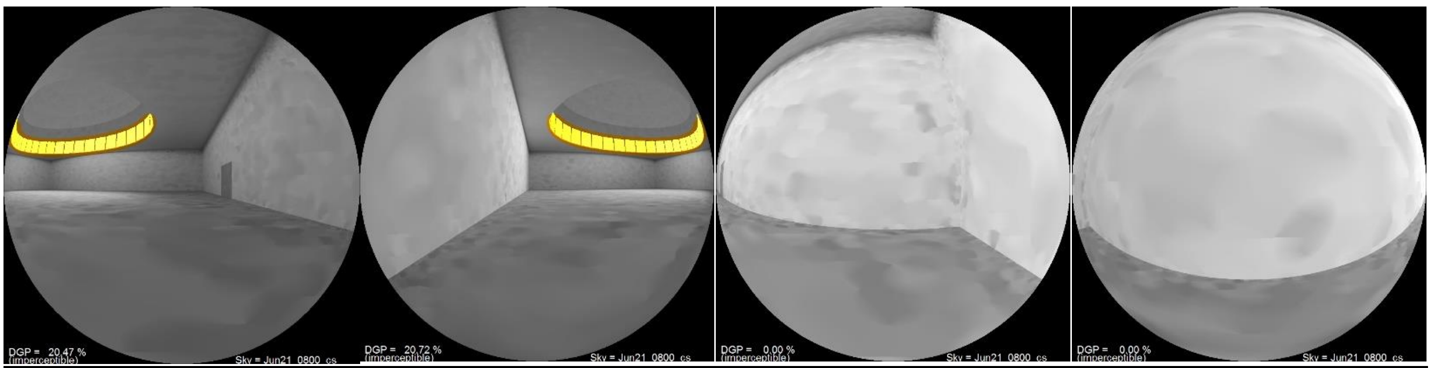
East **North** **South** **West**

Point A4:



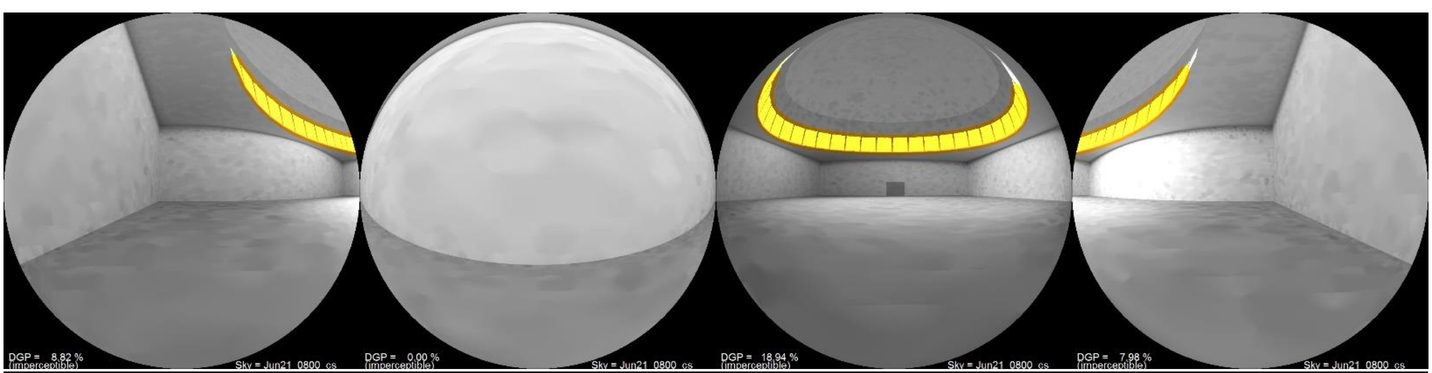
East **North** **South** **West**

Point A5:



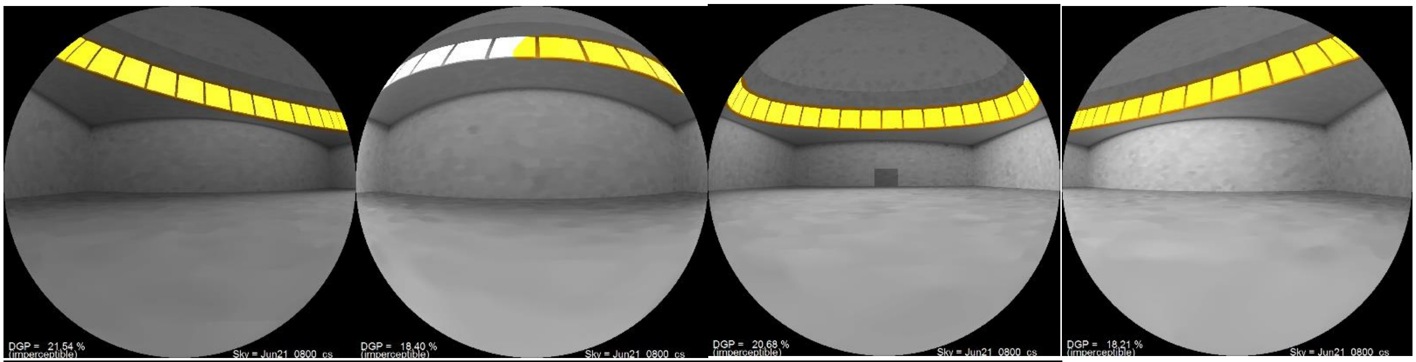
East **North** **South** **West**

Point B1:



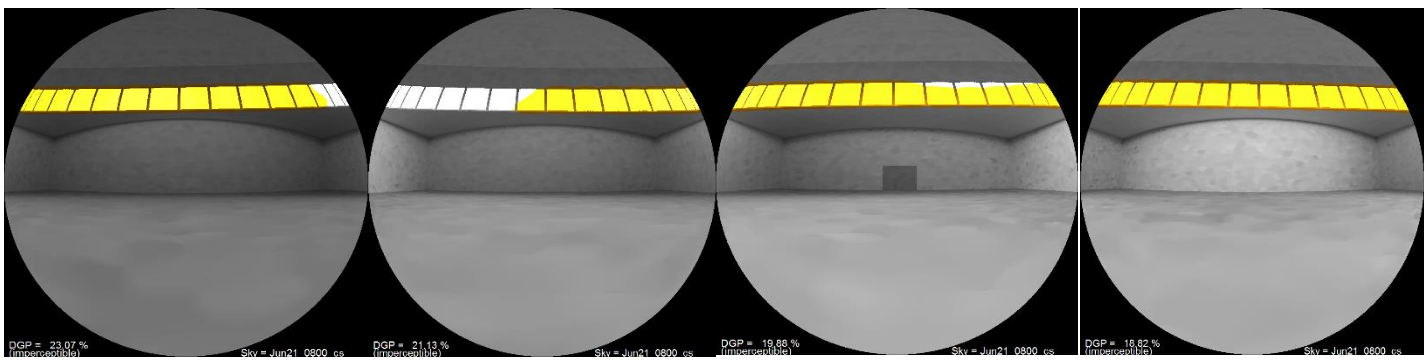
East **North** **South** **West**

Point B2:



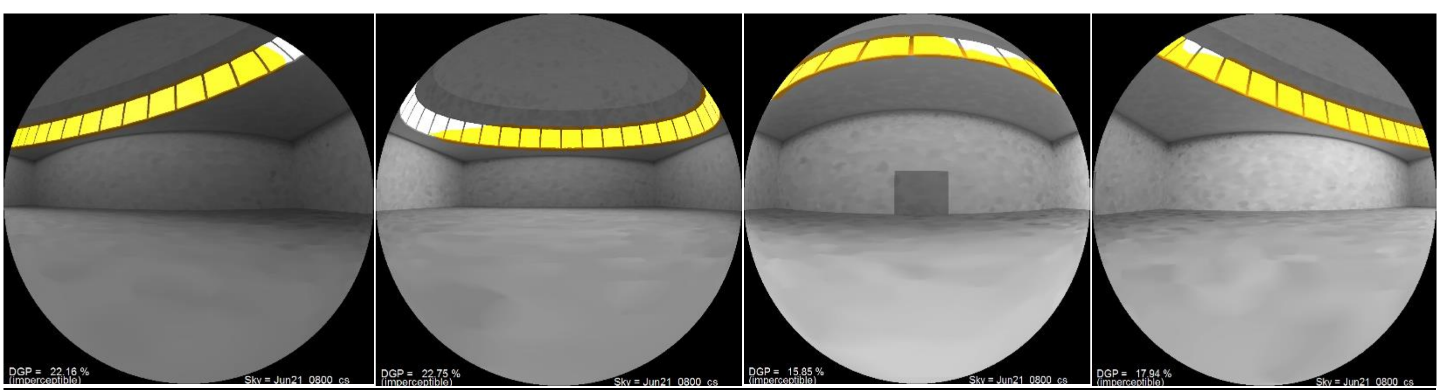
East **North** **South** **West**

Point B3:



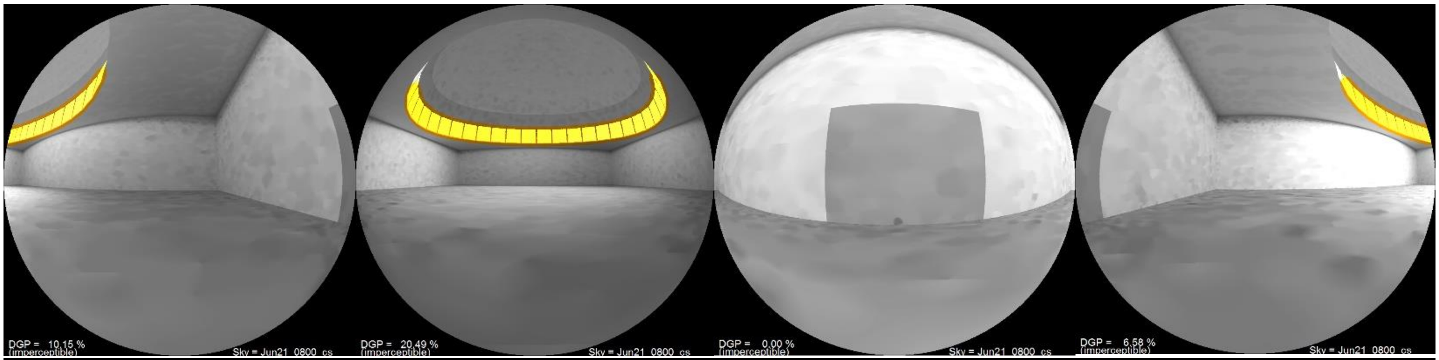
East **North** **South** **West**

Point B4:



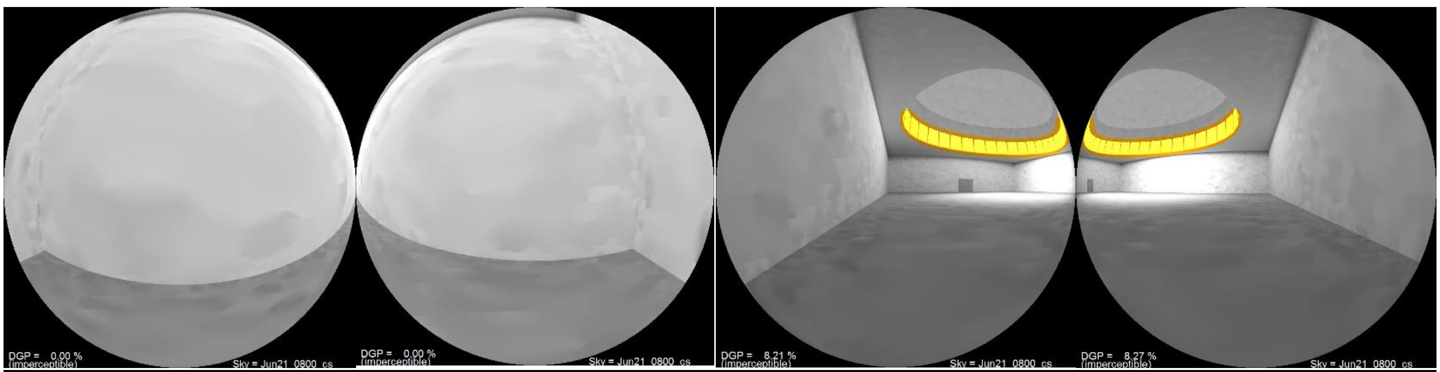
East **North** **South** **West**

Point B5:



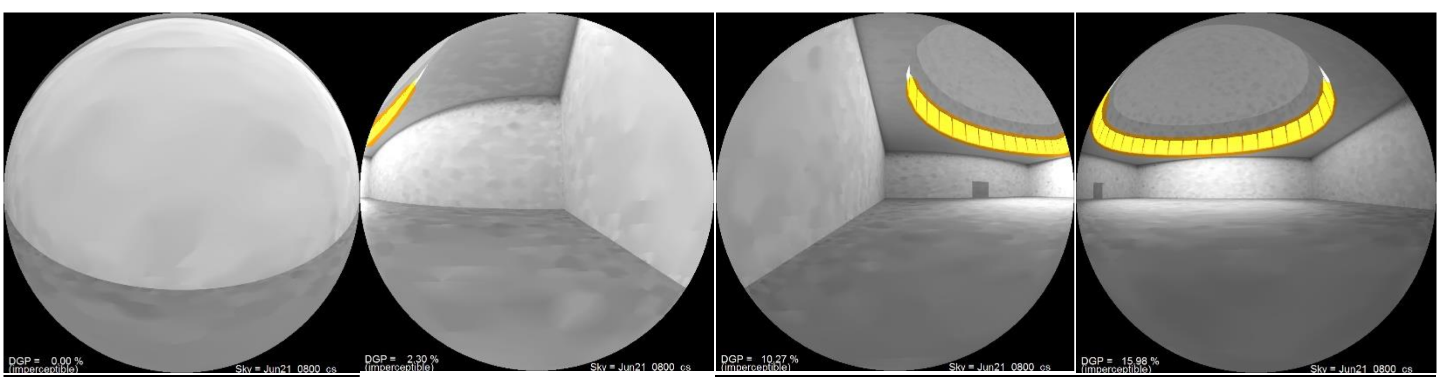
East **North** **South** **West**

Point C1:



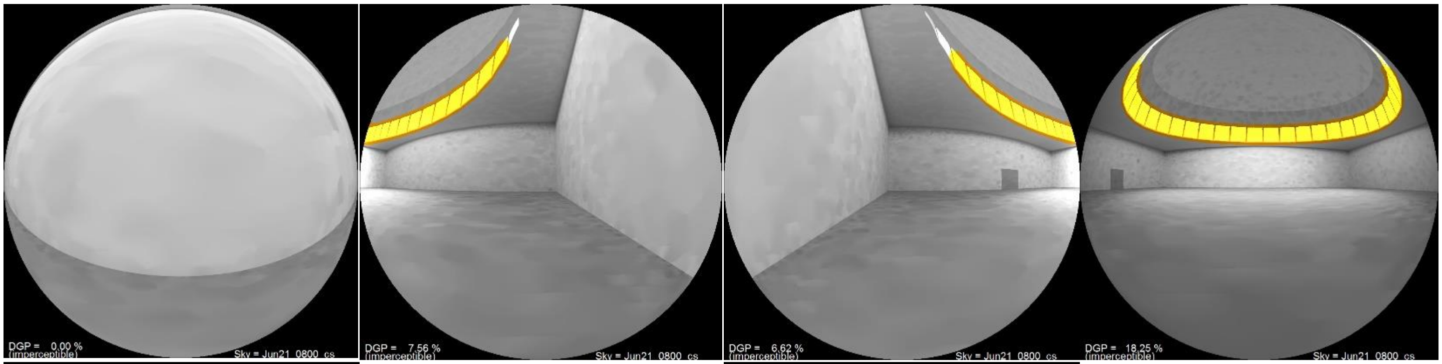
East **North** **South** **West**

Point C2:



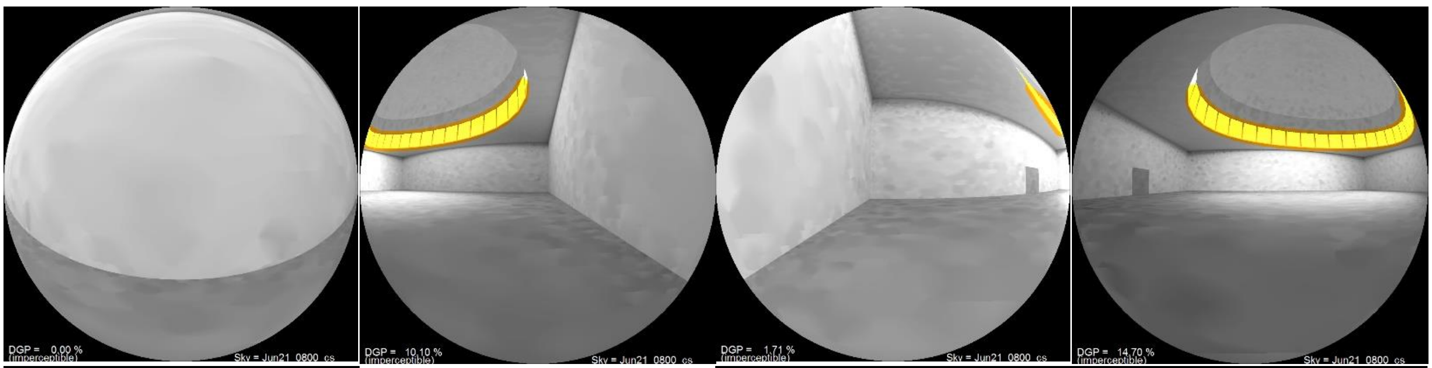
East **North** **South** **West**

Point C3:



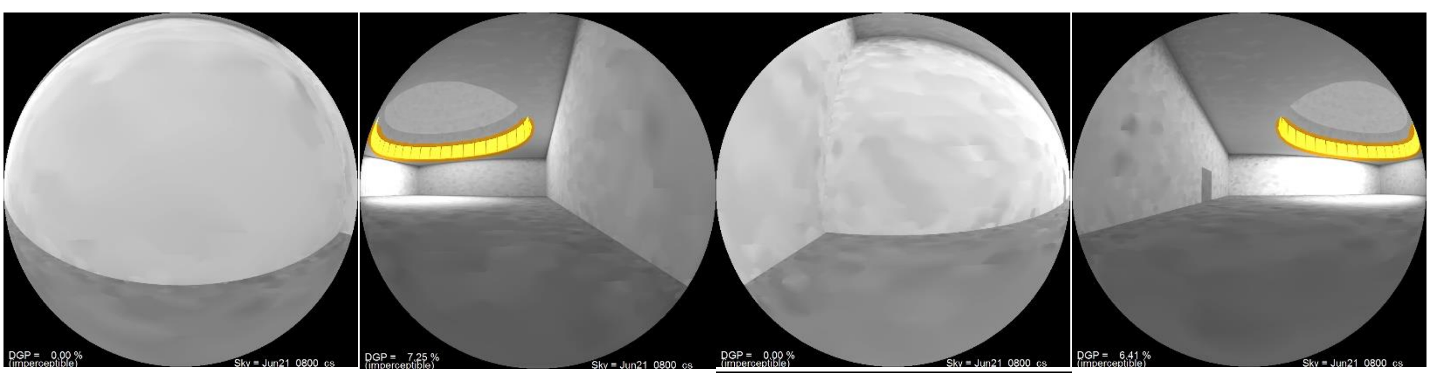
East **North** **South** **West**

Point C4:



East **North** **South** **West**

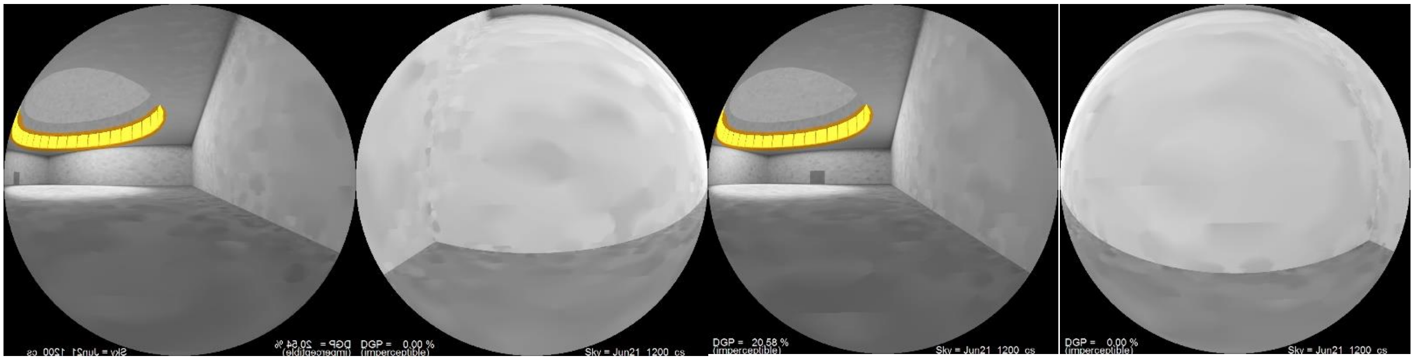
Point C5:



East **North** **South** **West**

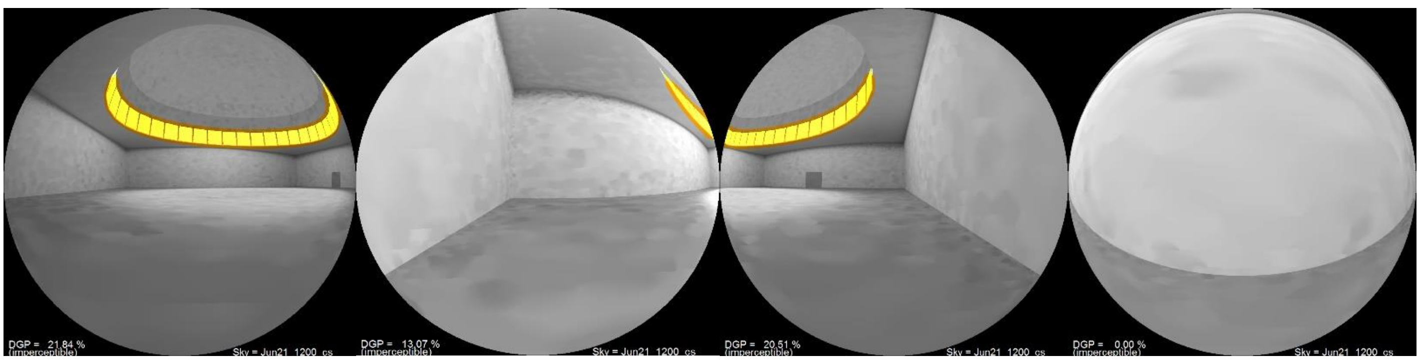
2. 21 Jun 12:00 pm

Point A1:



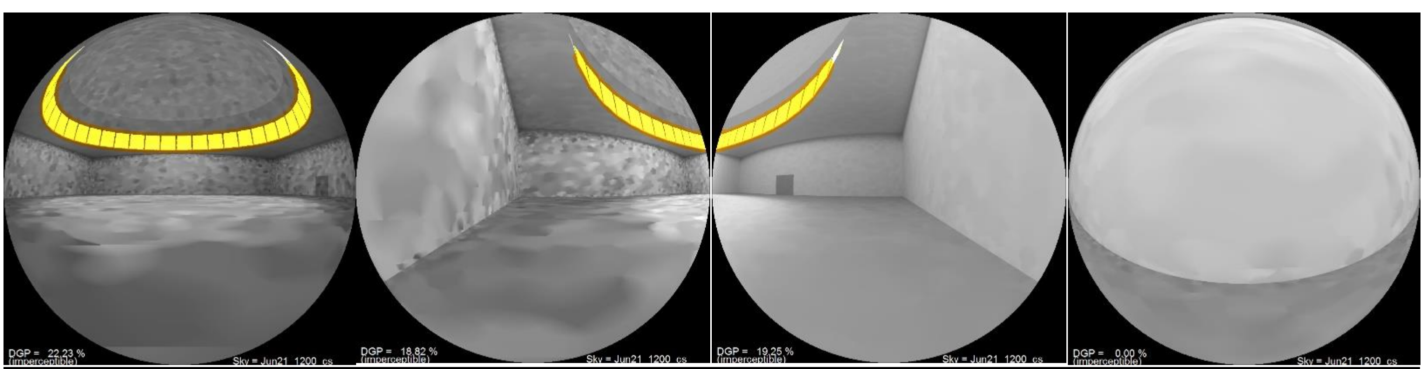
East **North** **South** **West**

Point A2:



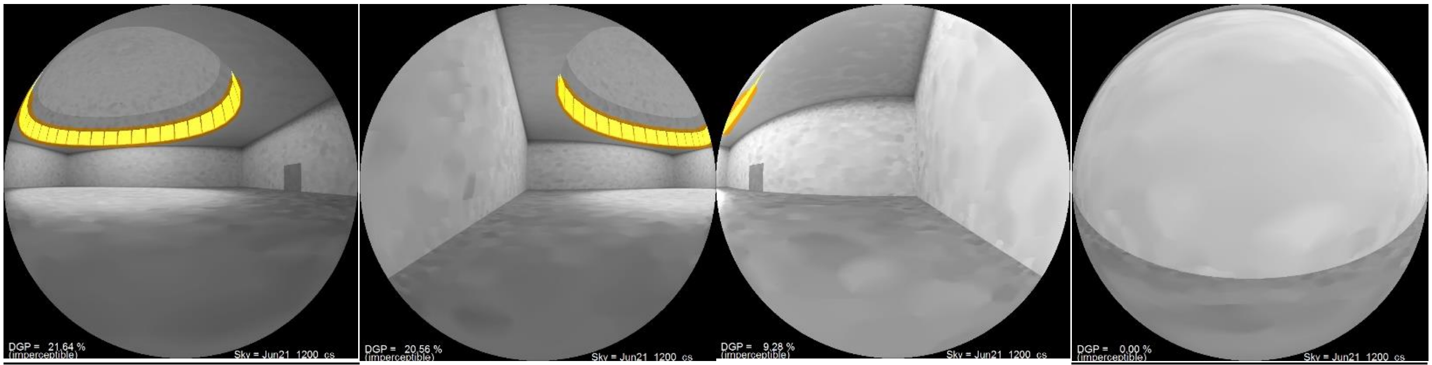
East **North** **South** **West**

Point A3:



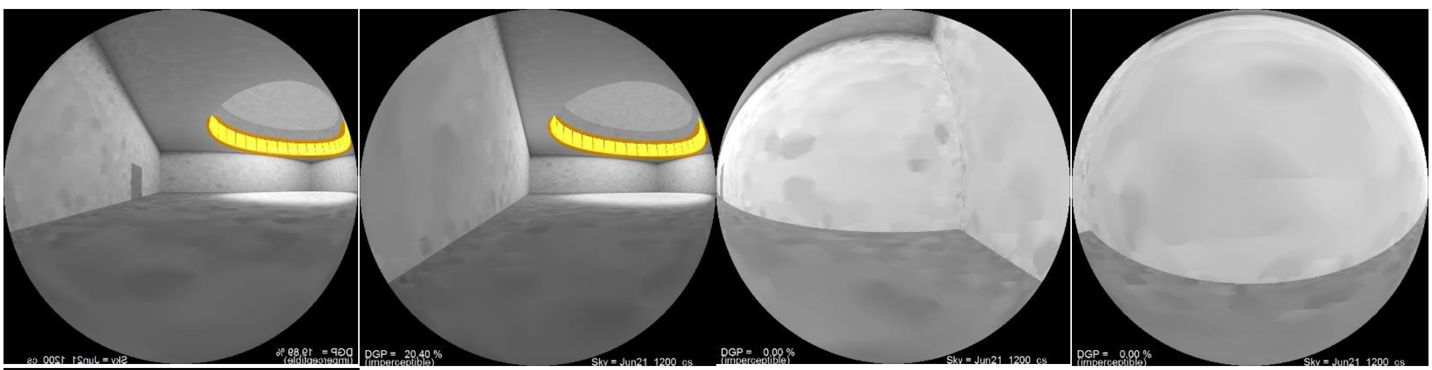
East **North** **South** **West**

Point A4:



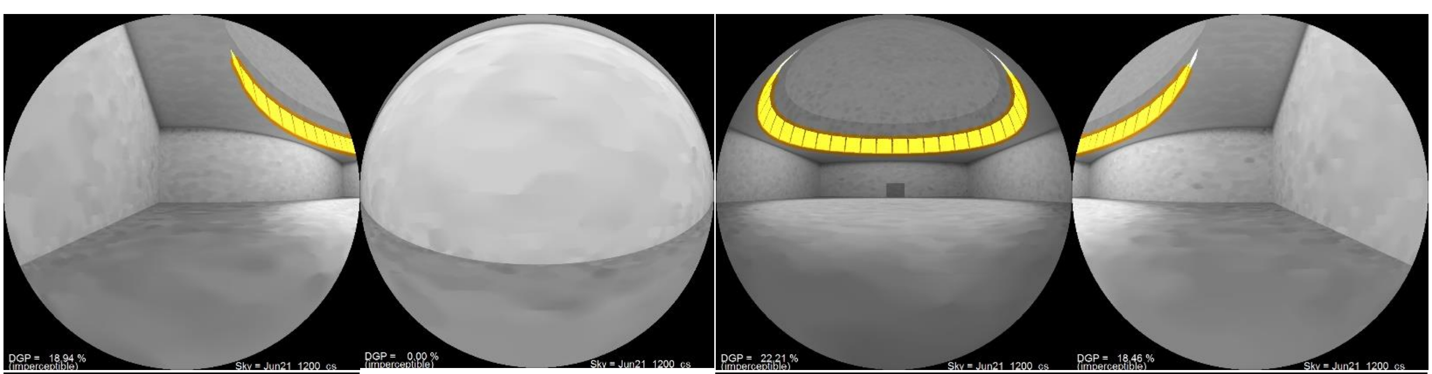
East **North** **South** **West**

Point A5:



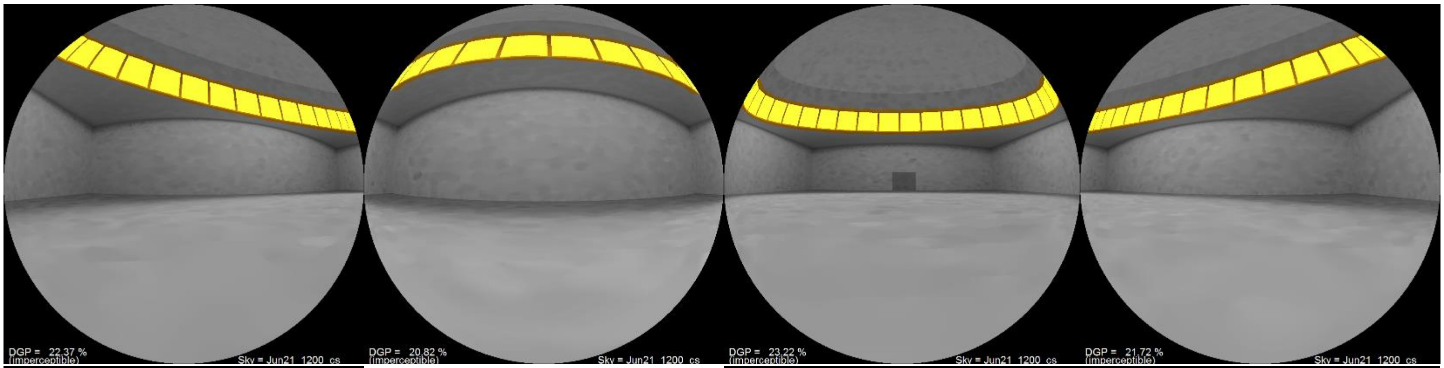
East **North** **South** **West**

Point B1



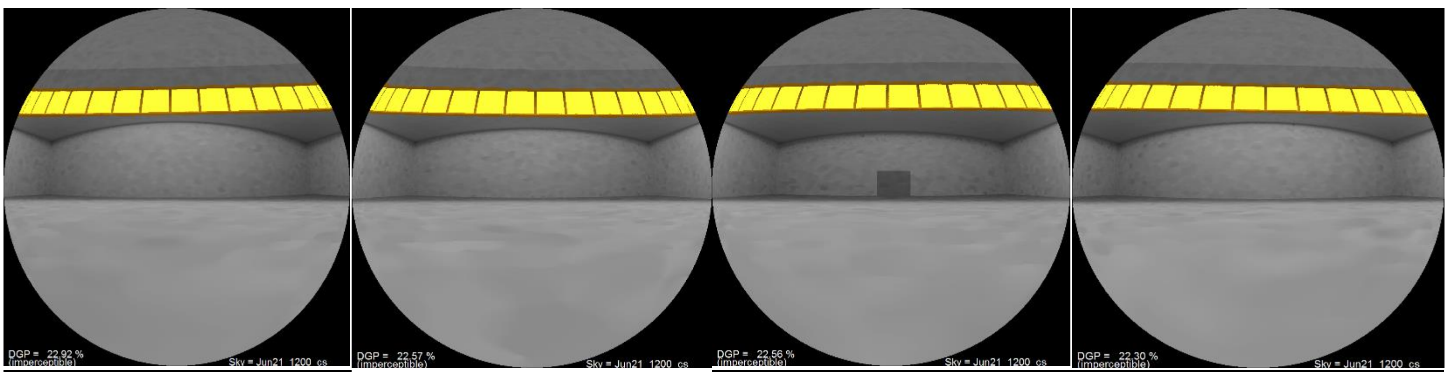
East **North** **South** **West**

Point B2:



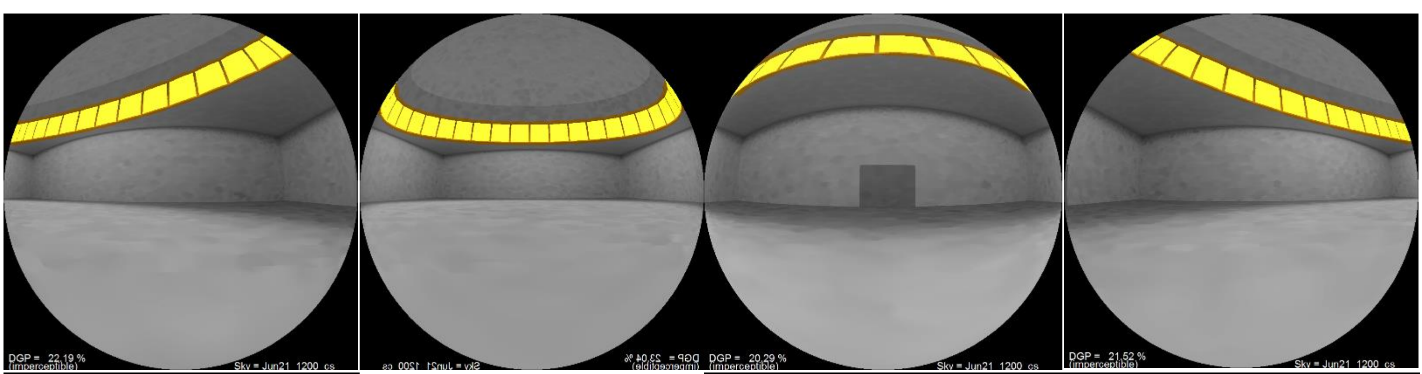
East **North** **South** **West**

Point B3:



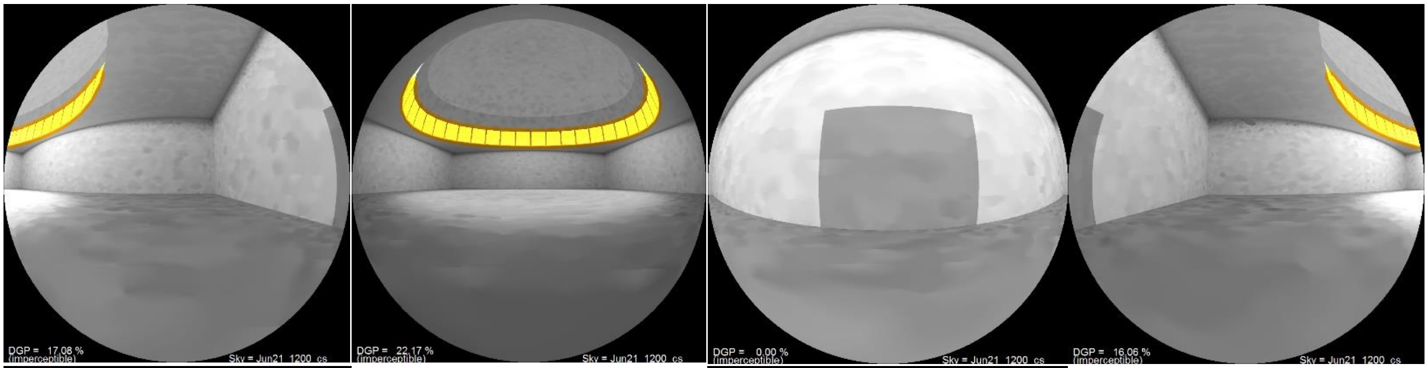
East **North** **South** **West**

Point B4:



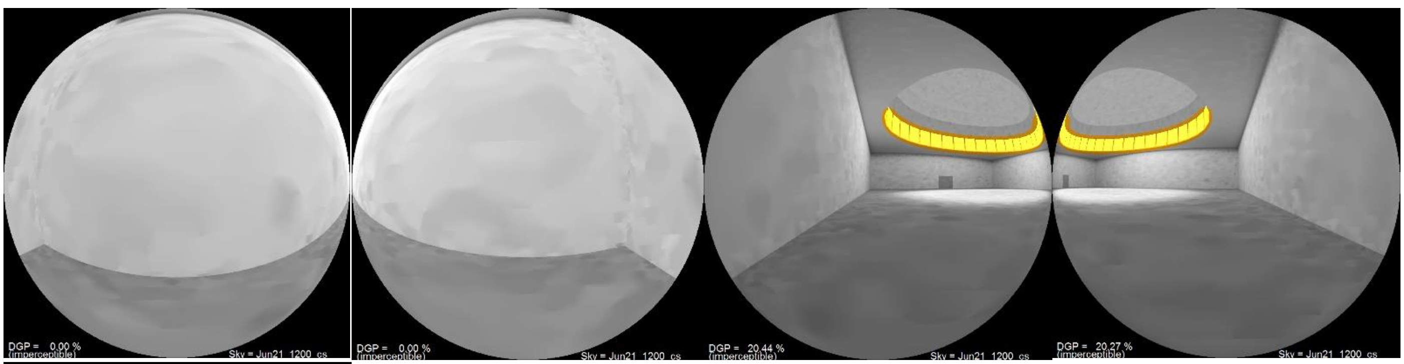
East **North** **South** **West**

Point B5:



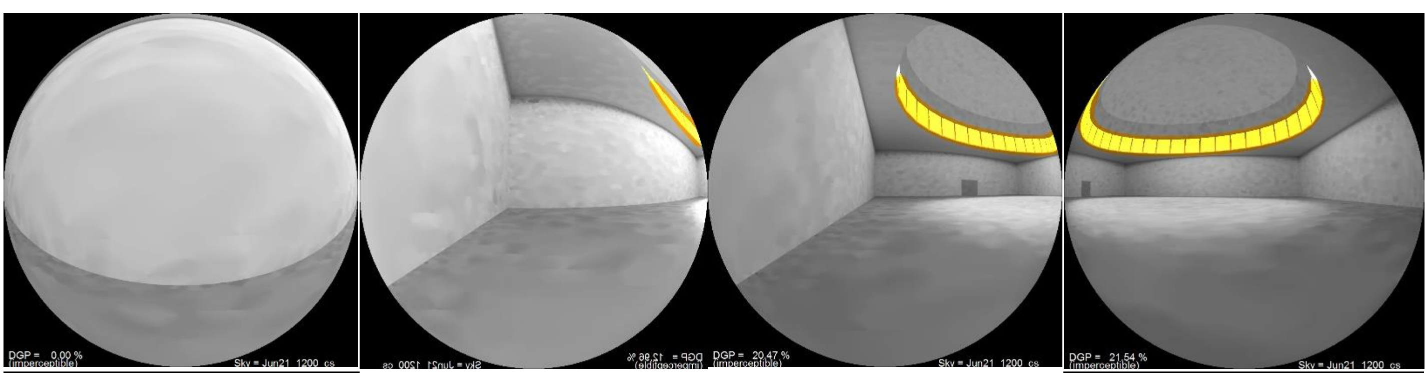
East **North** **South** **West**

Point C1:



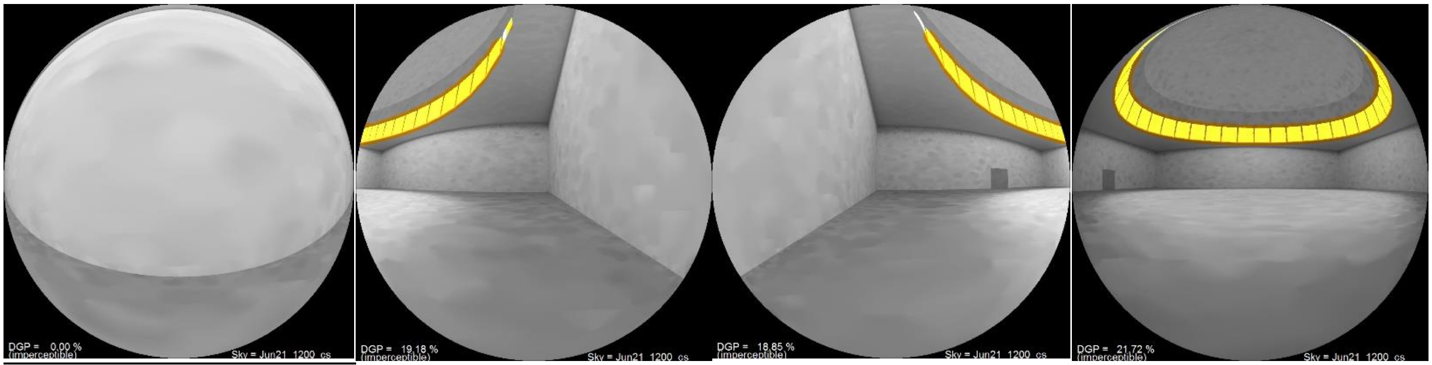
East **North** **South** **West**

Point C2:



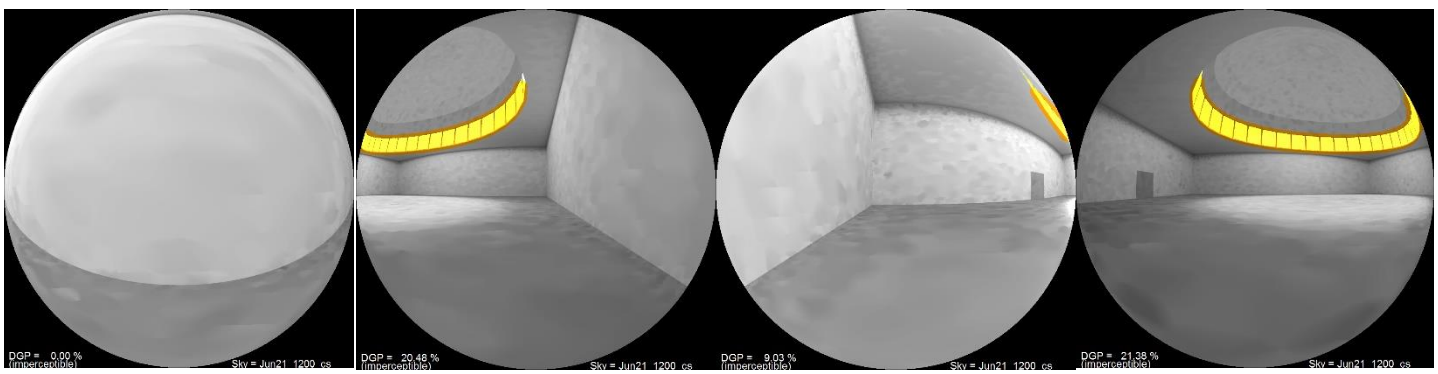
East **North** **South** **West**

Point C3:



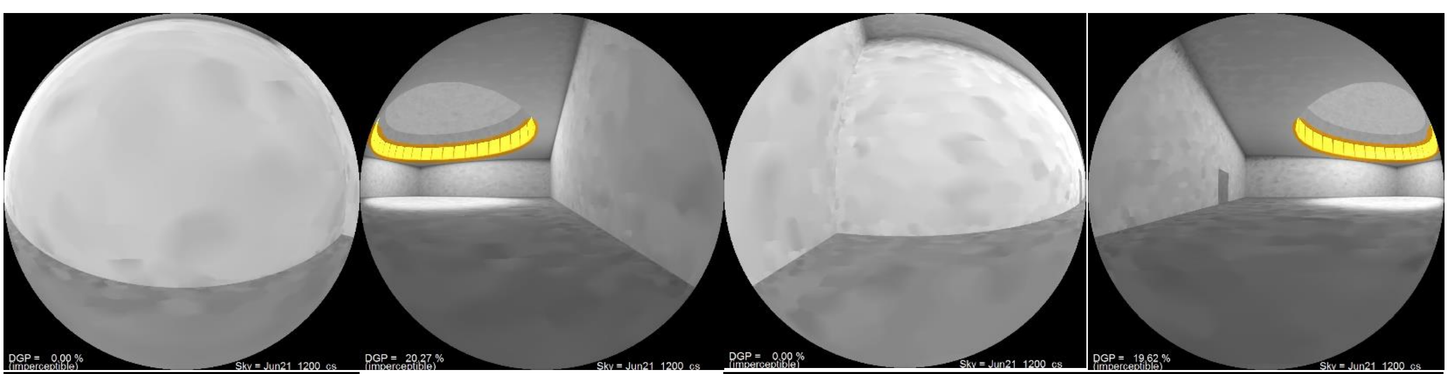
East **North** **South** **West**

Point C4:



East **North** **South** **West**

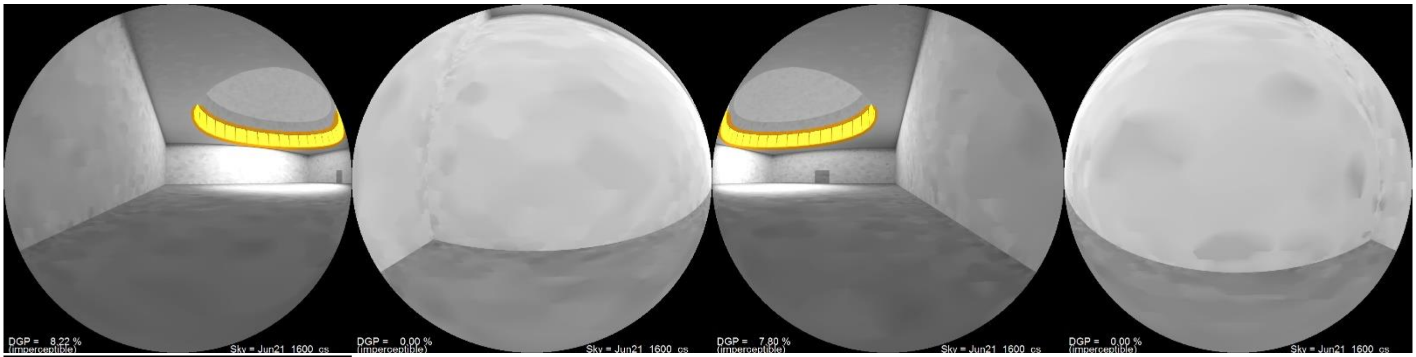
Point C5:



East **North** **South** **West**

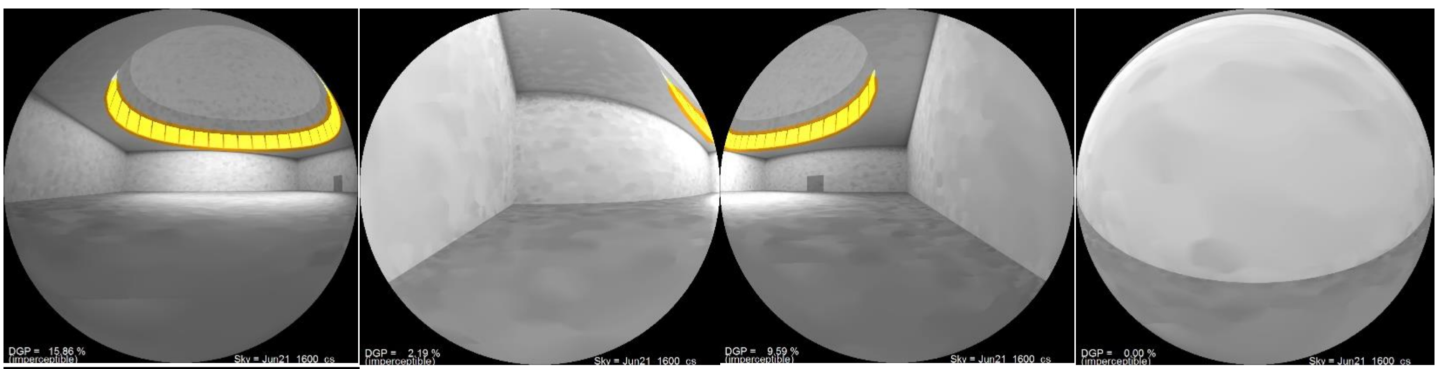
3. 21 Jun 04:00 pm

Point A1:



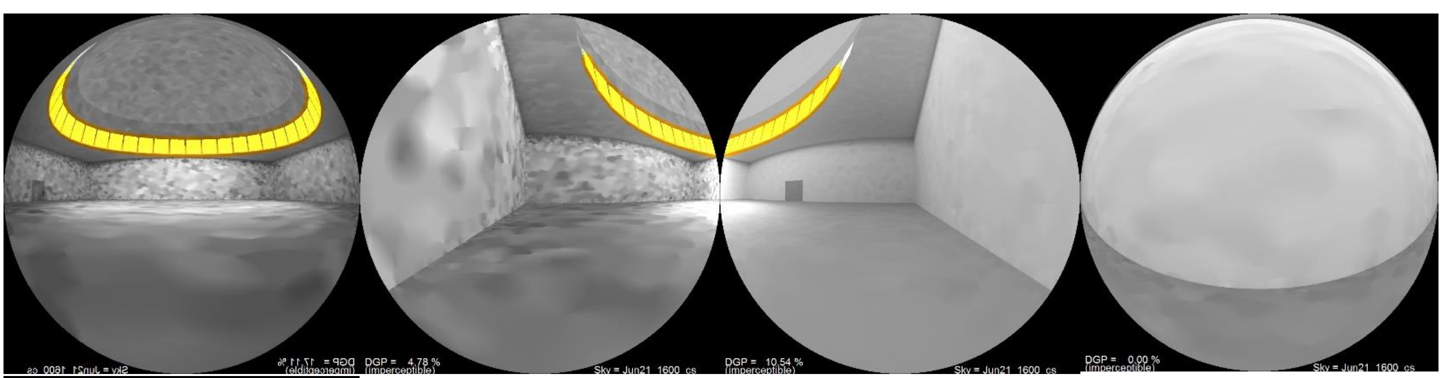
East North South West

Point A2:



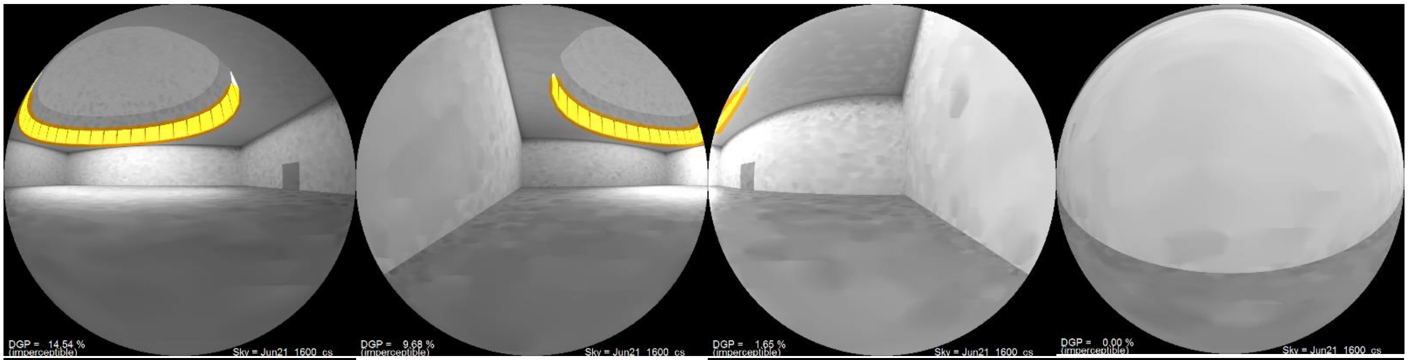
East North South West

Point A3:



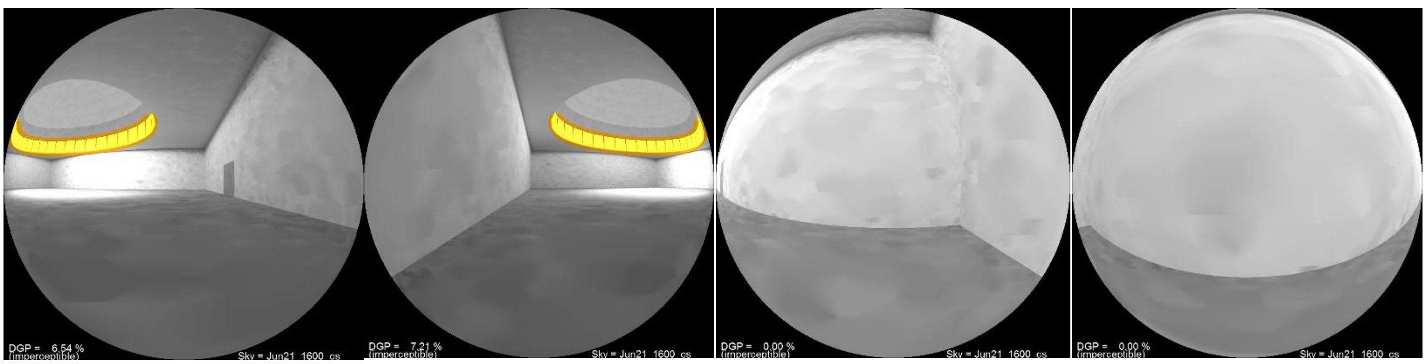
East North South West

Point A4:



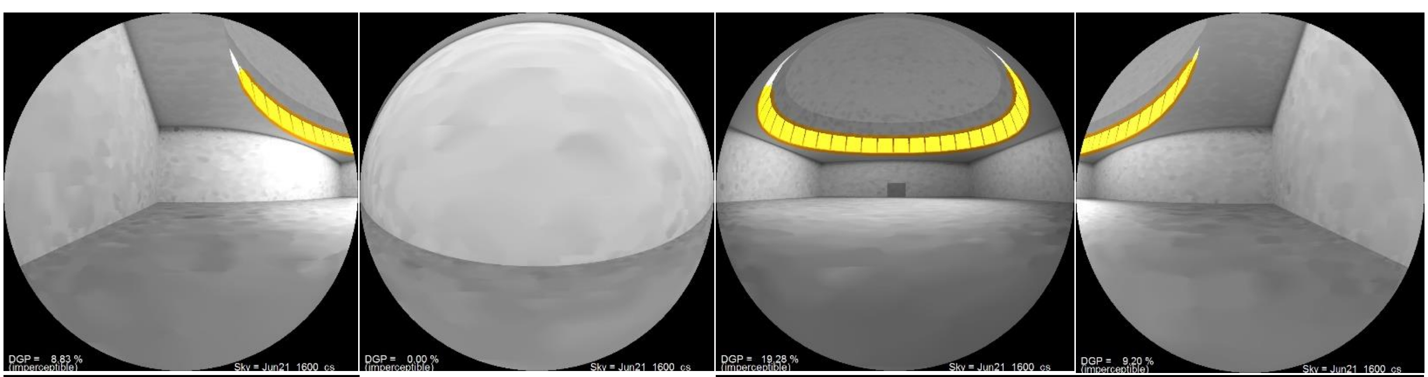
East North South West

Point A5:



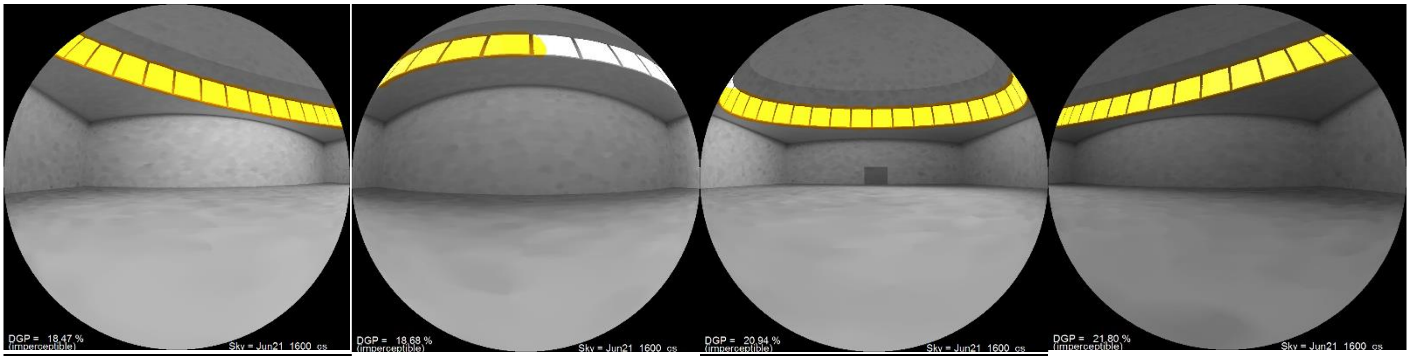
East North South West

Point B1:



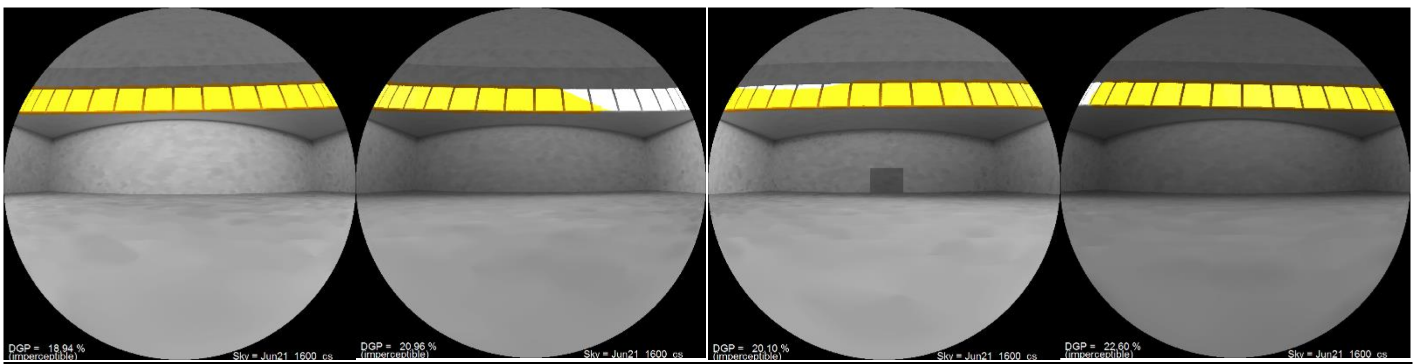
East North South West

Point B2:



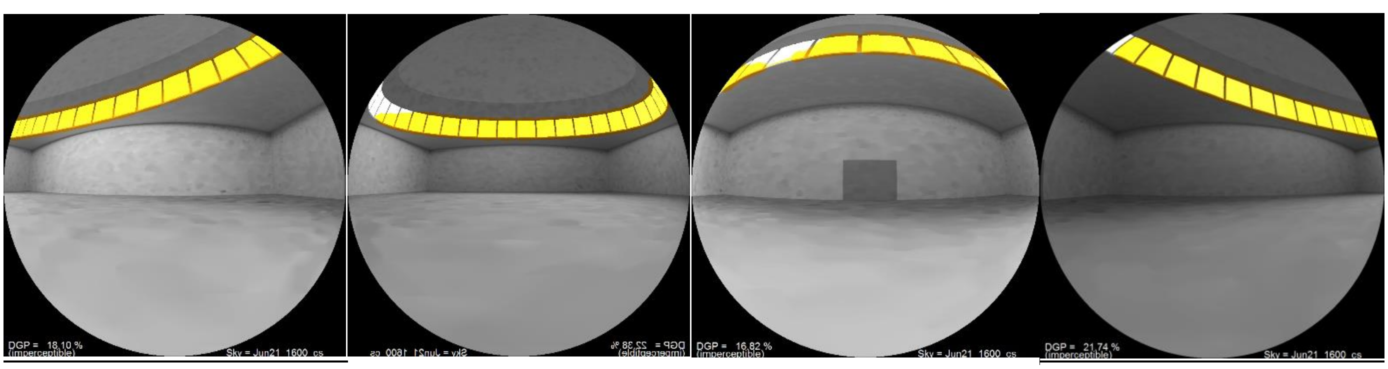
East **North** **South** **West**

Point B3:



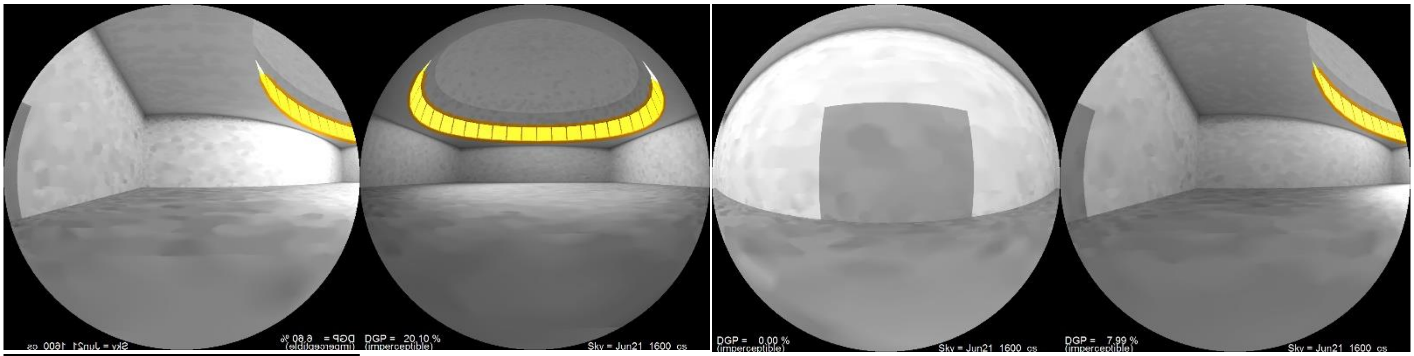
East **North** **South** **West**

Point B4:



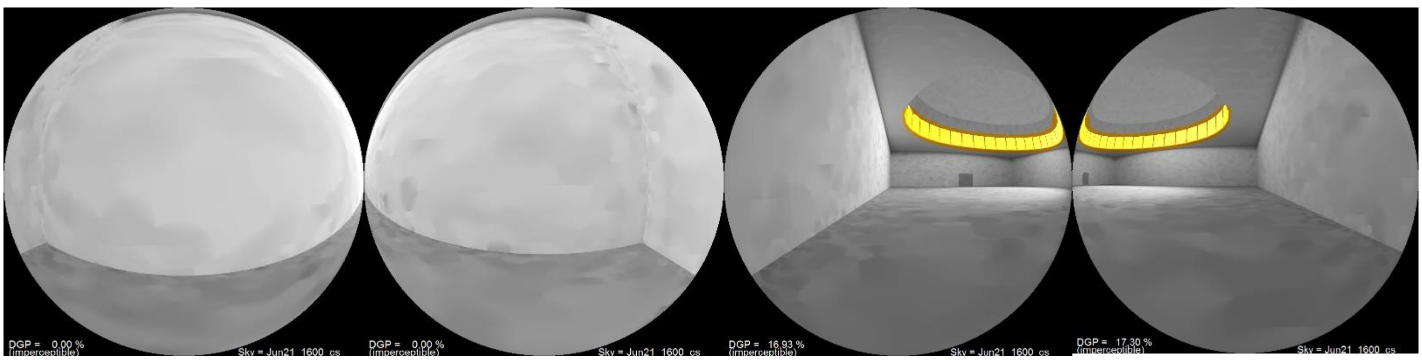
East **North** **South** **West**

Point B5:



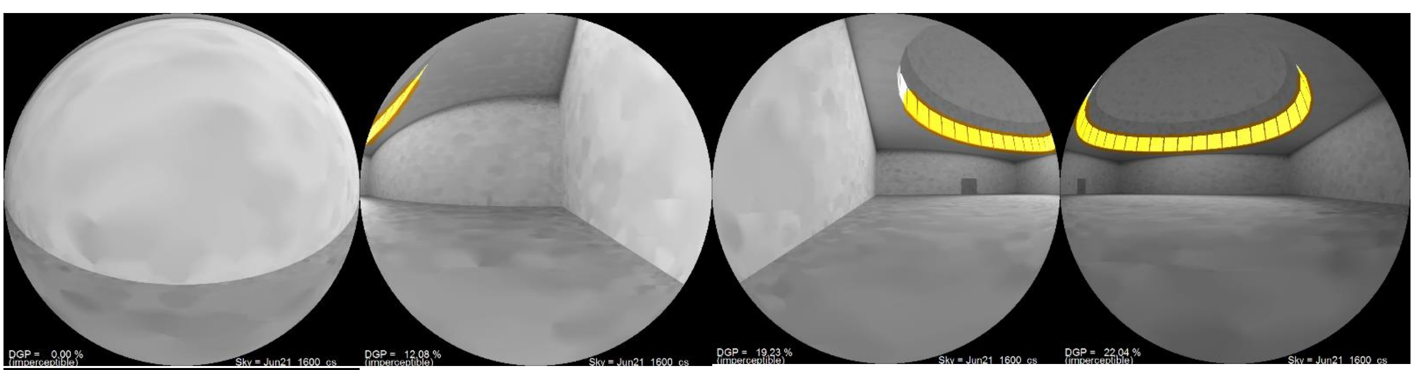
East **North** **South** **West**

Point C1:



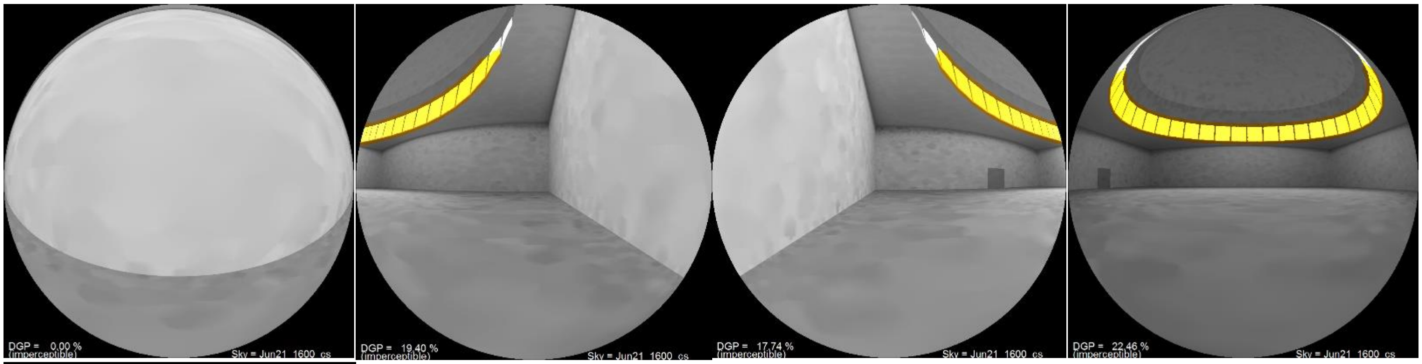
East **North** **South** **West**

Point C2:



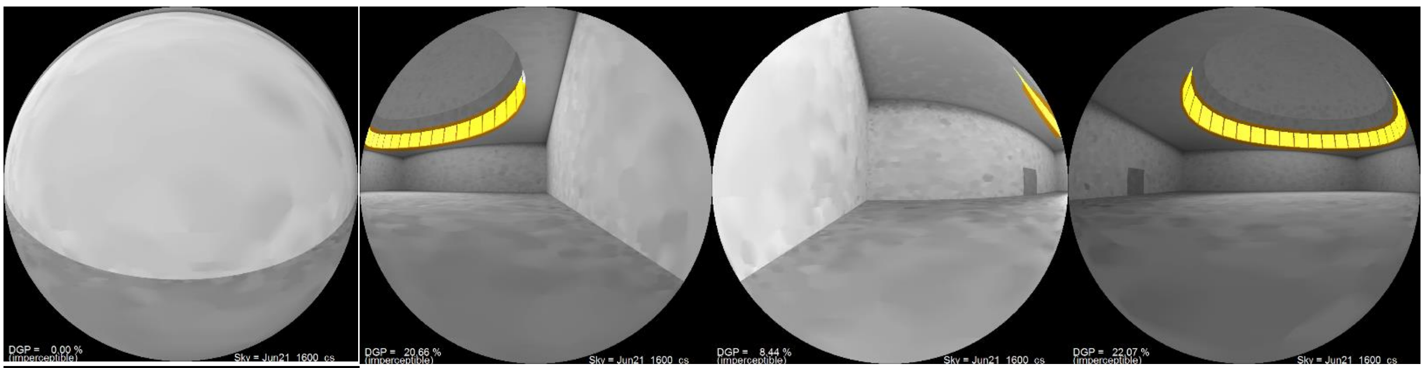
East **North** **South** **West**

Point C3:



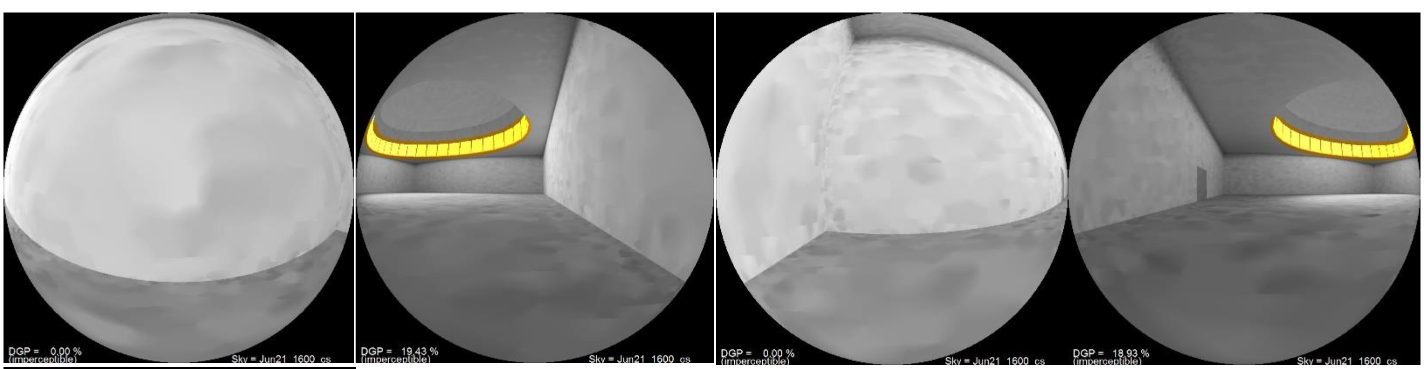
East North South West

Point C4:



East North South West

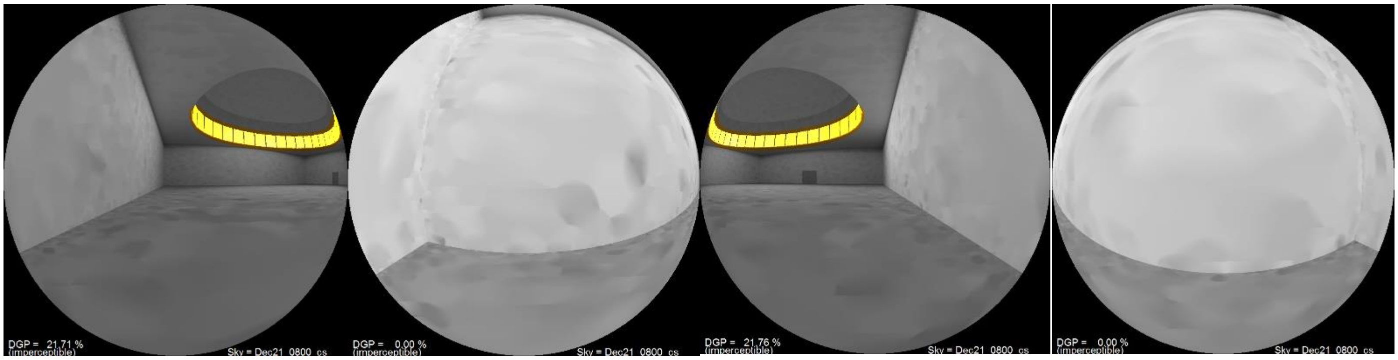
Point C5:



East North South West

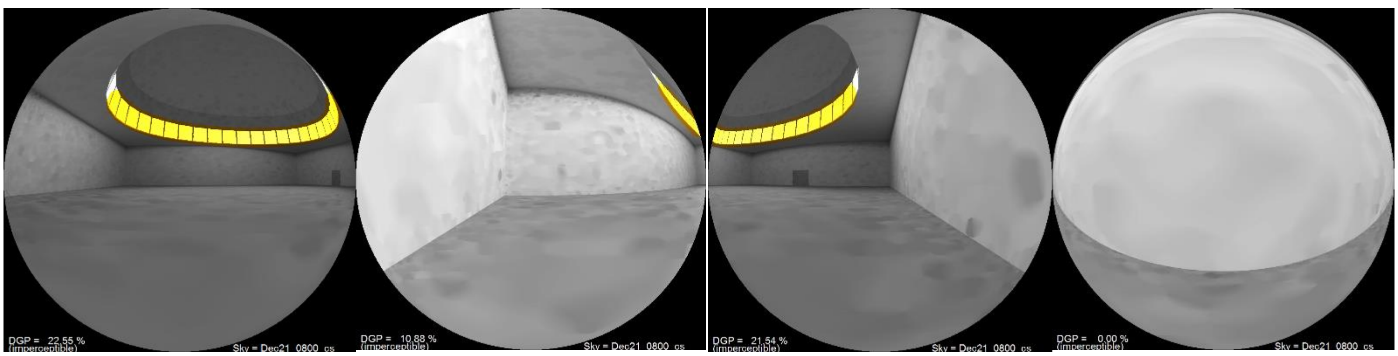
21 Dec 8:00 am

Point A1:



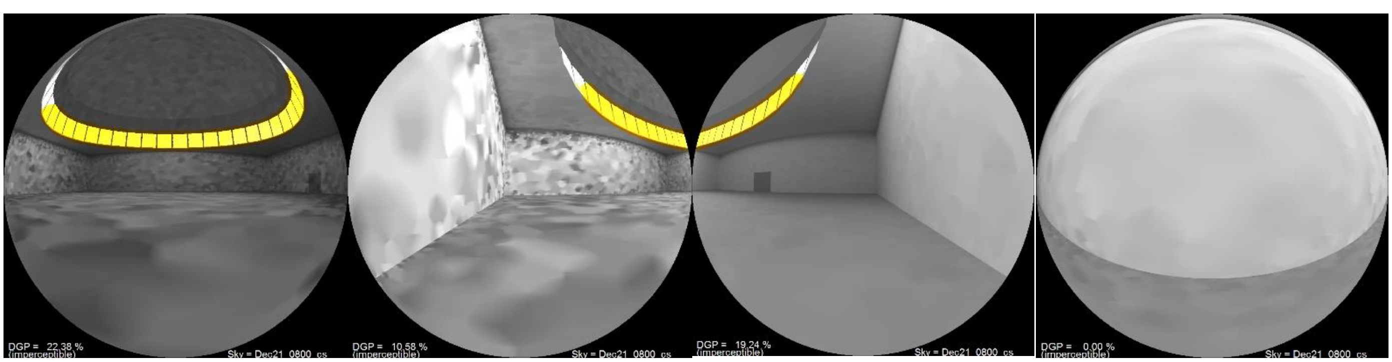
East **North** **South** **West**

Point A2:



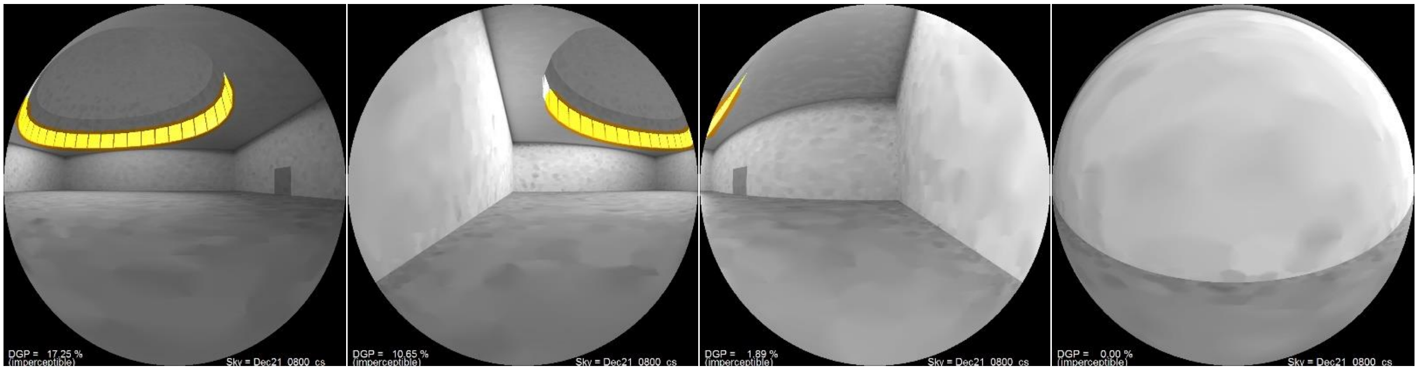
East **North** **South** **West**

Point A3:



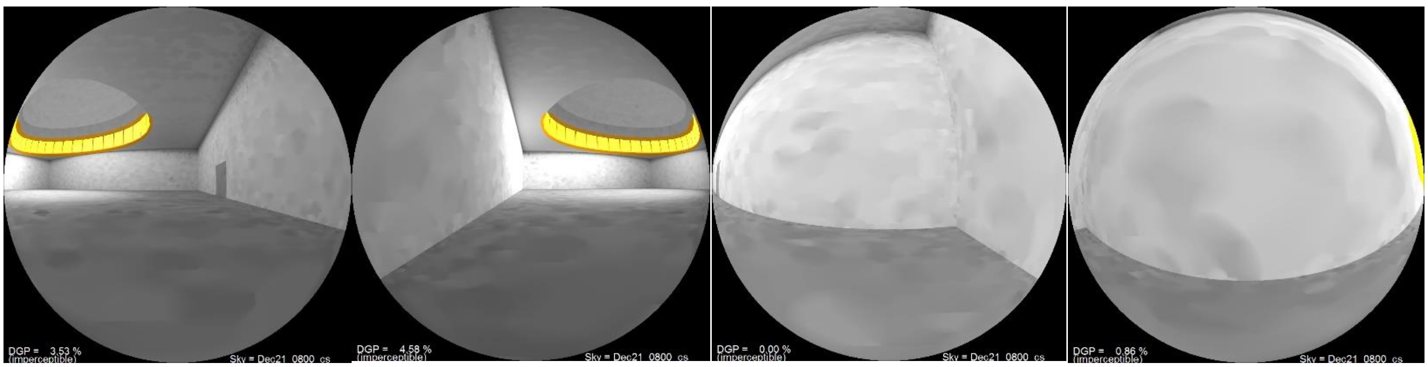
East **North** **South** **West**

Point A4:



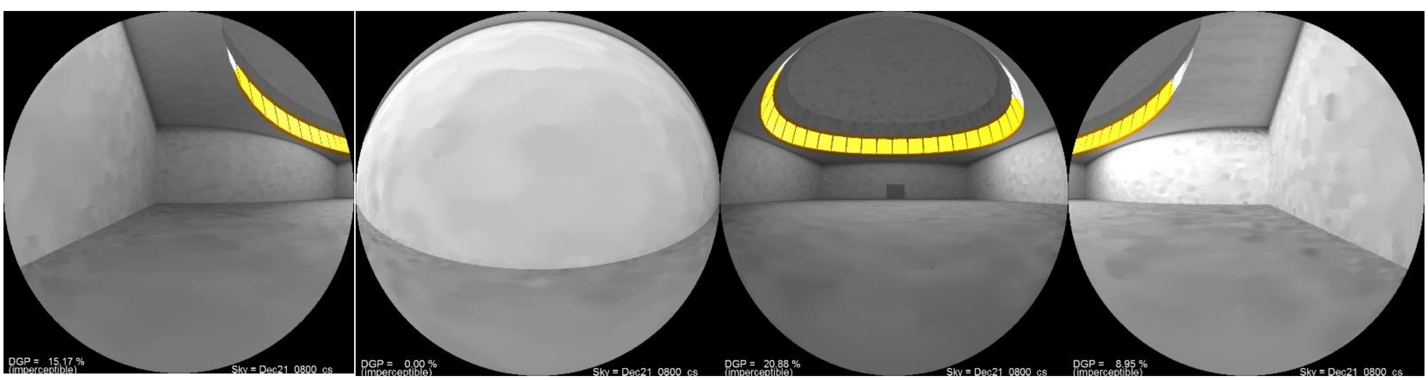
East **North** **South** **West**

Point A5:



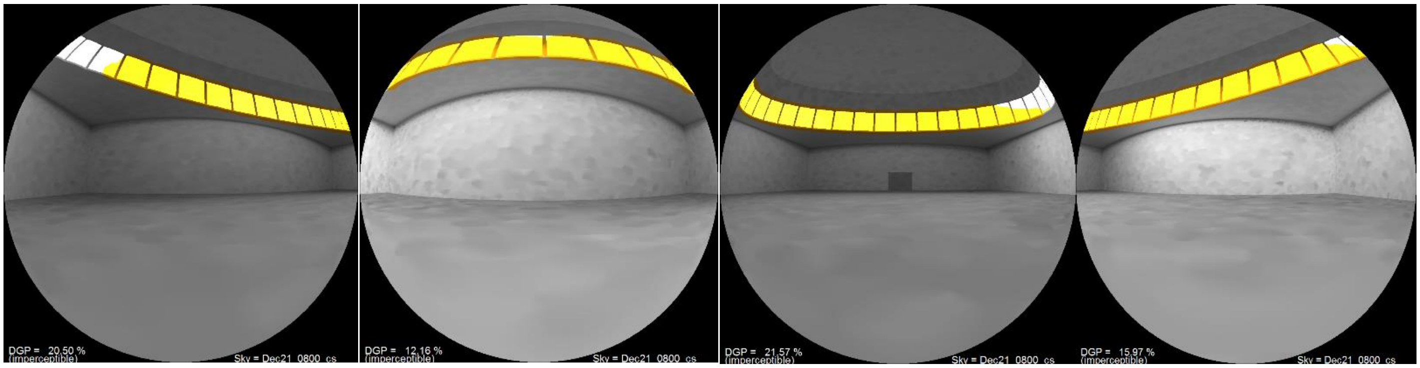
East **North** **South** **West**

Point B1:



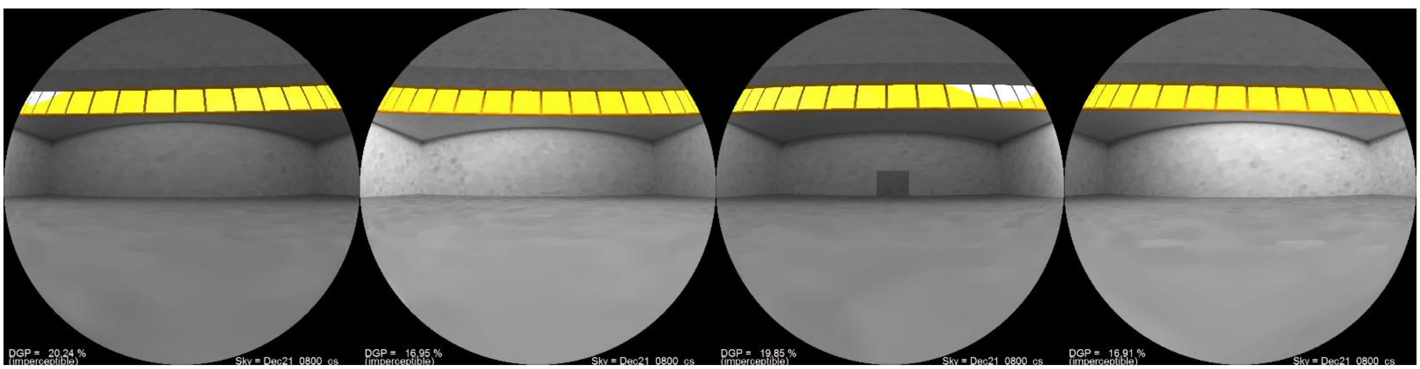
East **North** **South** **West**

Point B2:



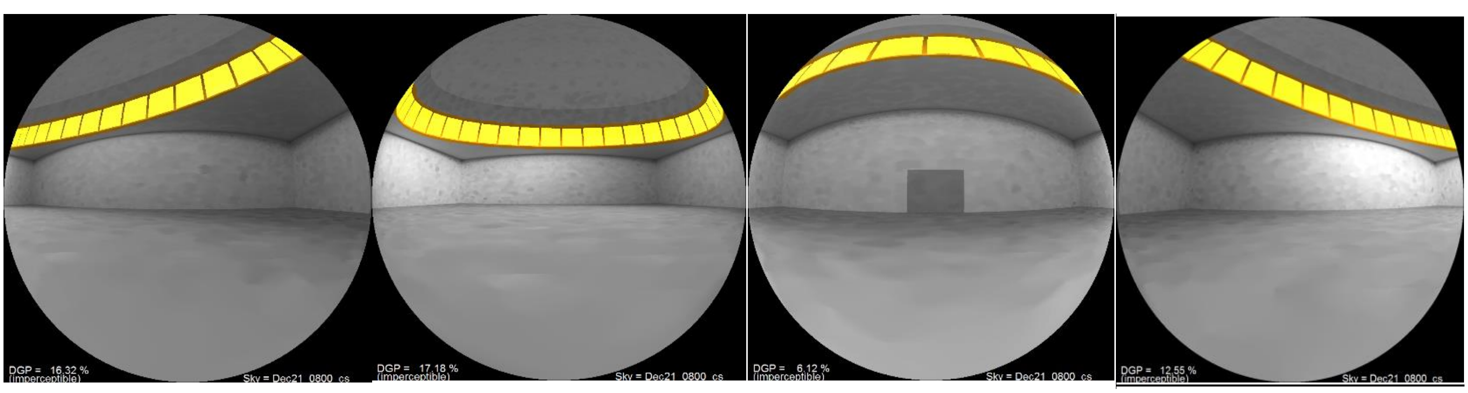
East **North** **South** **West**

Point B3:



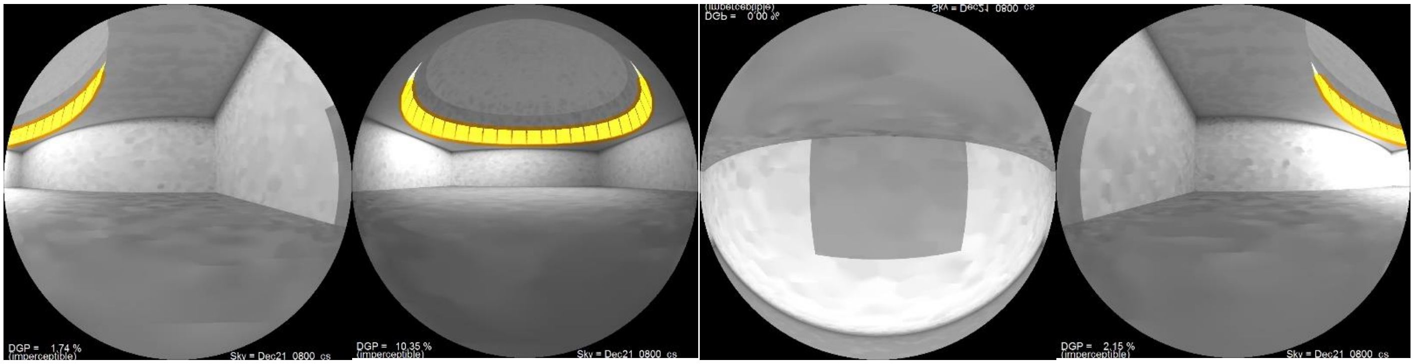
East **North** **South** **West**

Point B4:



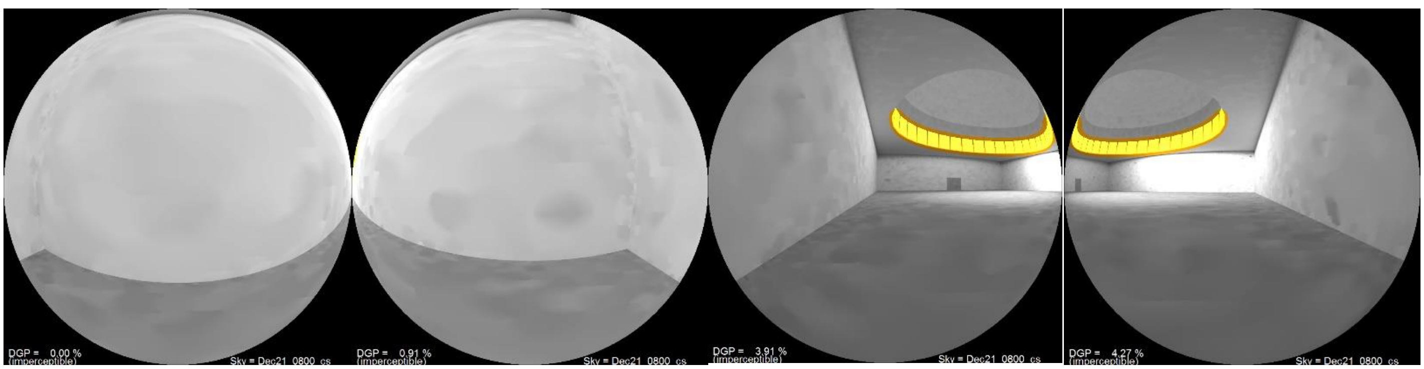
East **North** **South** **West**

Point B5:



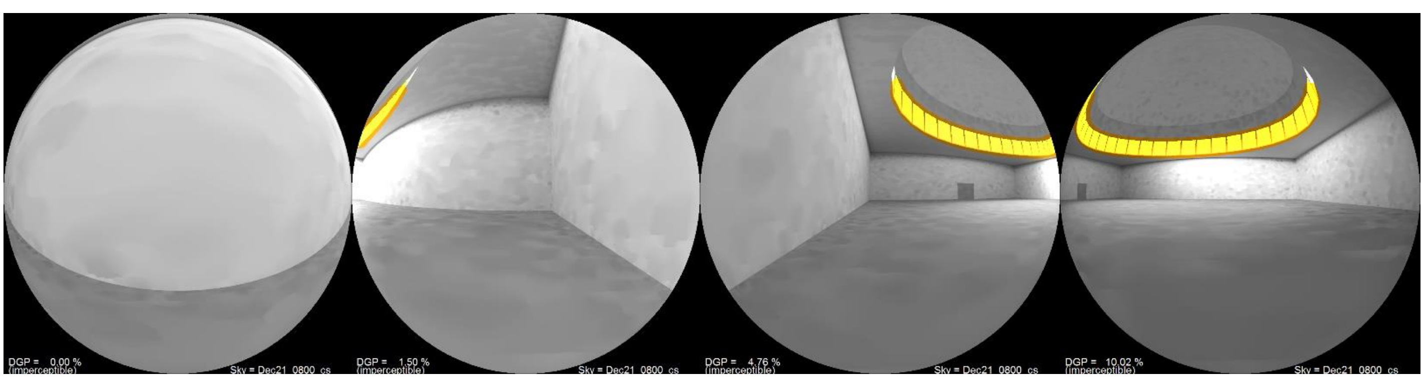
East North South West

Point C1:



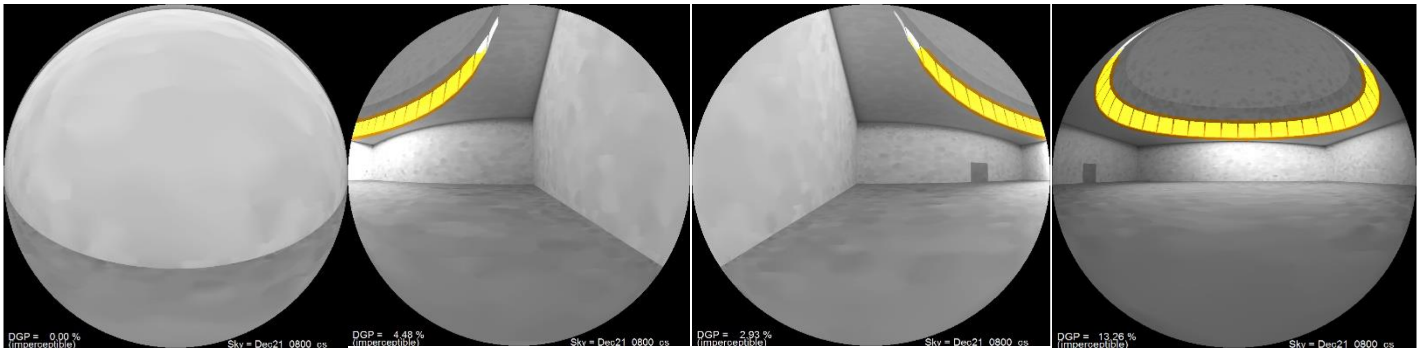
East North South West

Point C2:



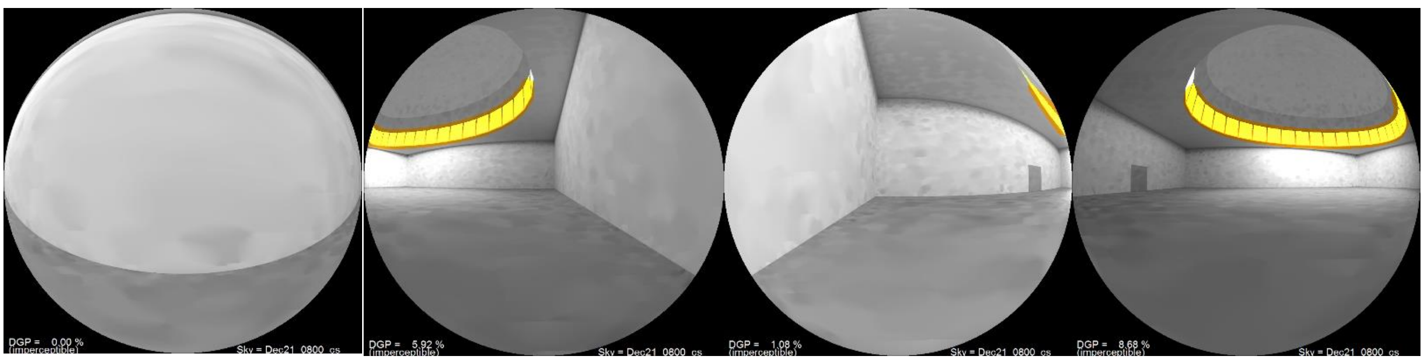
East North South West

Point C3:



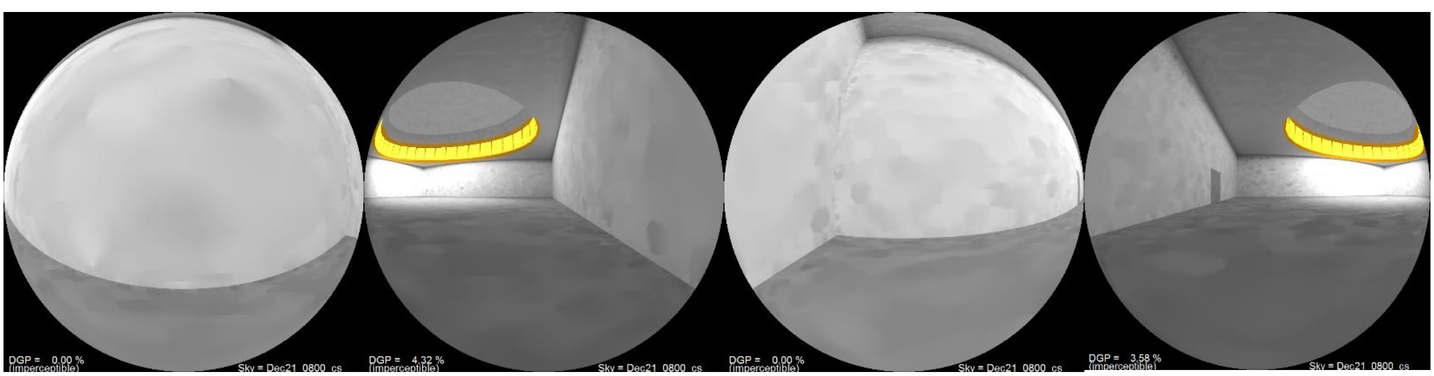
East **North** **South** **West**

Point C4:



East **North** **South** **West**

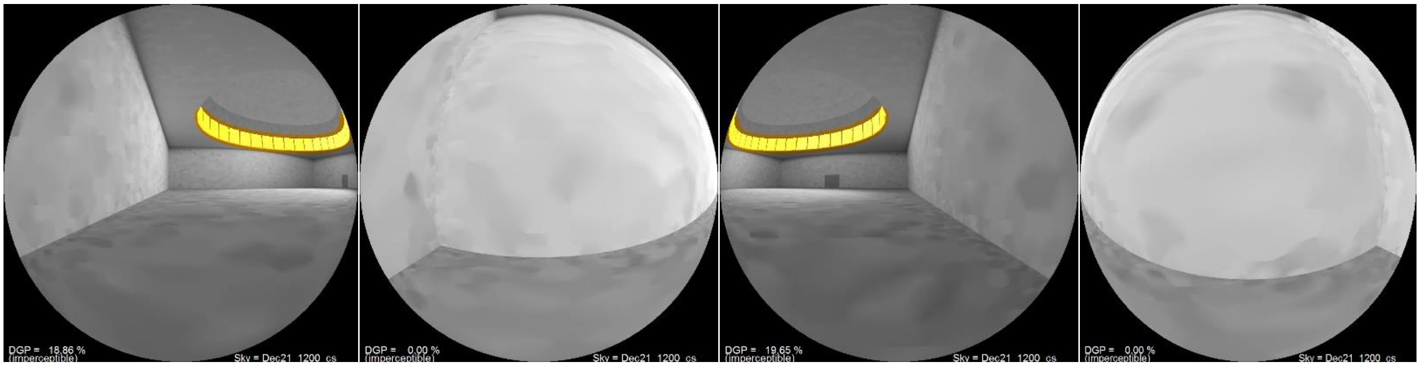
Point C5:



East **North** **South** **West**

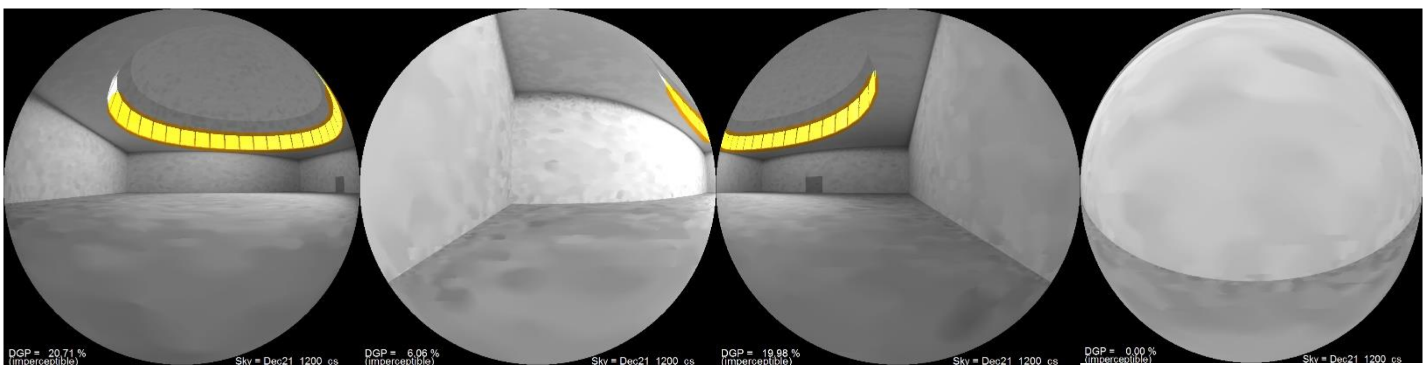
1. **<u>21 Dec 12:00 pm</u>**

<u>Point A1:</u>



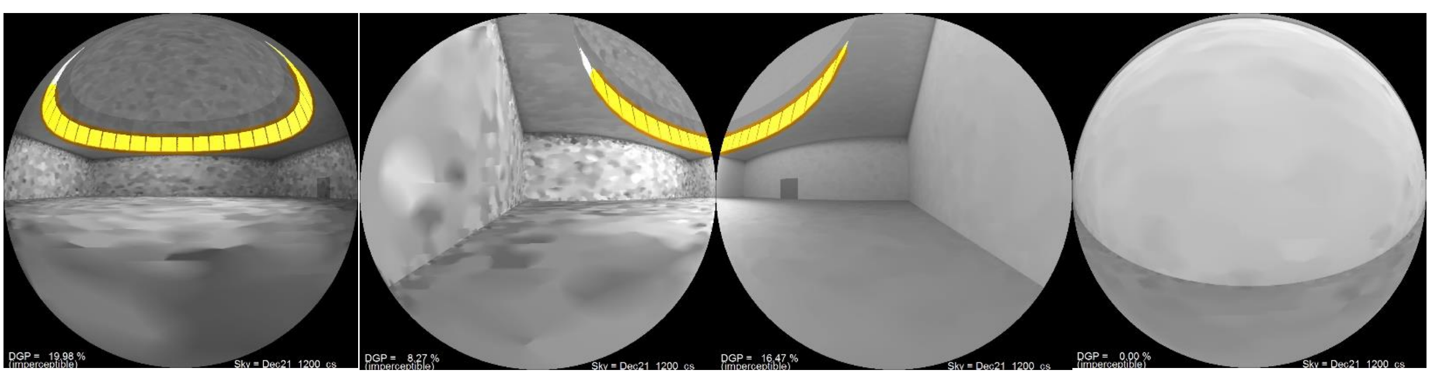
East **North** **South** **West**

<u>Point A2:</u>



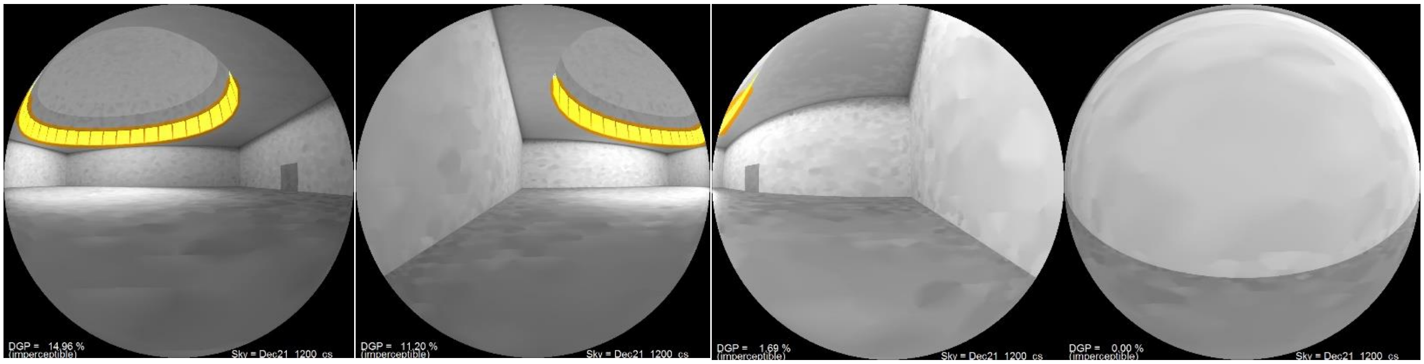
East **North** **South** **West**

<u>Point A3:</u>



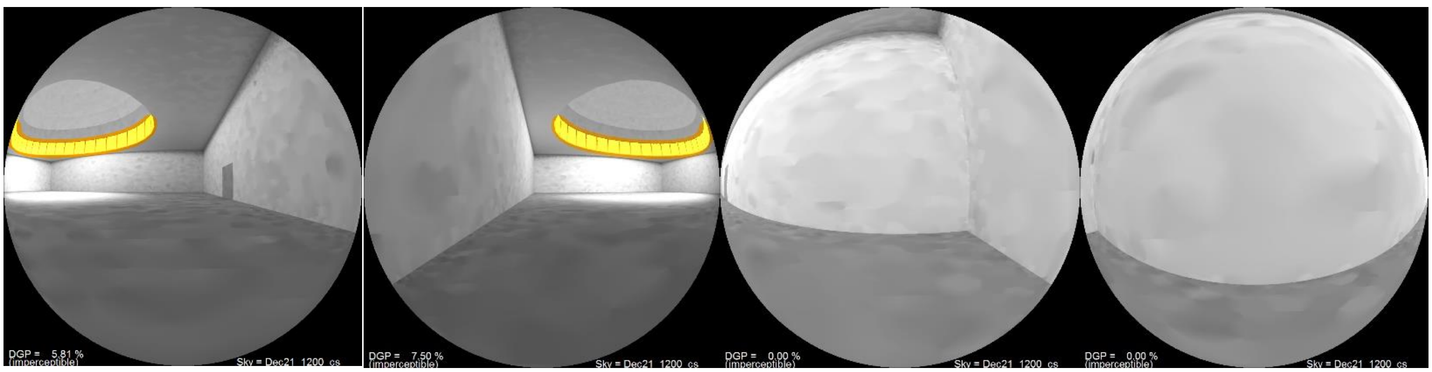
East **North** **South** **West**

Point A4:



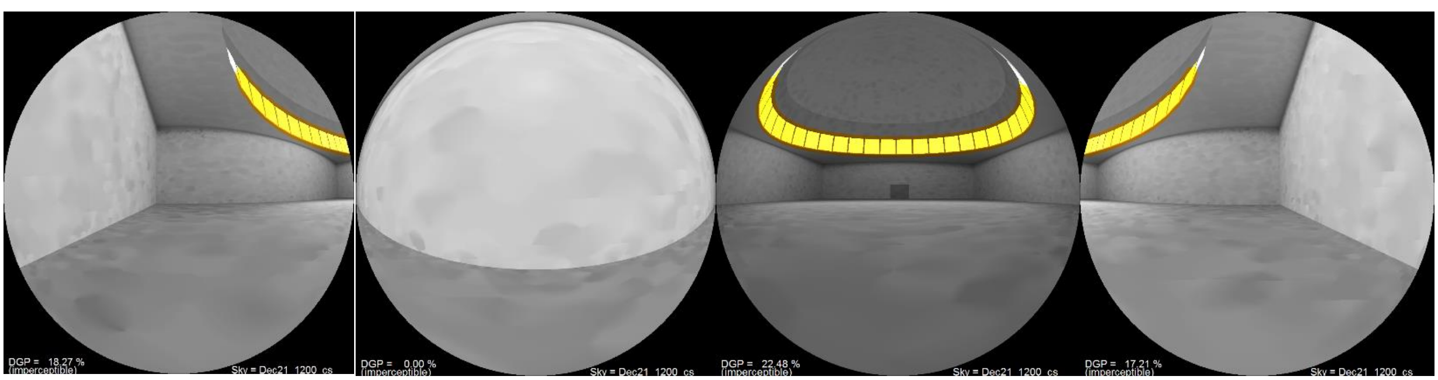
East North South West

Point A5:



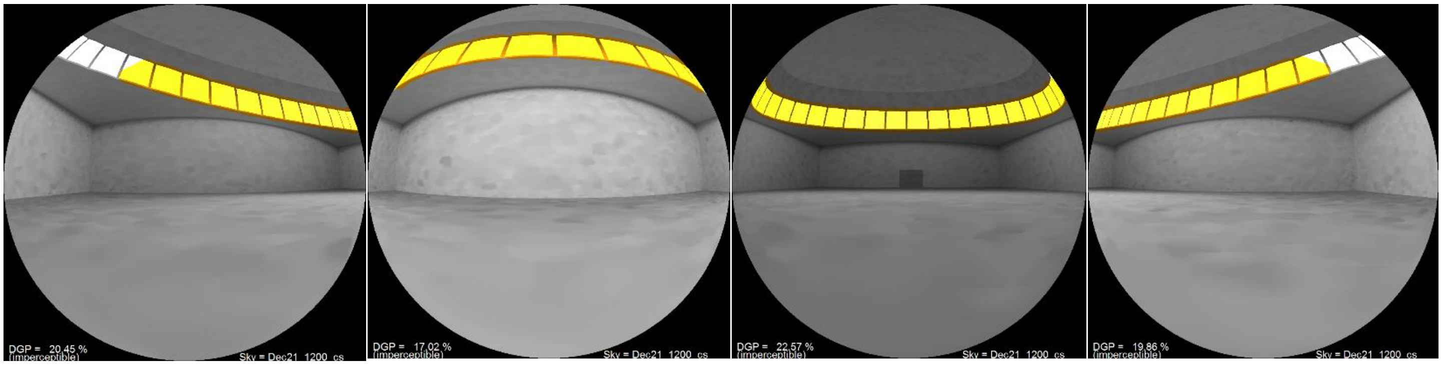
East North South West

Point B1:



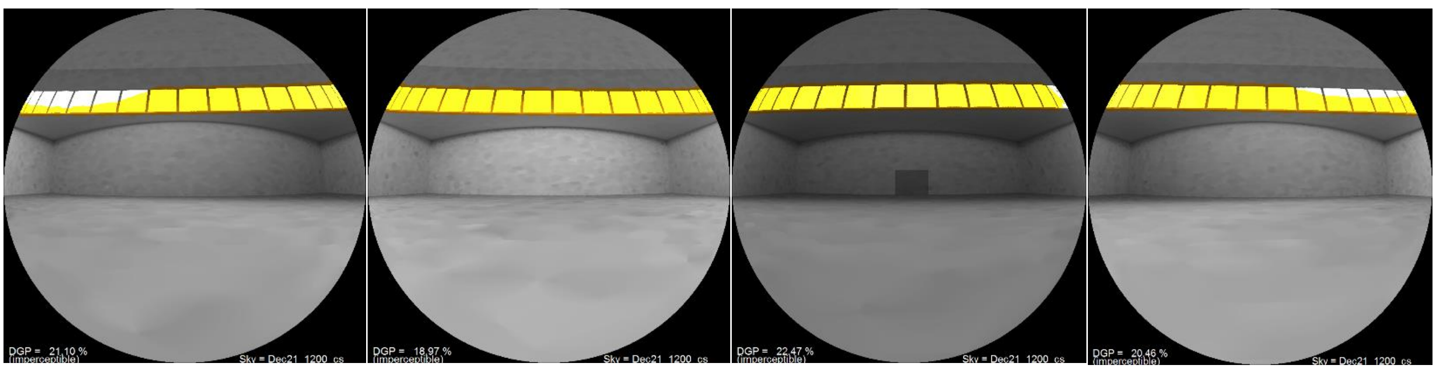
East North South West

Point B2:



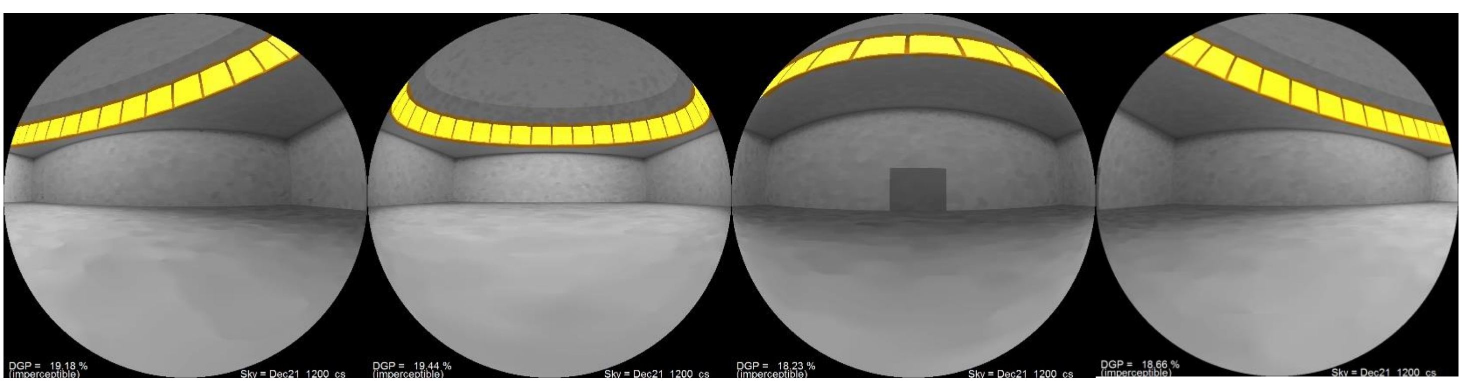
East North South West

Point B3:



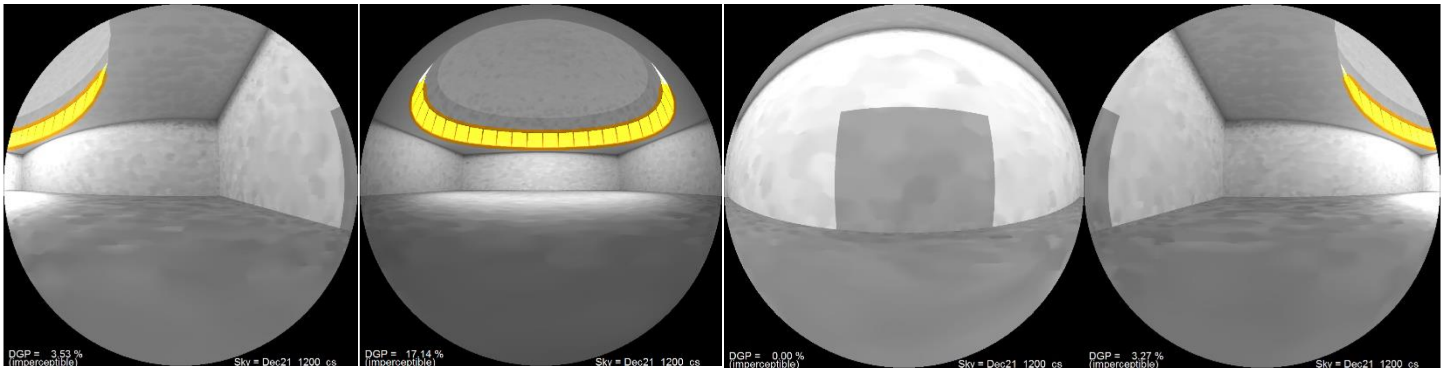
East North South West

Point B4:



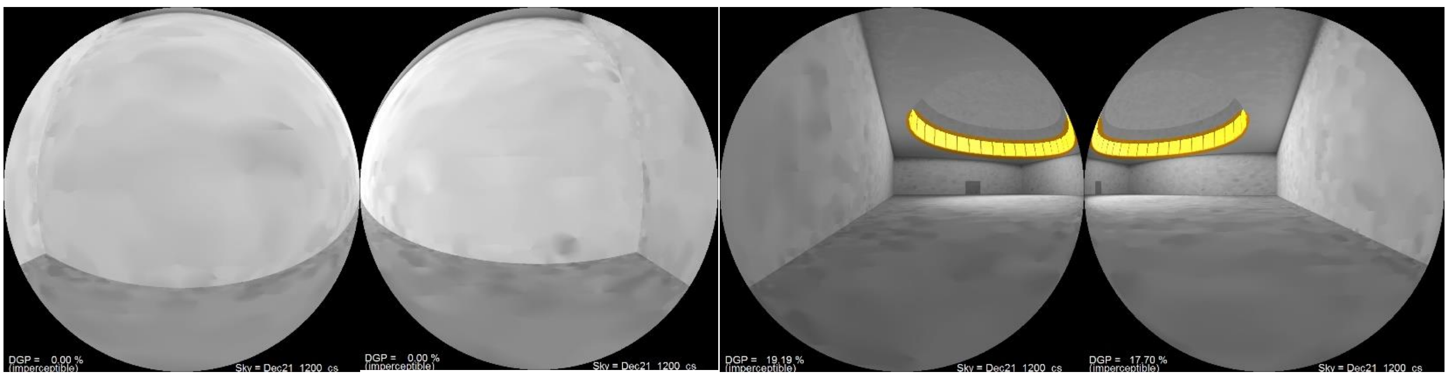
East North South West

Point B5:



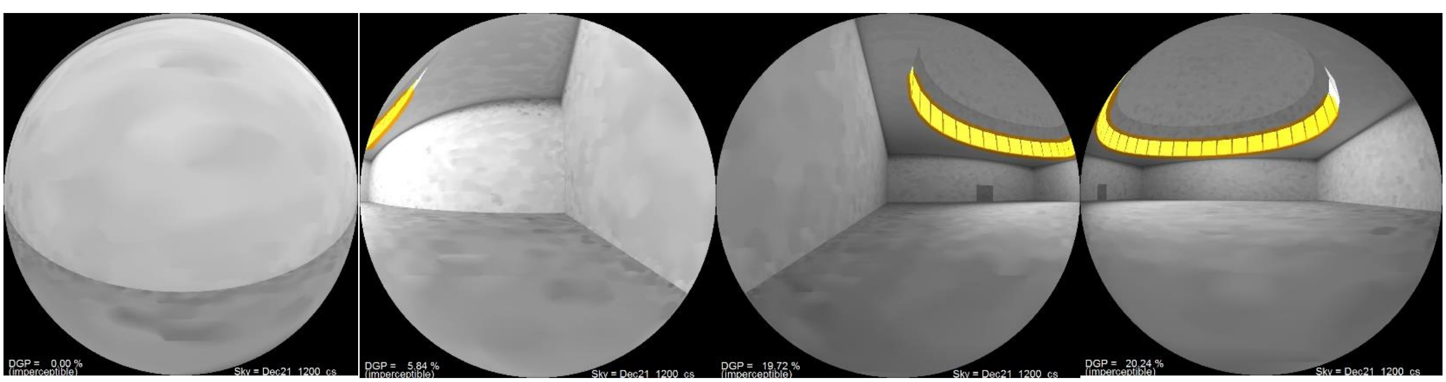
East North South West

Point C1:



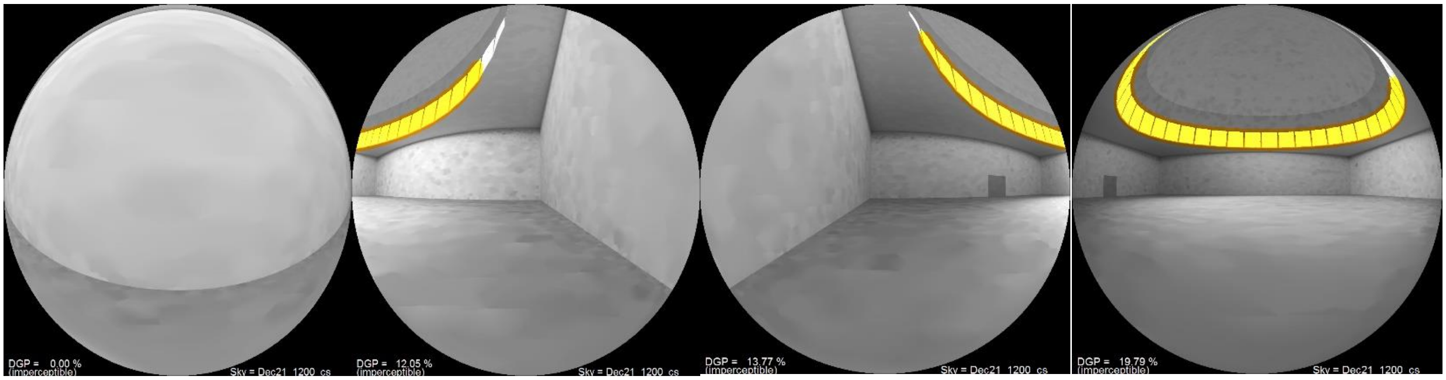
East North South West

Point C2:



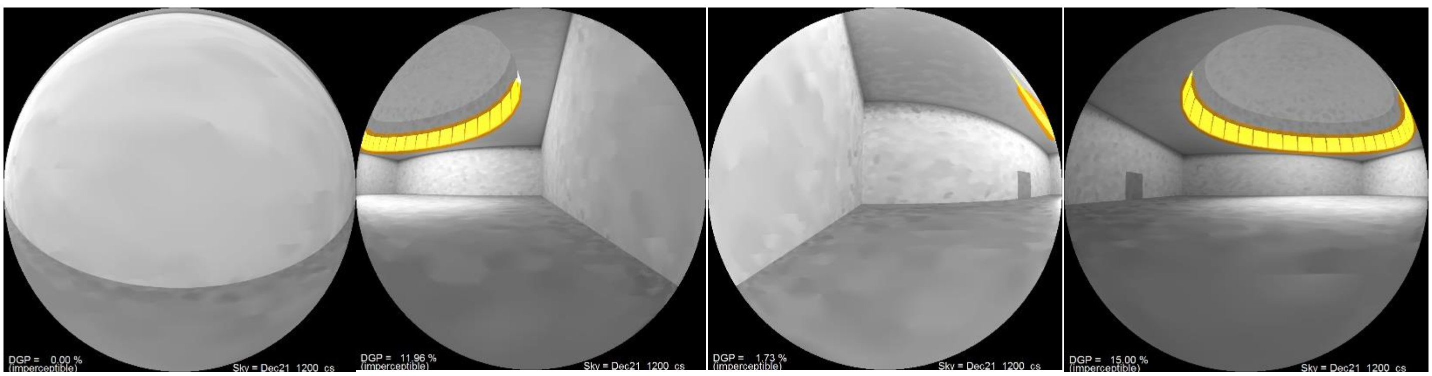
East North South West

Point C3:



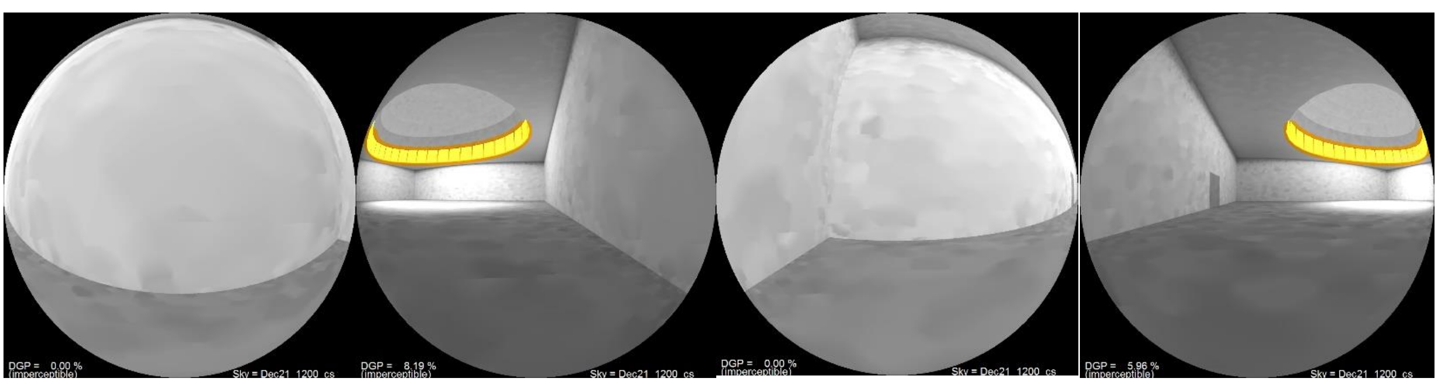
East **North** **South** **West**

Point C4:



East **North** **South** **West**

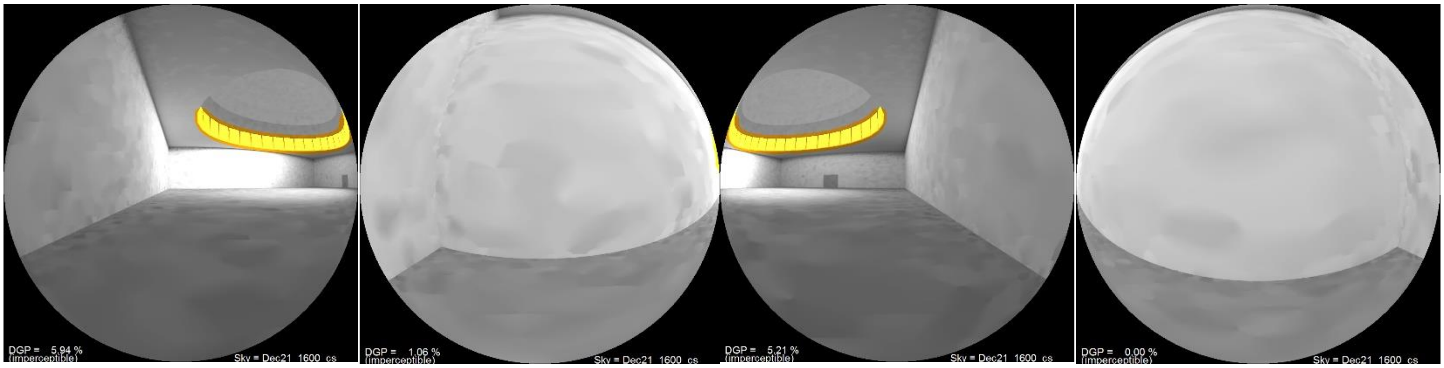
Point C5:



East **North** **South** **West**

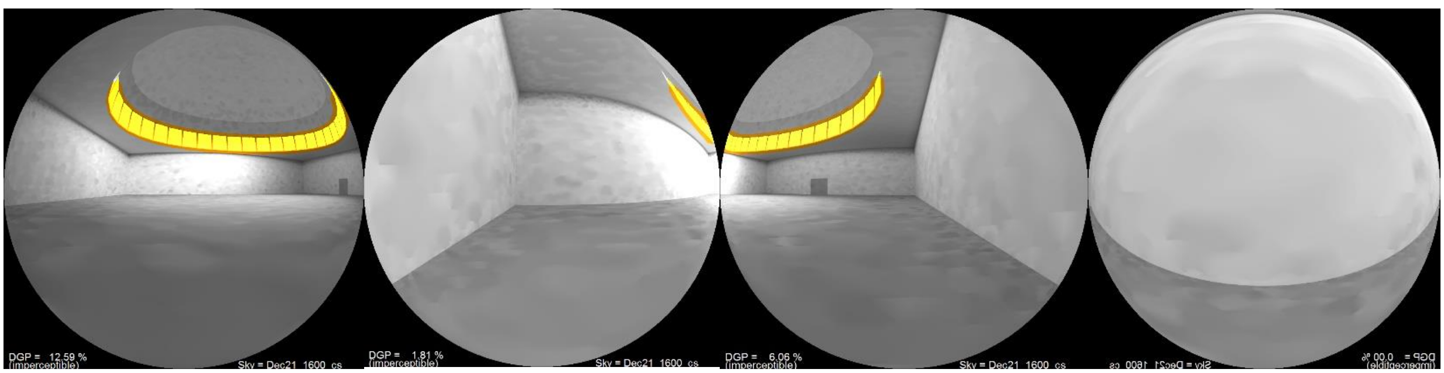
2. <u>21 Dec 04:00 pm</u>

<u>Point A1:</u>



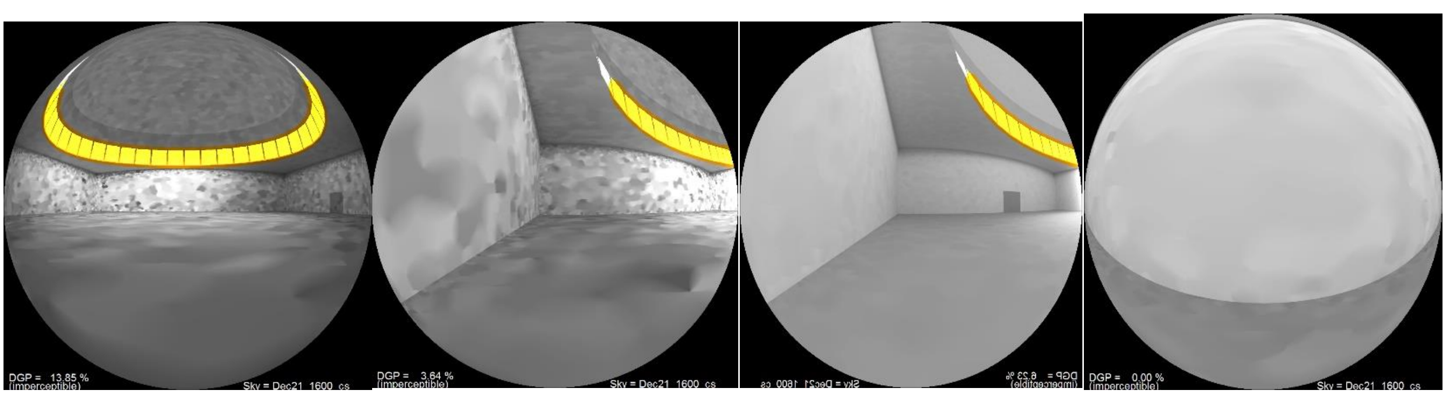
East **North** **South** **West**

<u>Point A2:</u>



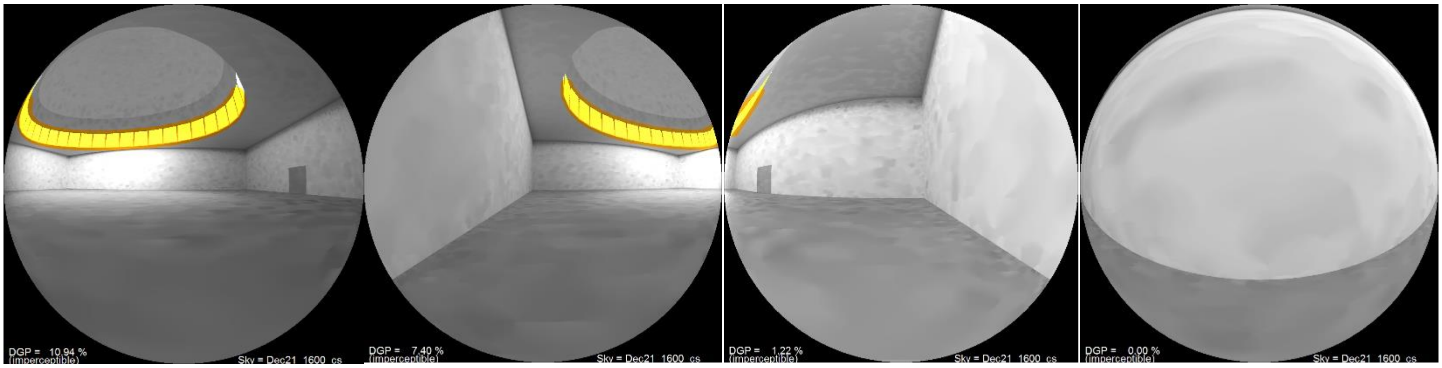
East **North** **South** **West**

<u>Point A3:</u>



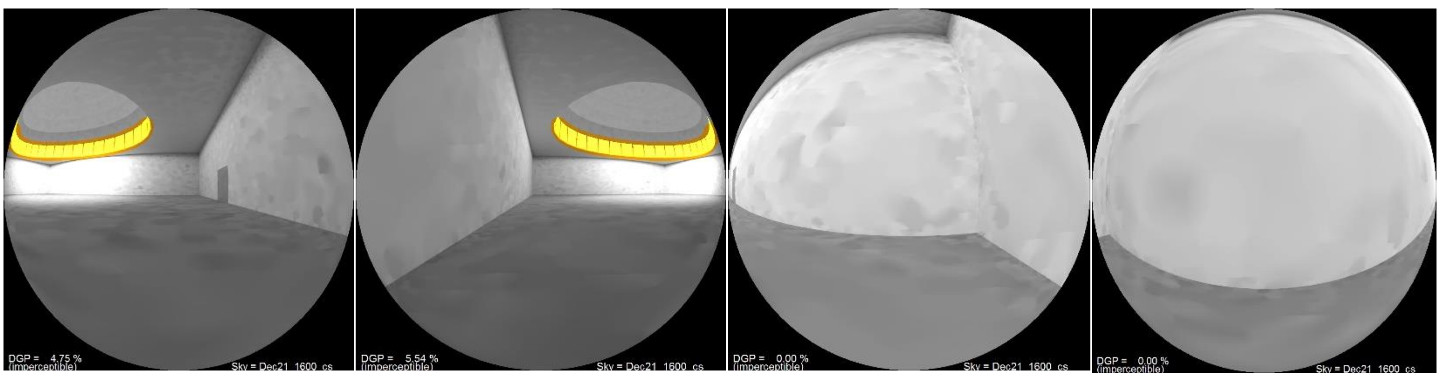
East **North** **South** **West**

Point A4:



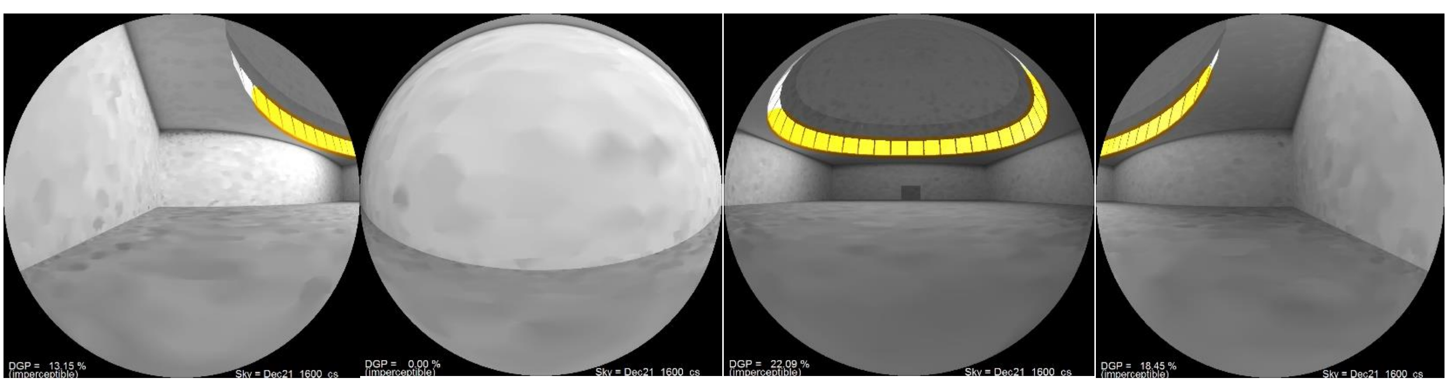
East **North** **South** **West**

Point A5:



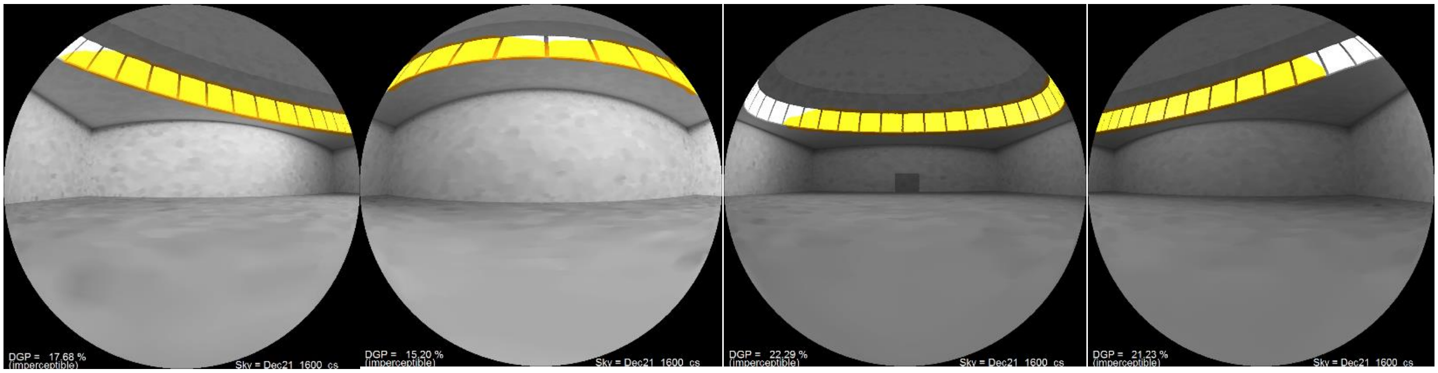
East **North** **South** **West**

Point B1:



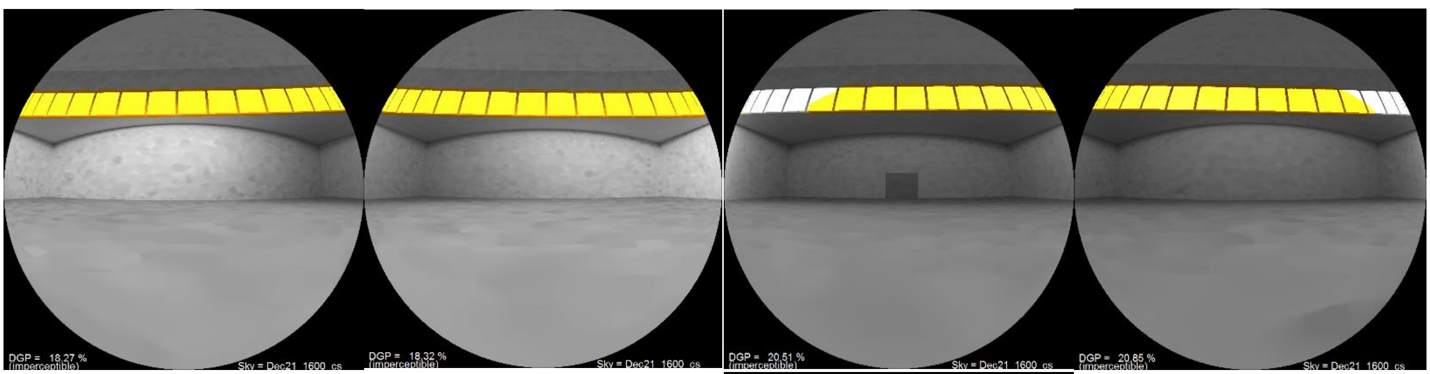
East **North** **South** **West**

Point B2:



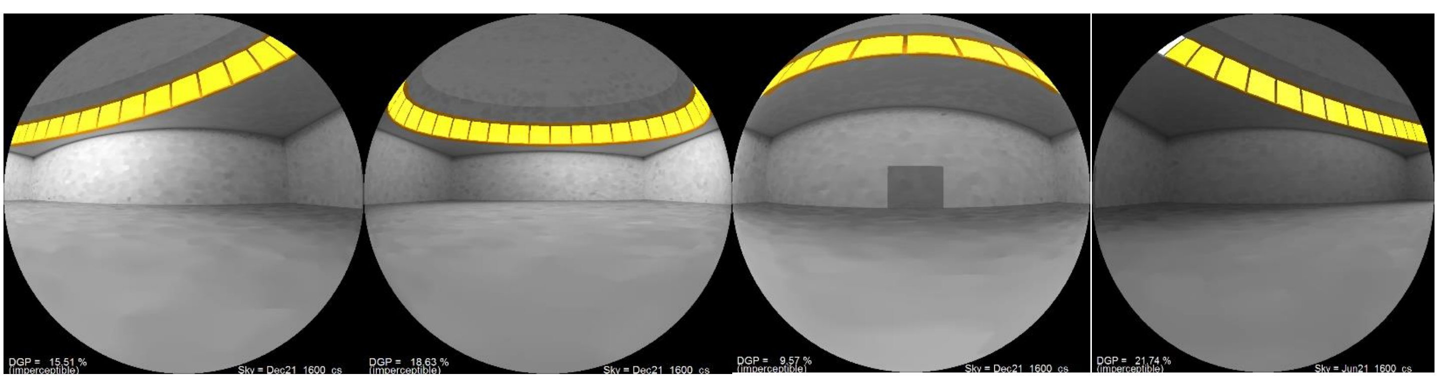
East **North** **South** **West**

Point B3:



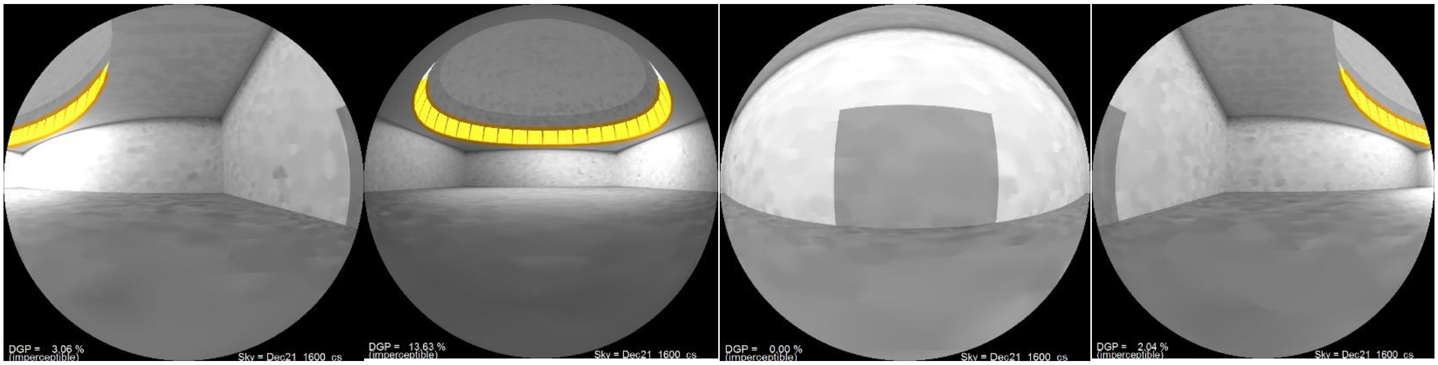
East **North** **South** **West**

Point B4:



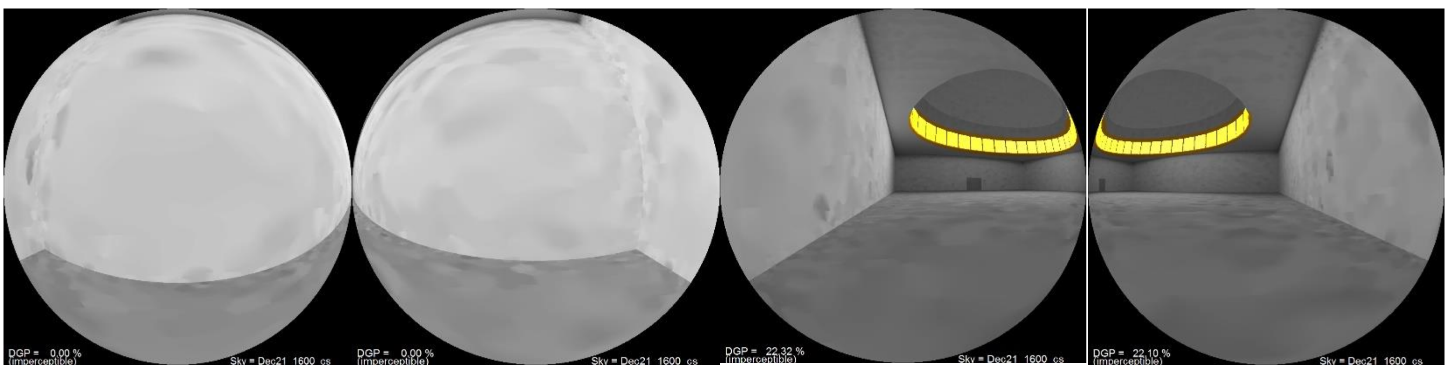
East **North** **South** **West**

Point B5:



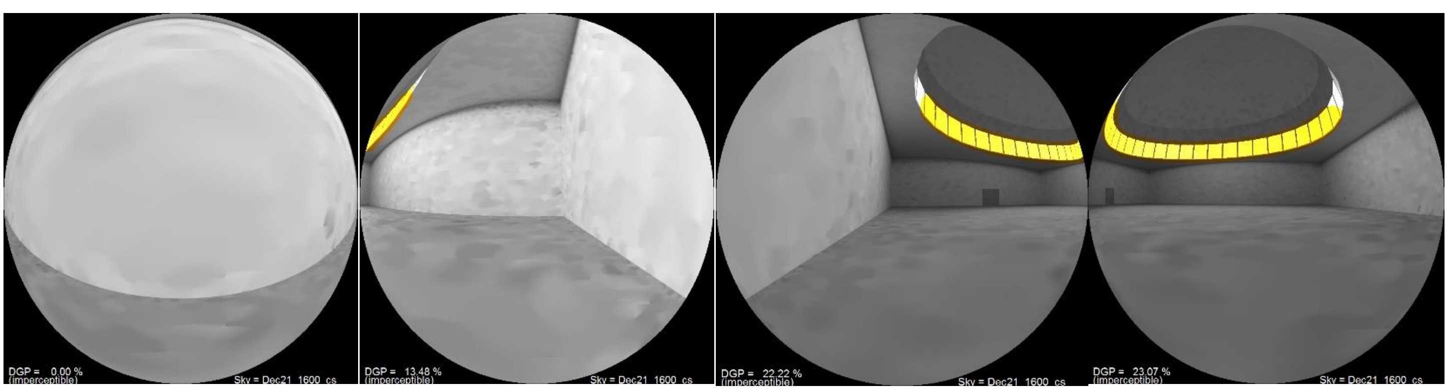
East **North** **South** **West**

Point C1:



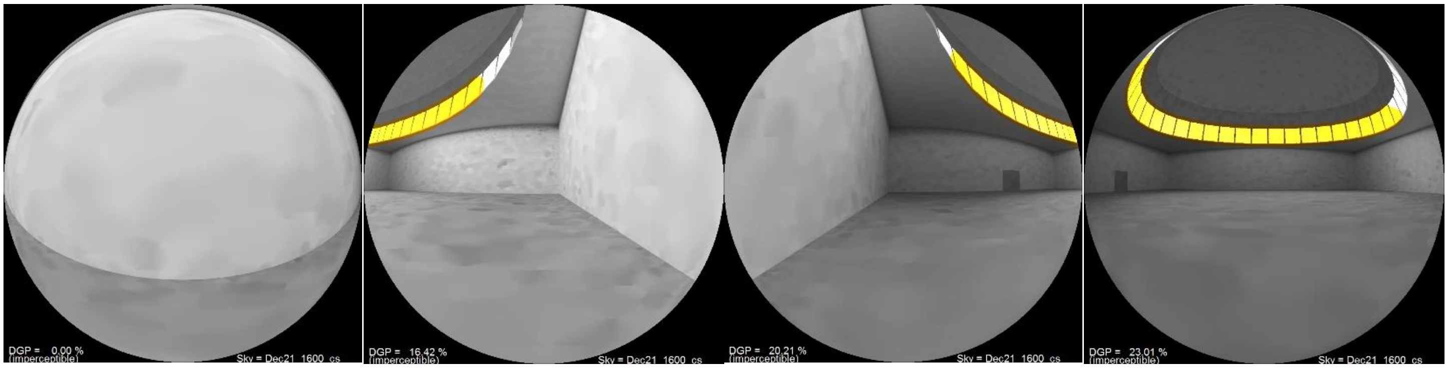
East **North** **South** **West**

Point C2:



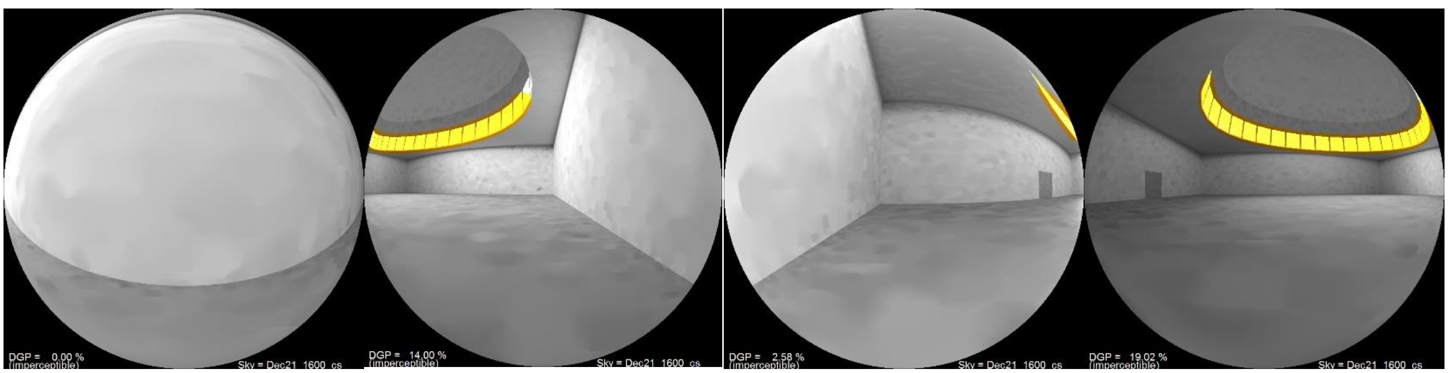
East **North** **South** **West**

Point C3:



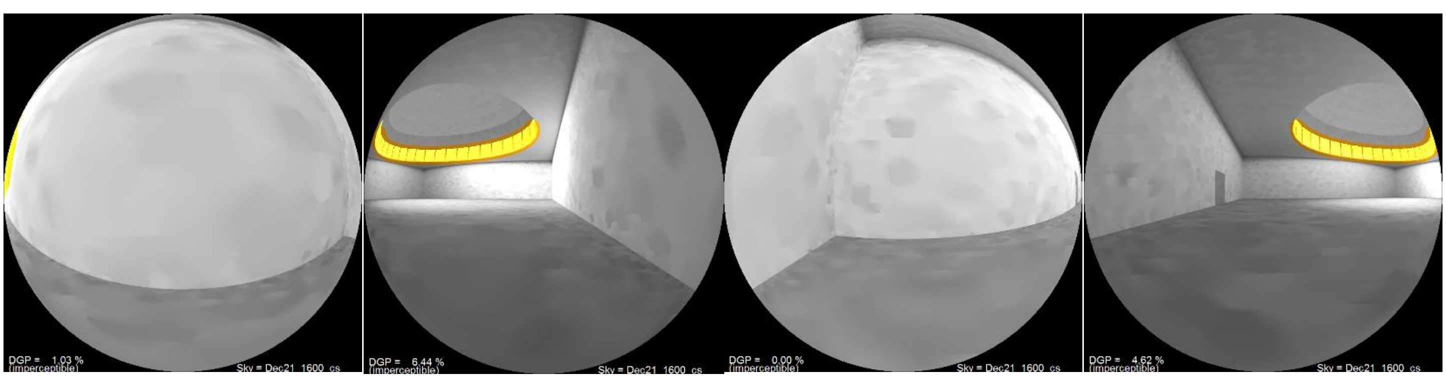
East **North** **South** **West**

Point C4:



East **North** **South** **West**

Point C5:

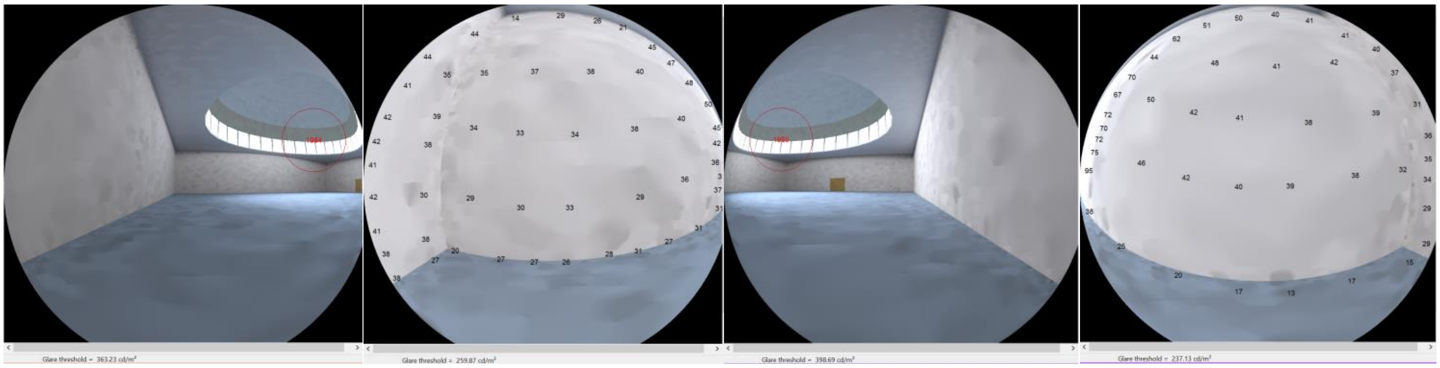


East **North** **South** **West**

Appendix C – Glare threshold simulation results for GTD calculations

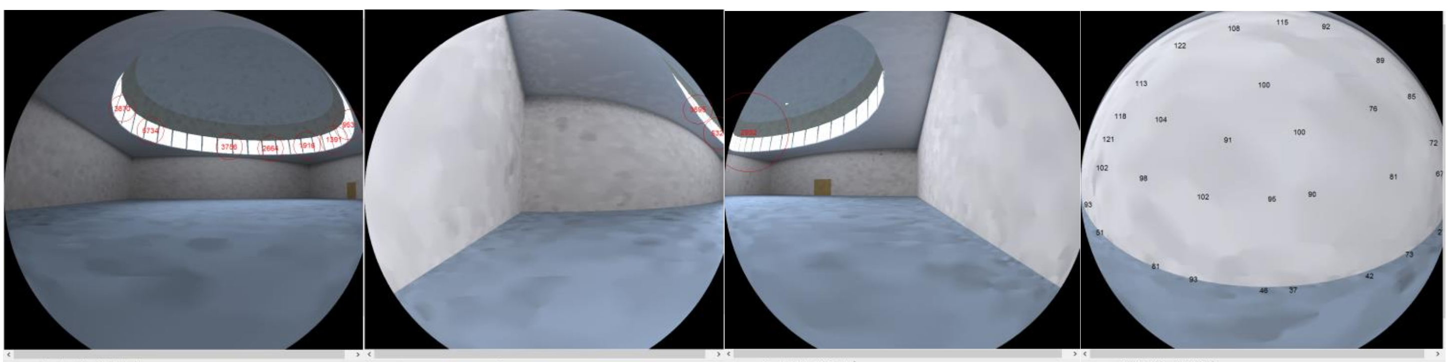
1. **<u>21 Jun 8:00 am</u>**

<u>Point A1:</u>



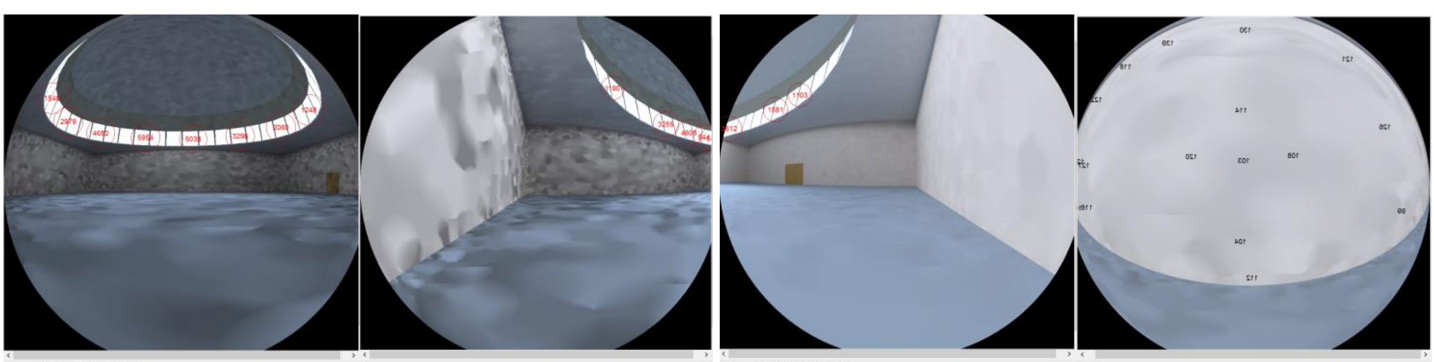
East North South West

<u>Point A2:</u>



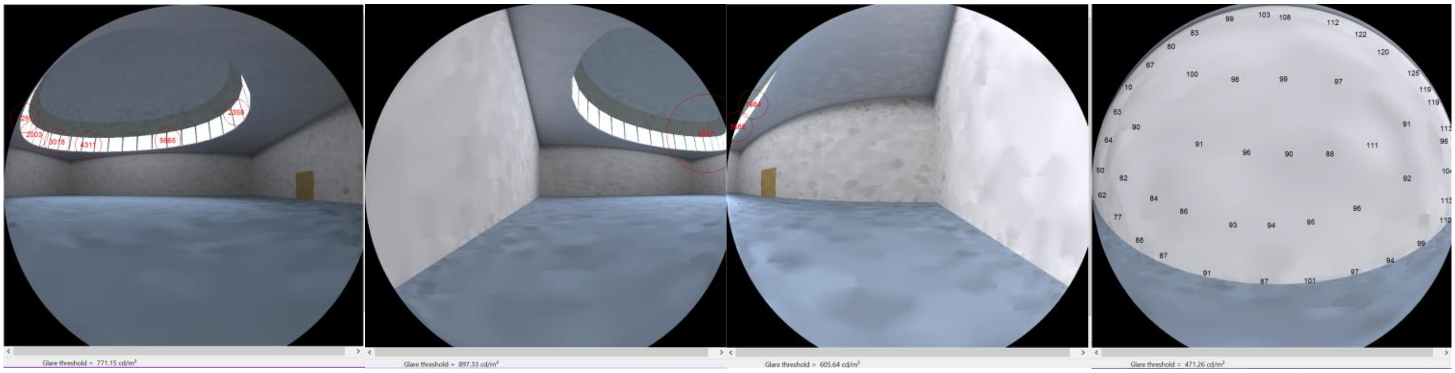
East North South West

<u>Point A3:</u>



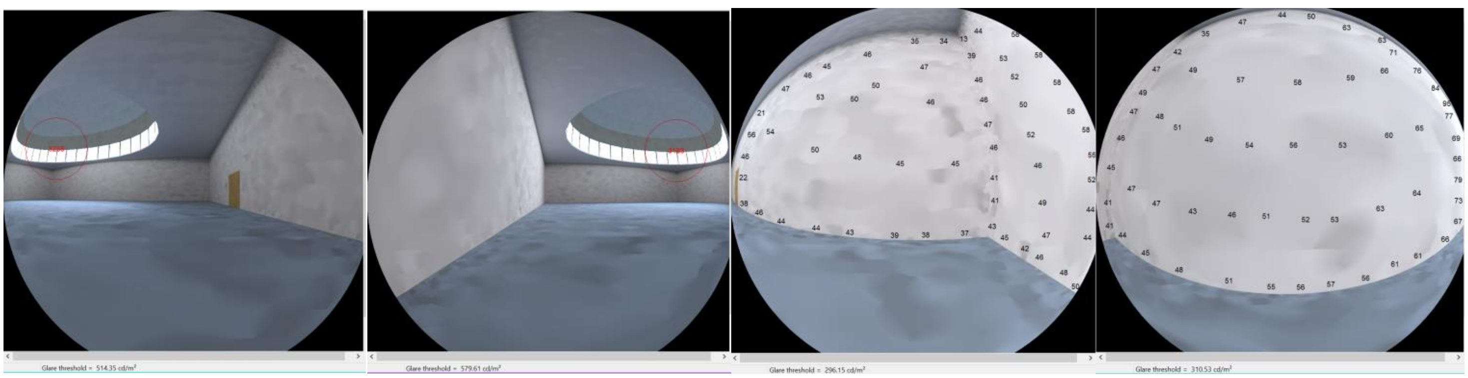
East North South West

Point A4:



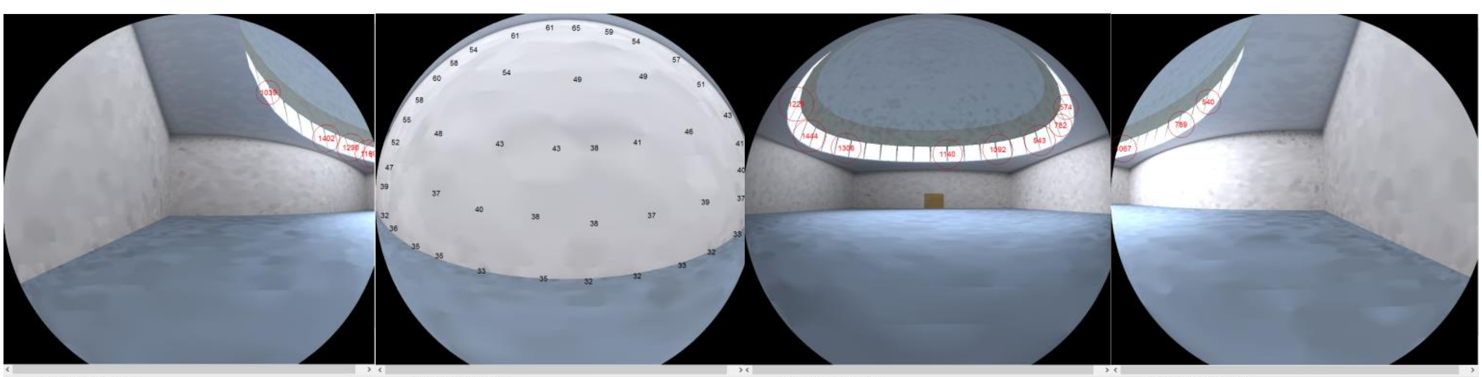
East **North** **South** **West**

Point A5:



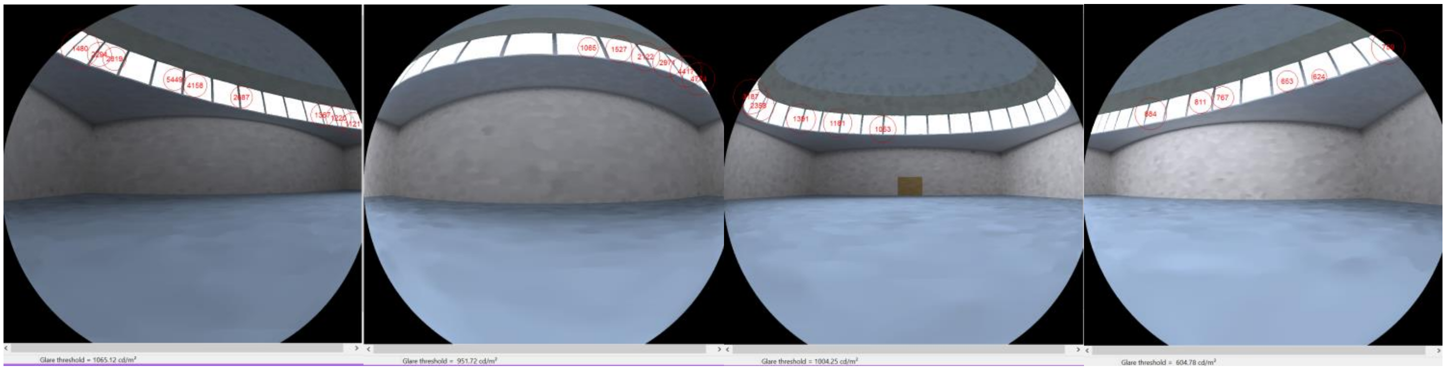
East **North** **South** **West**

Point B1:



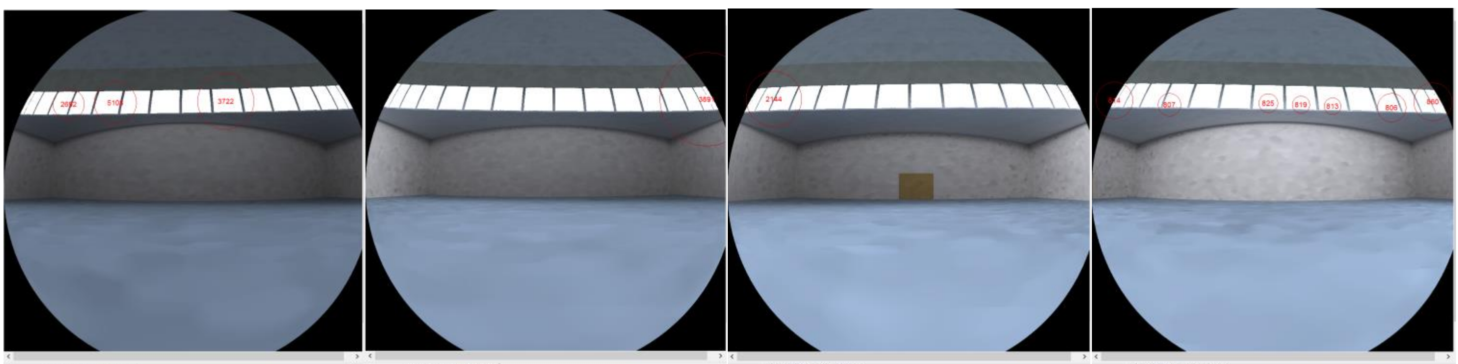
East **North** **South** **West**

Point B2:



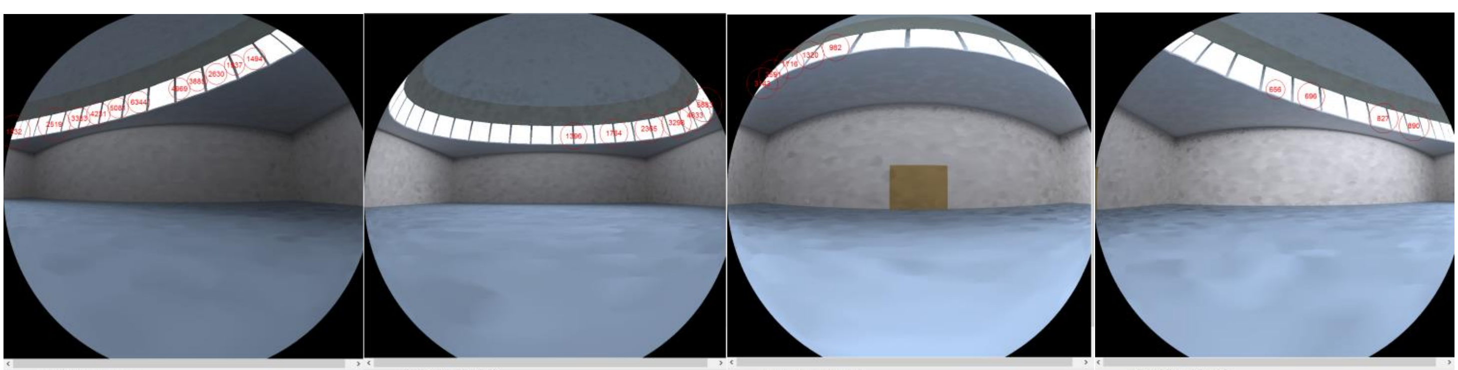
East **North** **South** **West**

Point B3:



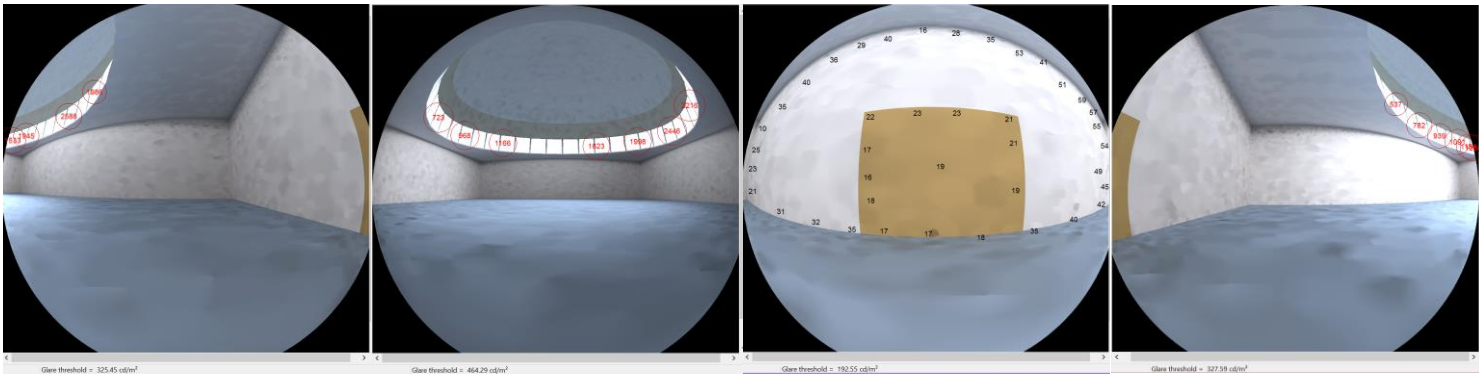
East **North** **South** **West**

Point B4:



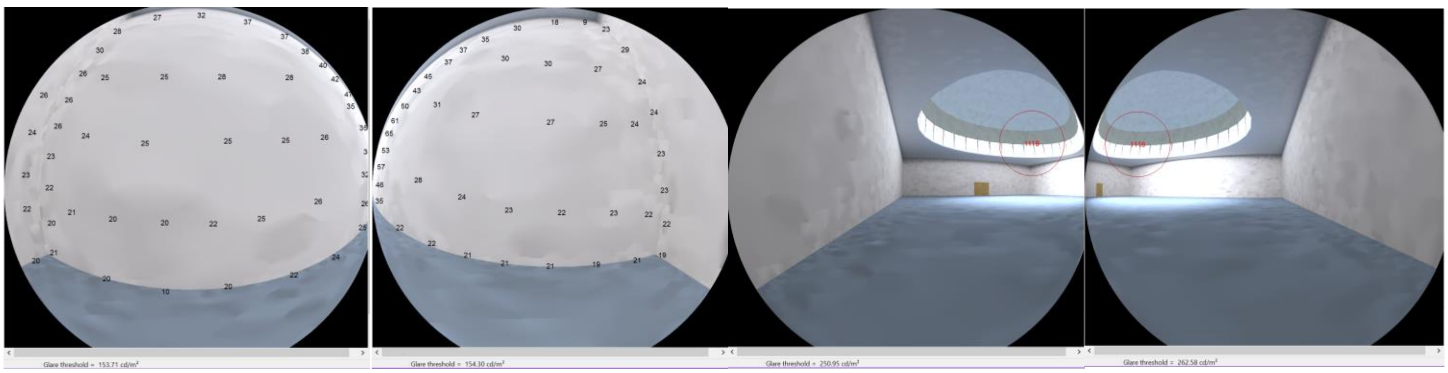
East **North** **South** **West**

Point B5:



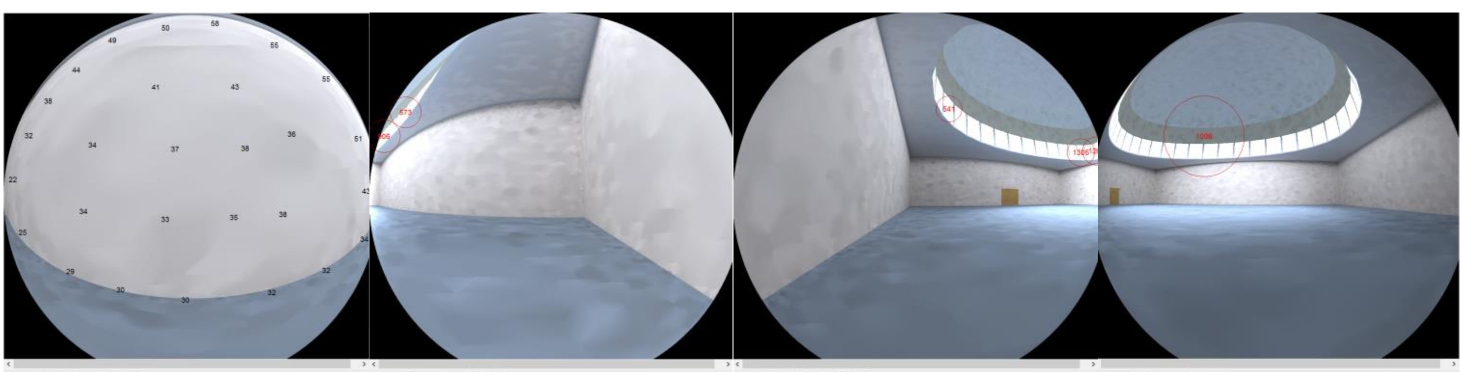
East **North** **South** **West**

Point C1:



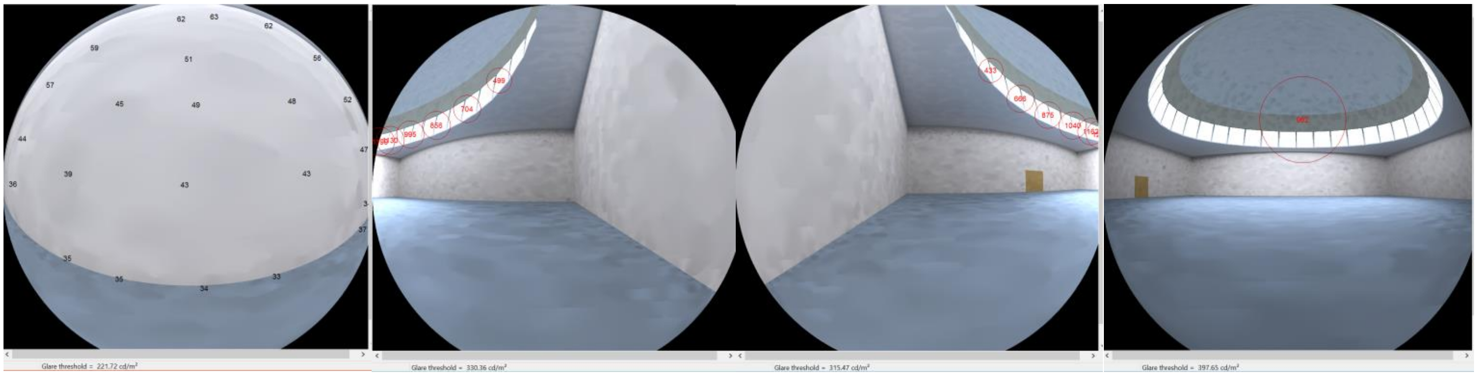
East **North** **South** **West**

Point C2:



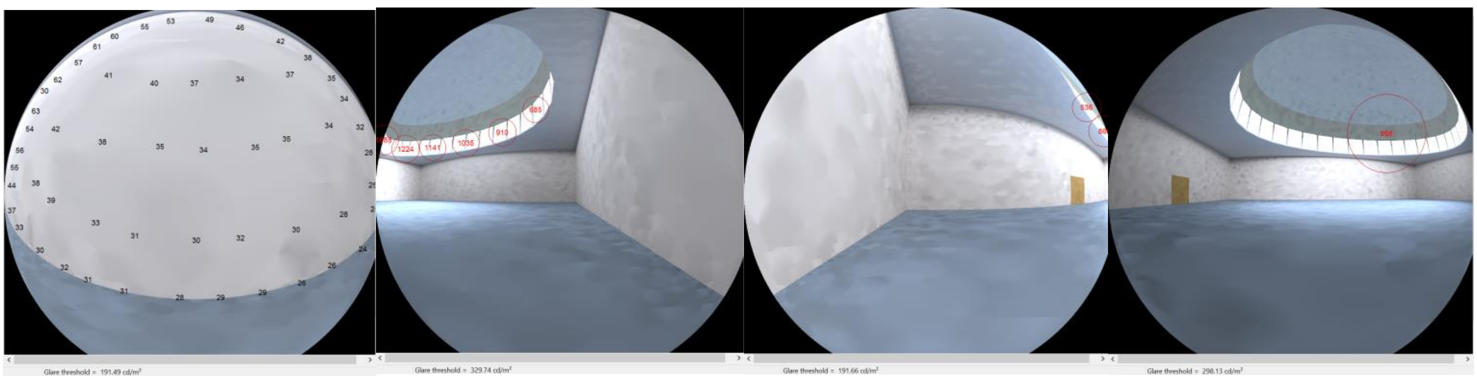
East **North** **South** **West**

Point C3:



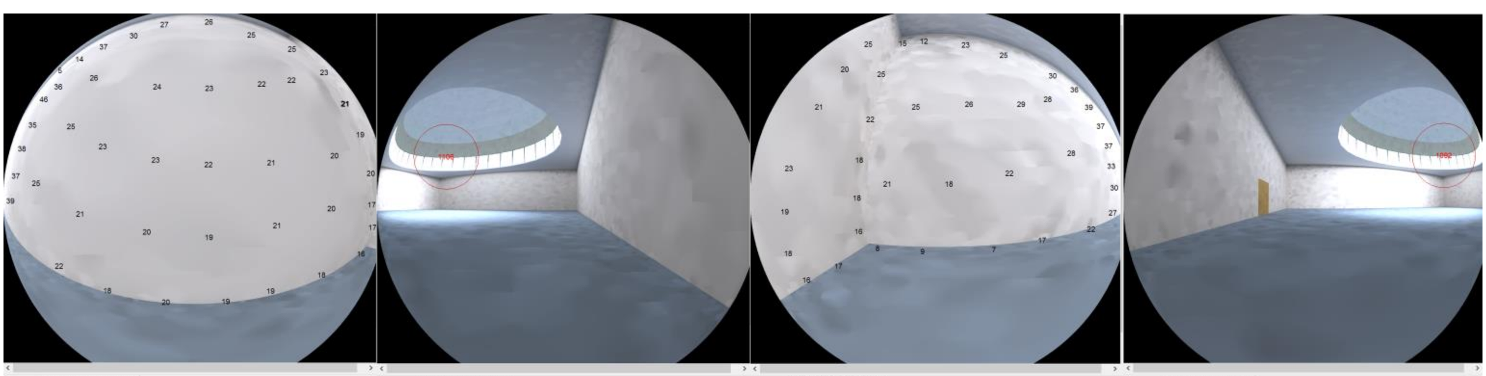
East **North** **South** **West**

Point C4:



East **North** **South** **West**

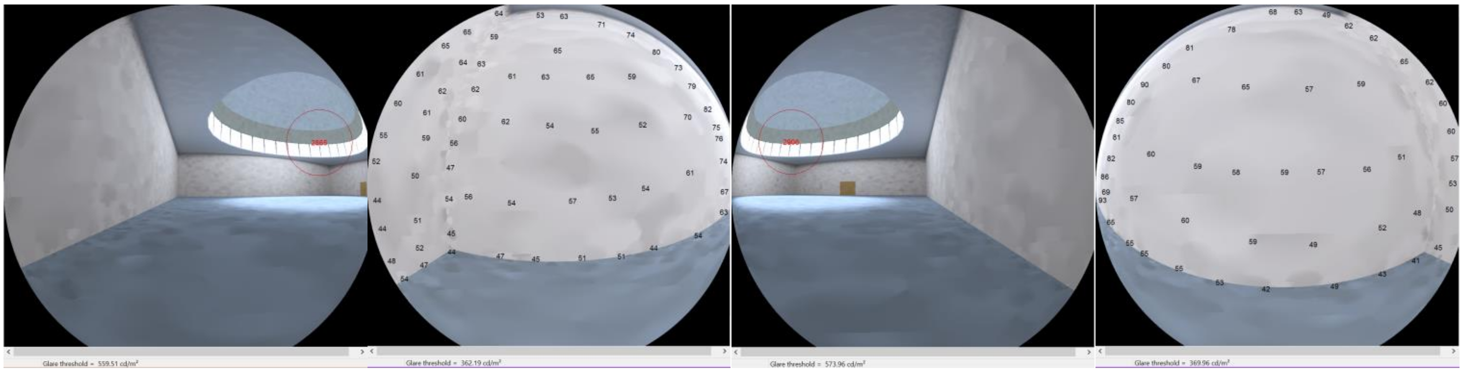
Point C5:



East **North** **South** **West**

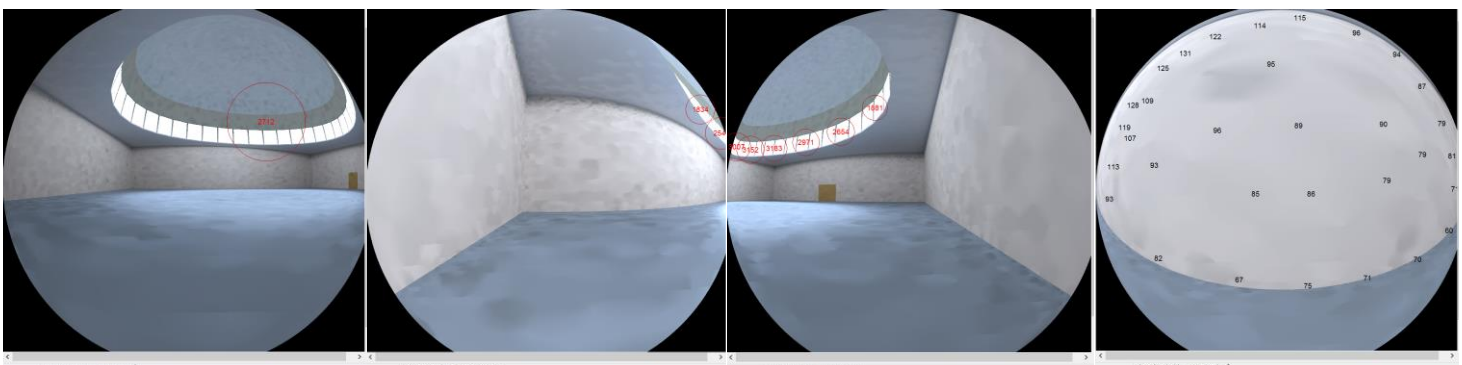
2. 21 Jun 12:00 pm

Point A1:



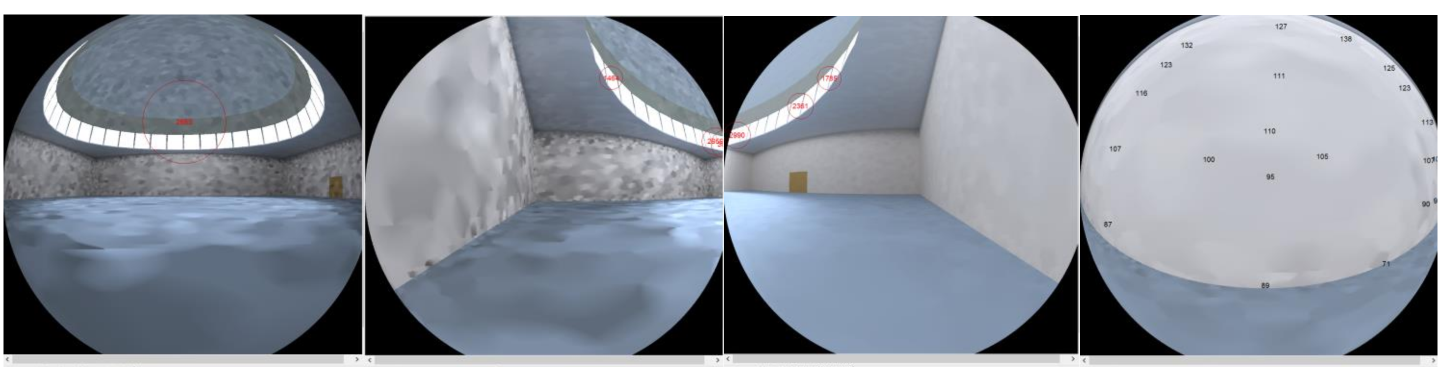
East **North** **South** **West**

Point A2:



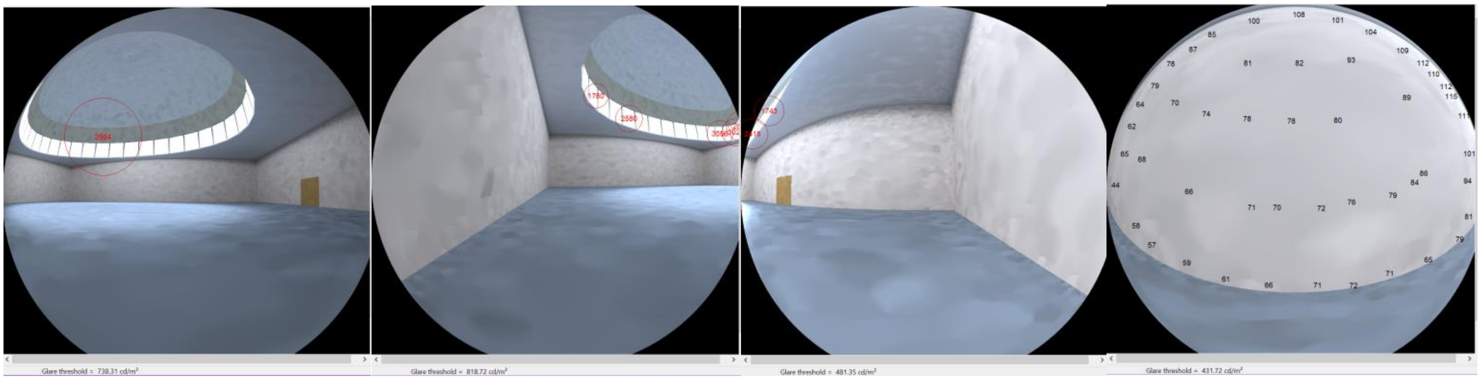
East **North** **South** **West**

Point A3:



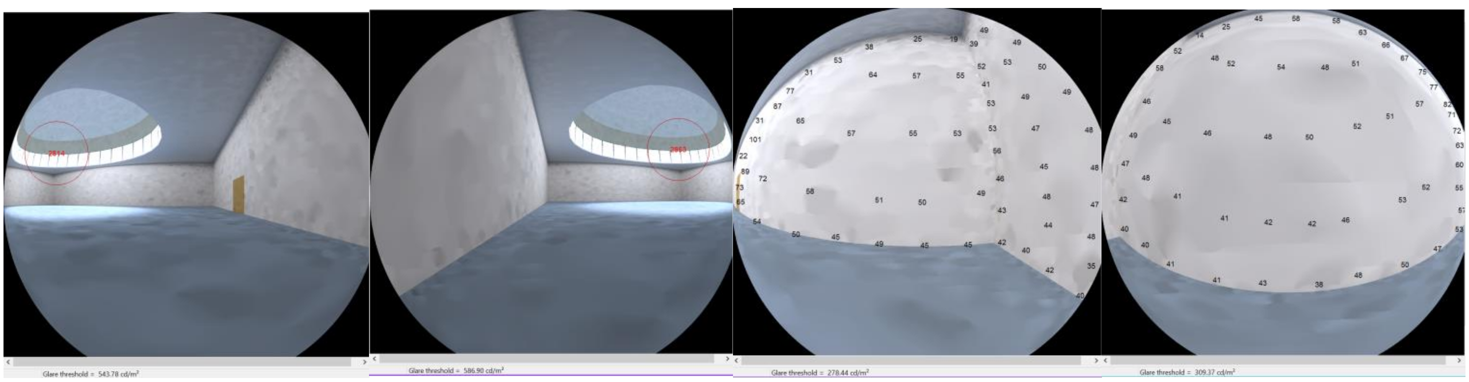
East **North** **South** **West**

Point A4:



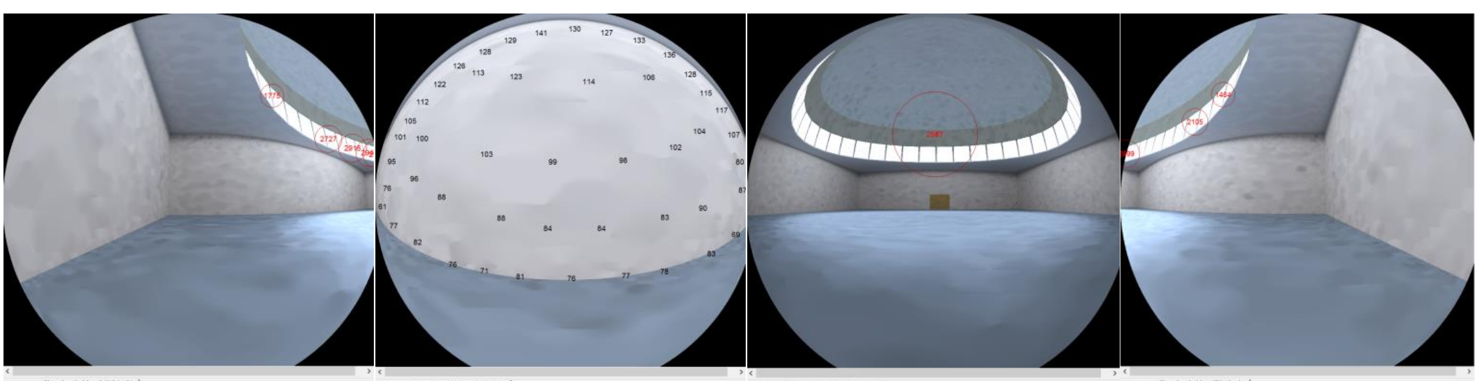
East **North** **South** **West**

Point A5:



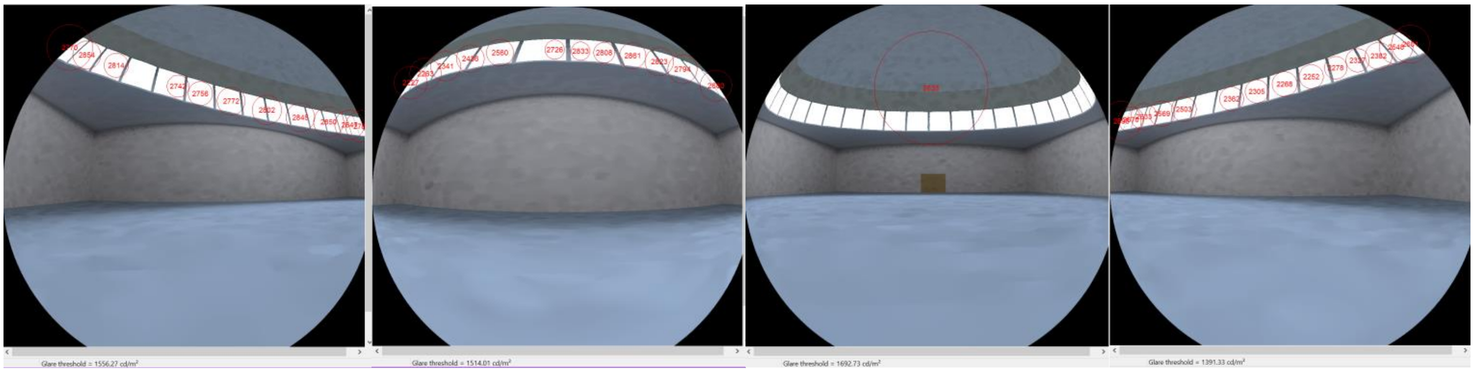
East **North** **South** **West**

Point B1:



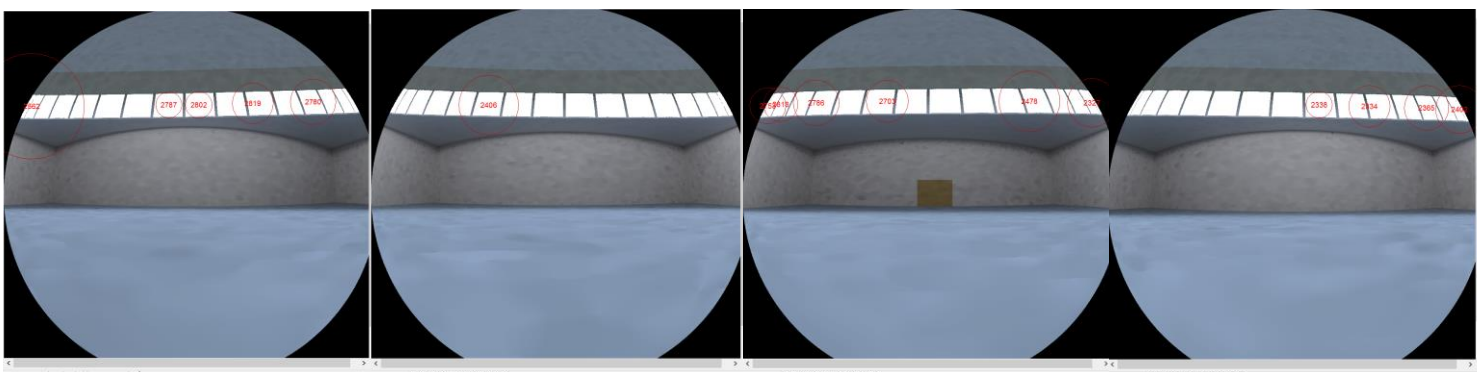
East **North** **South** **West**

Point B2:



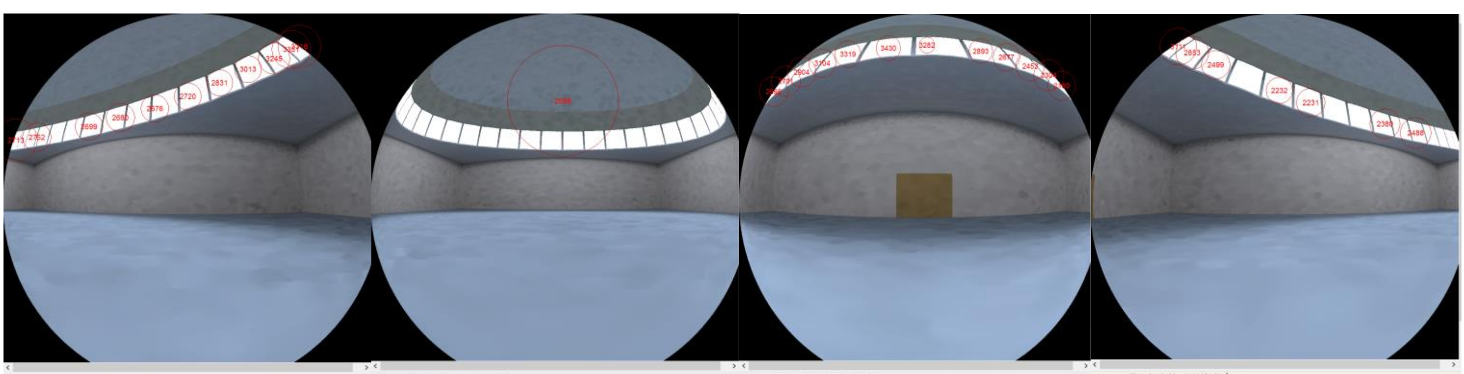
East **North** **South** **West**

Point B3:



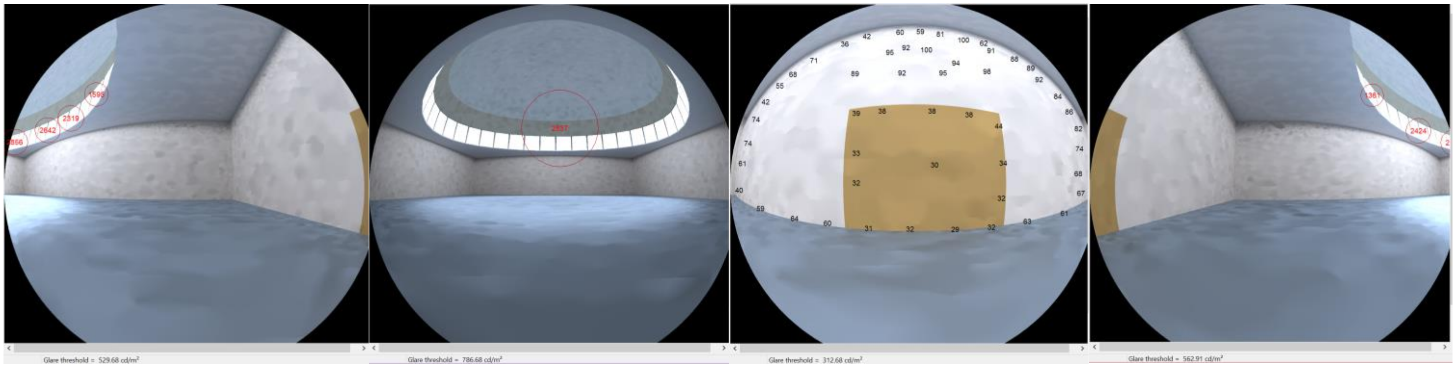
East **North** **South** **West**

Point B4:



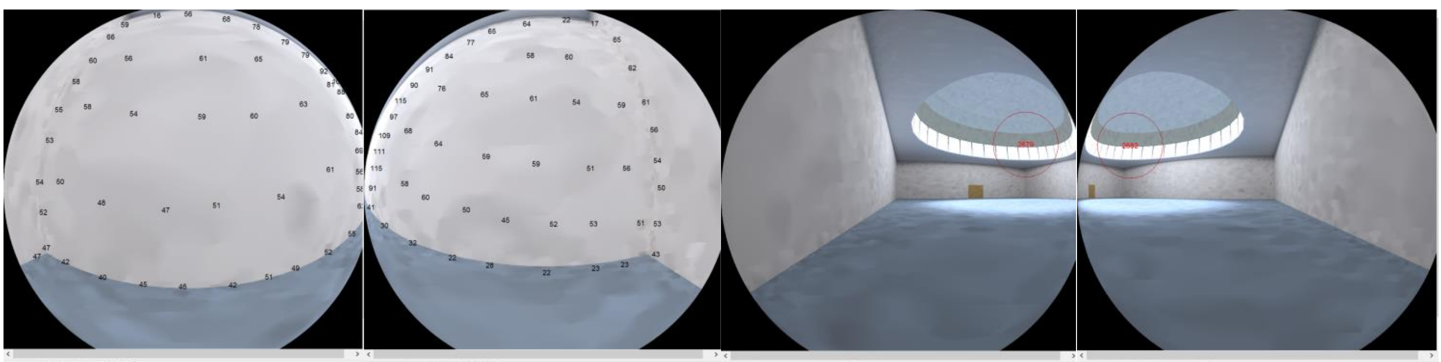
East **North** **South** **West**

Point B5:



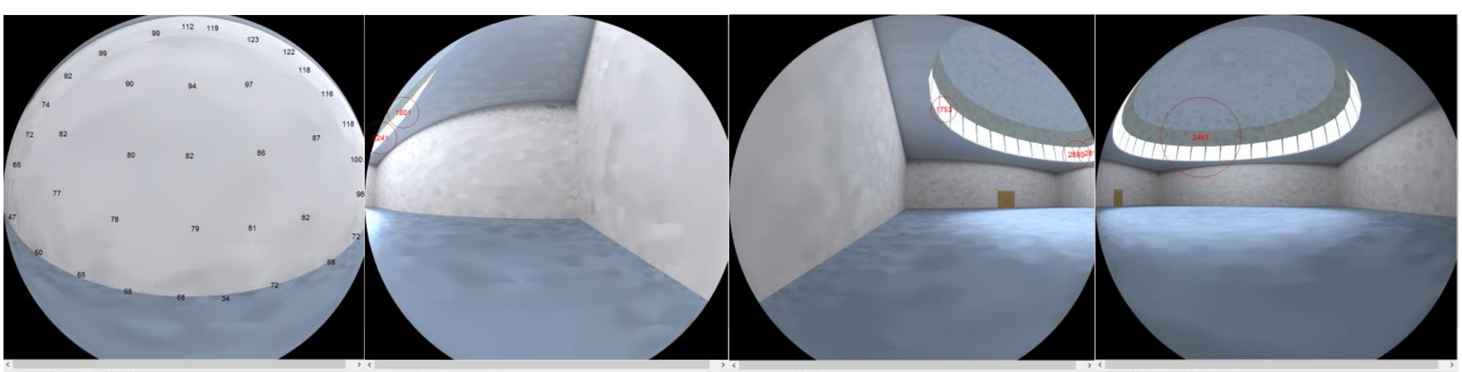
East **North** **South** **West**

Point C1:



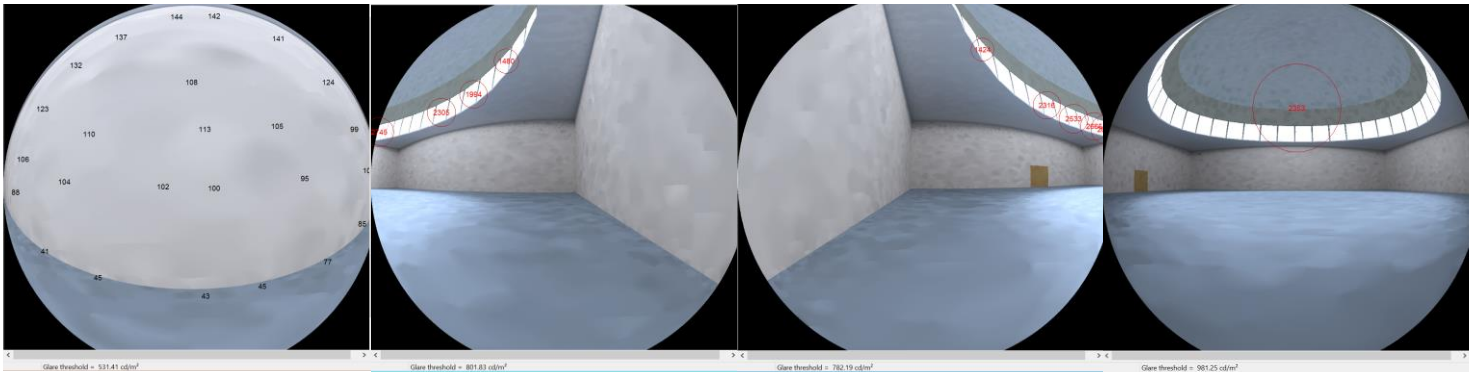
East **North** **South** **West**

Point C2:



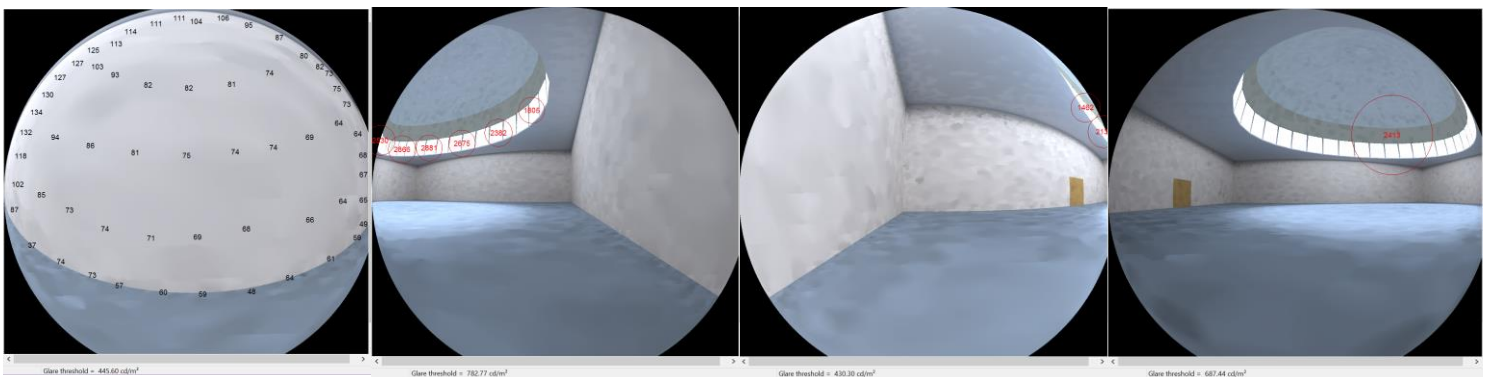
East **North** **South** **West**

Point C3:



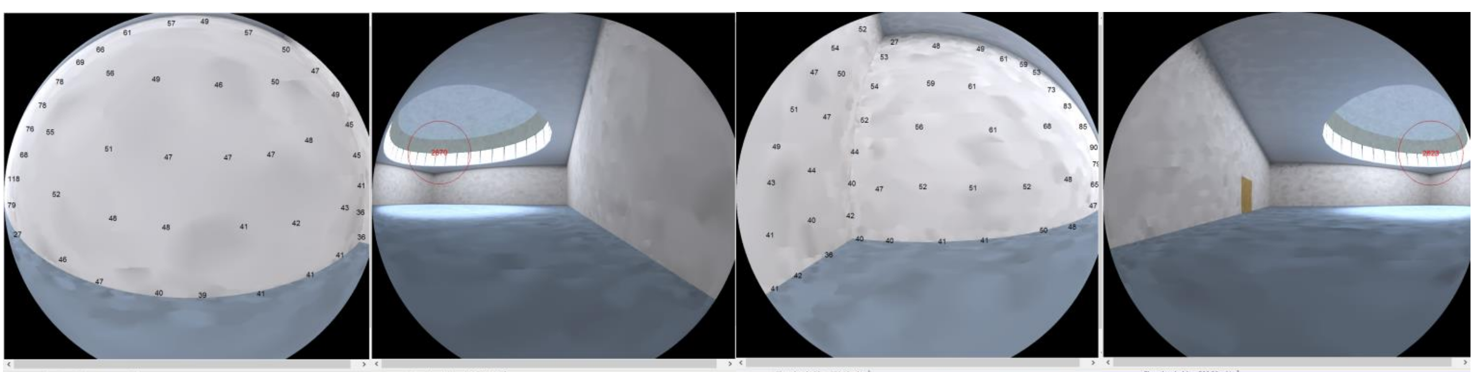
East **North** **South** **West**

Point C4:



East **North** **South** **West**

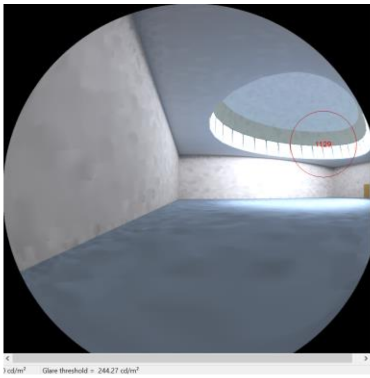
Point C5:

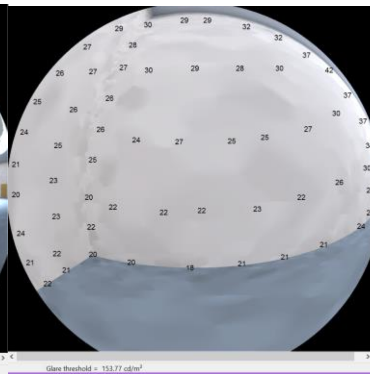


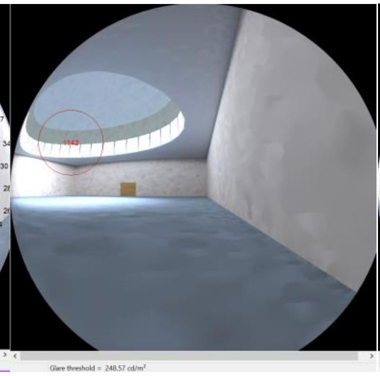
East **North** **South** **West**

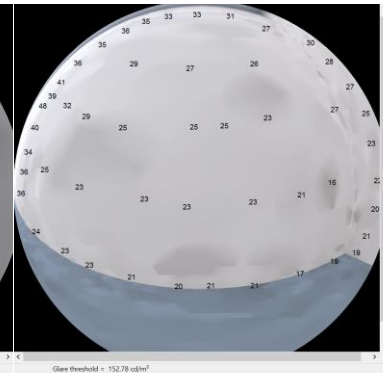
3. 21 Jun 4:00 pm

Point A1:



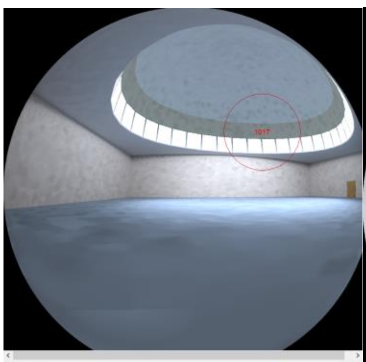


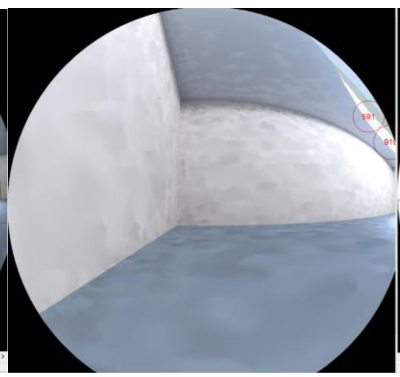
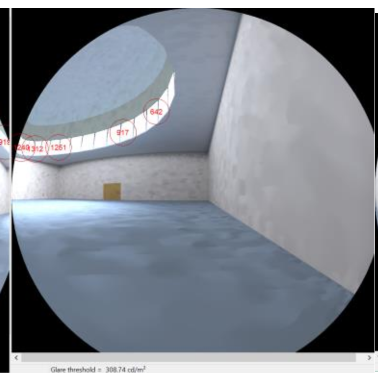


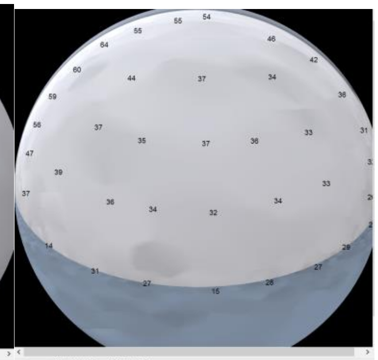


East **North** **South** **West**

Point A2:

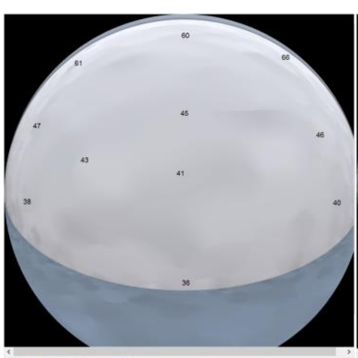


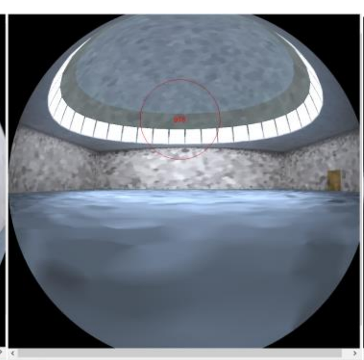



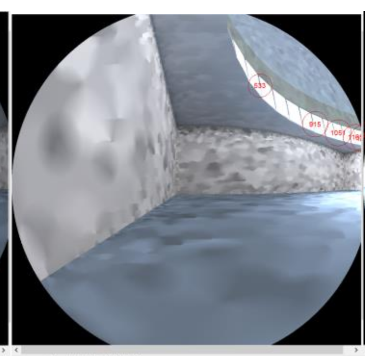


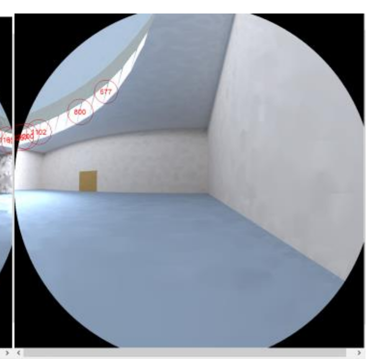
East **North** **South** **West**

Point A3:



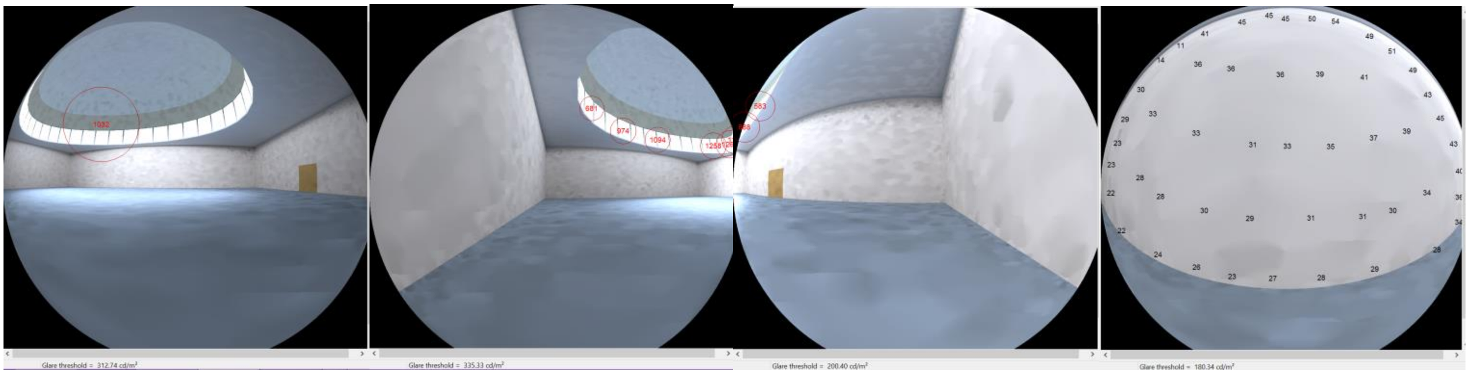






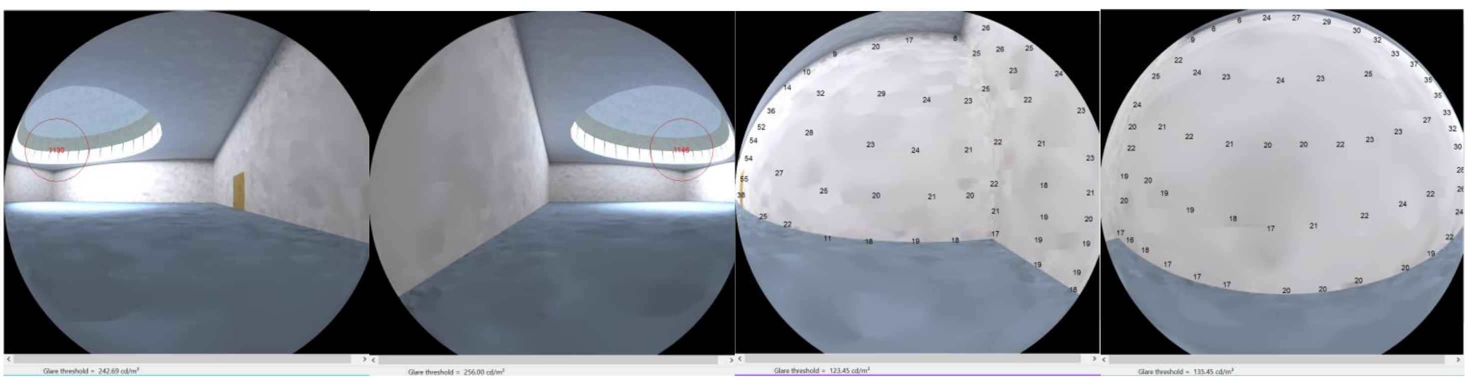
East **North** **South** **West**

Point A4:



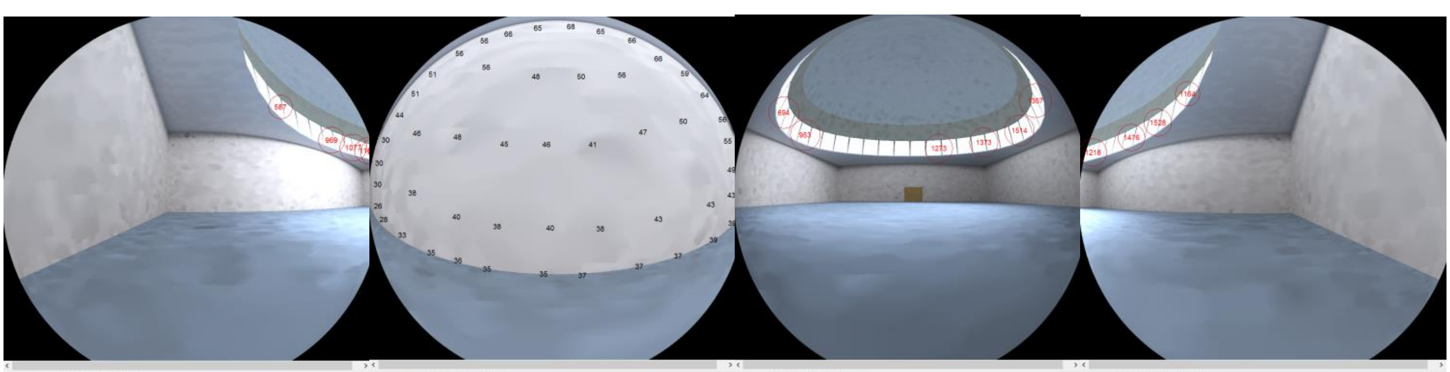
East **North** **South** **West**

Point A5:



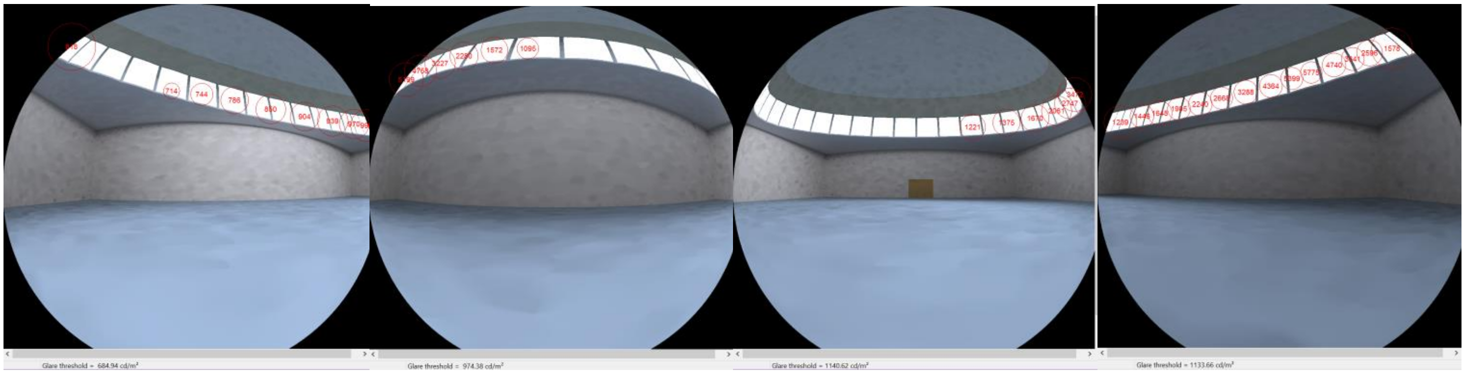
East **North** **South** **West**

Point B1:



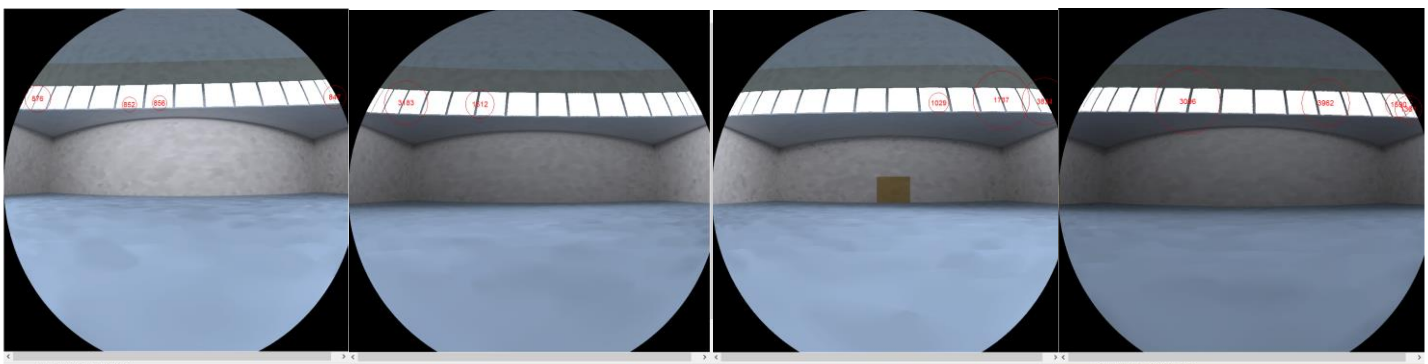
East **North** **South** **West**

Point B2:



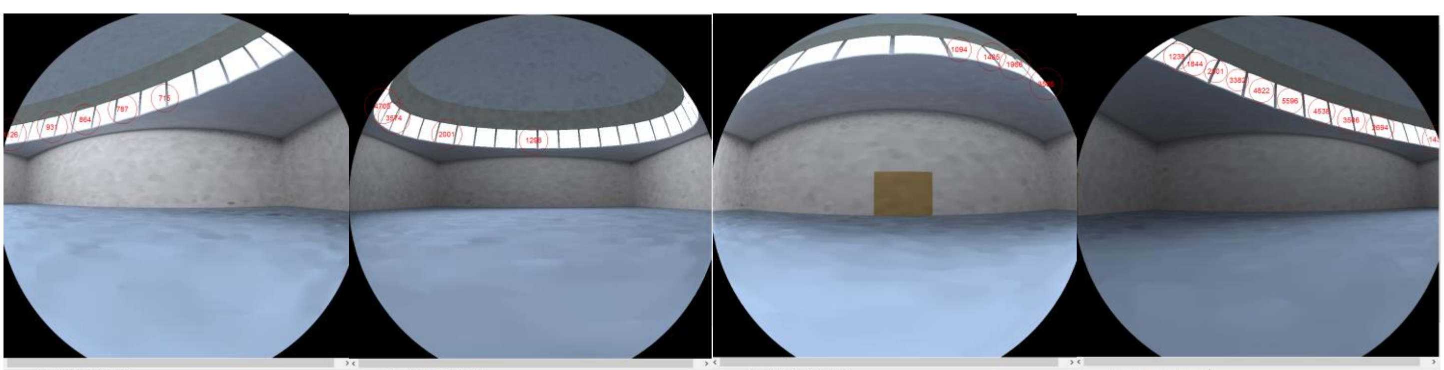
East **North** **South** **West**

Point B3:



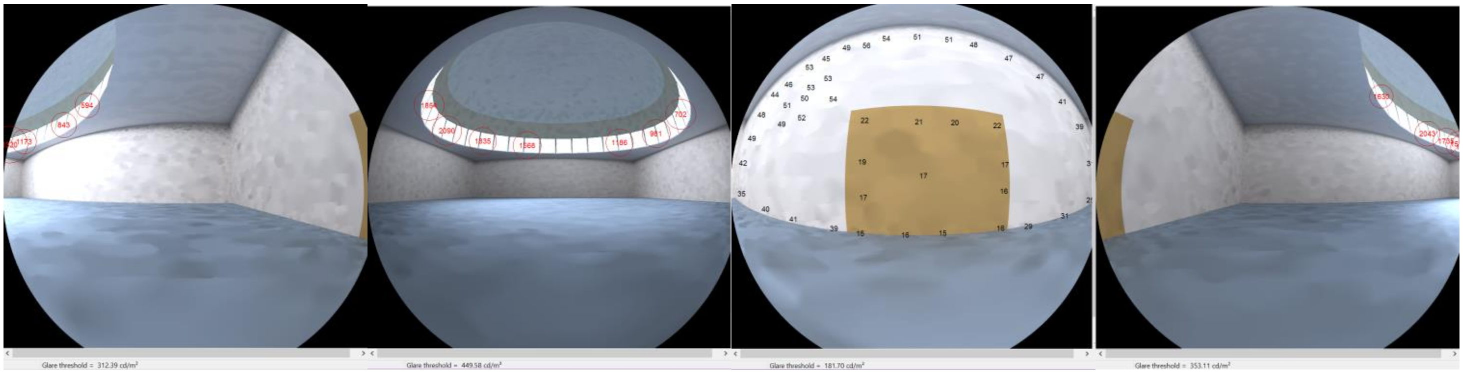
East **North** **South** **West**

Point B4:



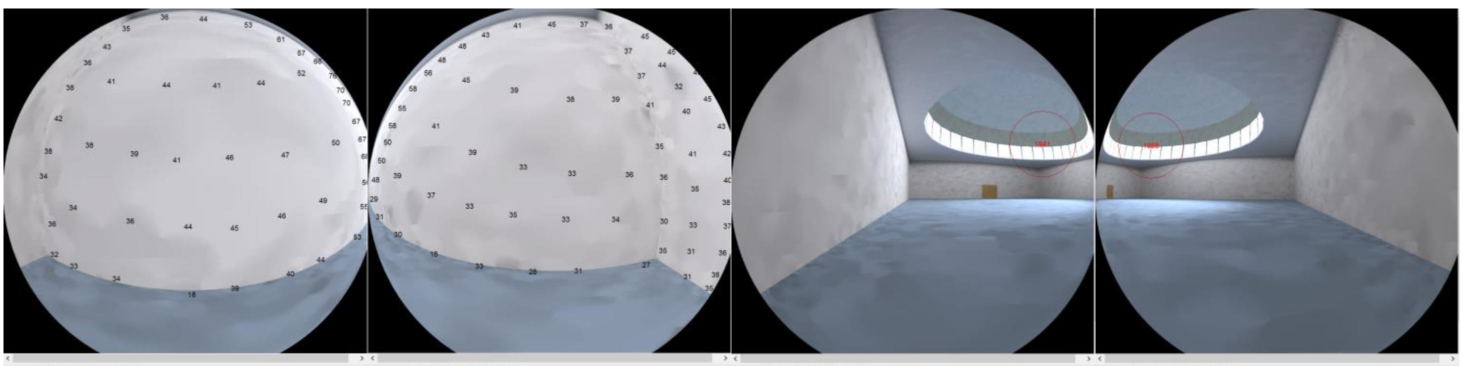
East **North** **South** **West**

Point B5:



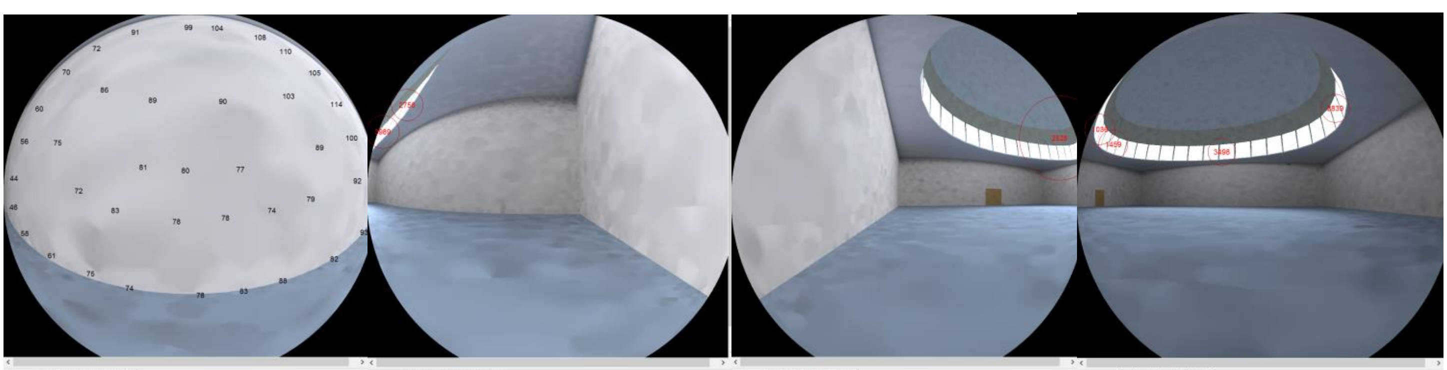
East **North** **South** **West**

Point C1:



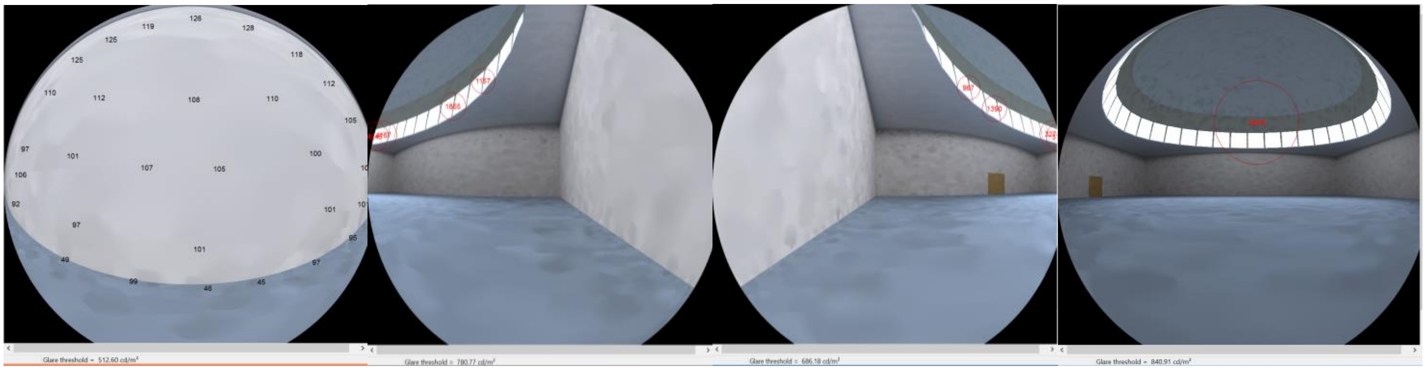
East **North** **South** **West**

Point C2:



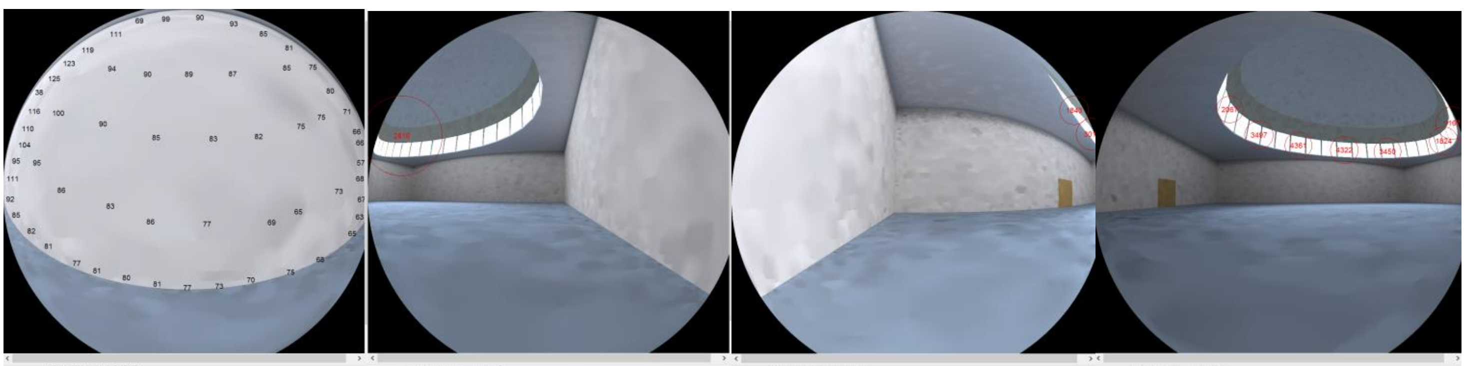
East **North** **South** **West**

Point C3:



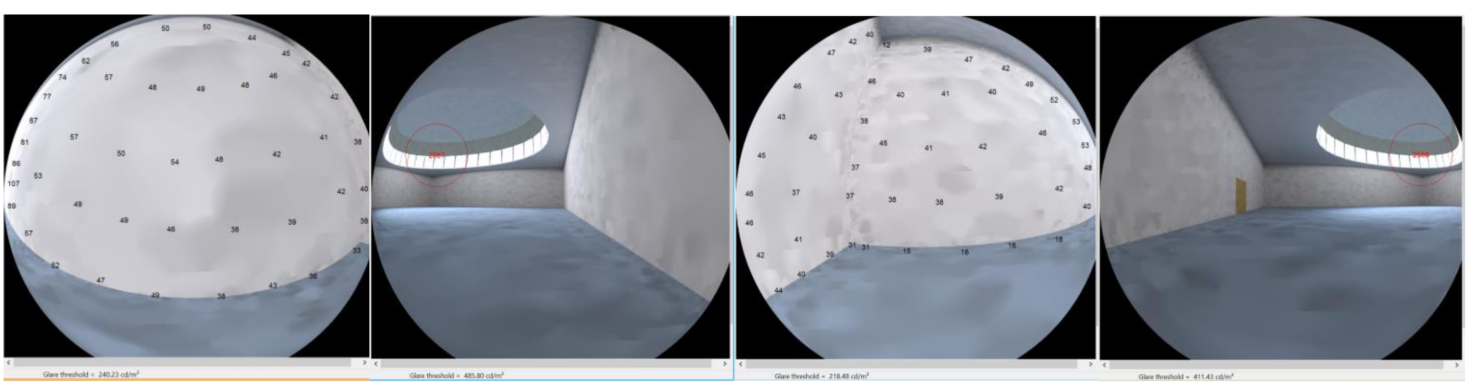
East **North** **South** **West**

Point C4:



East **North** **South** **West**

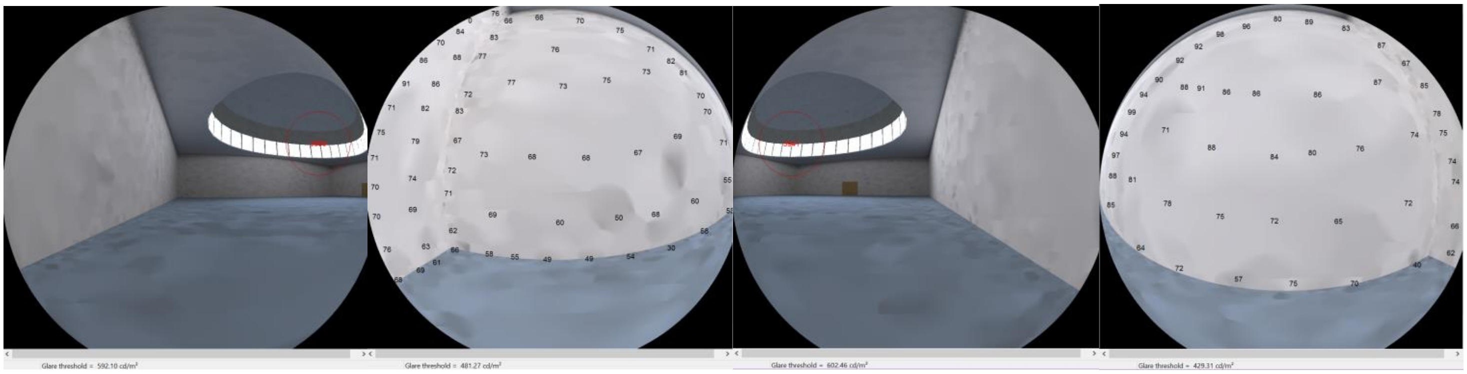
Point C5:



East **North** **South** **West**

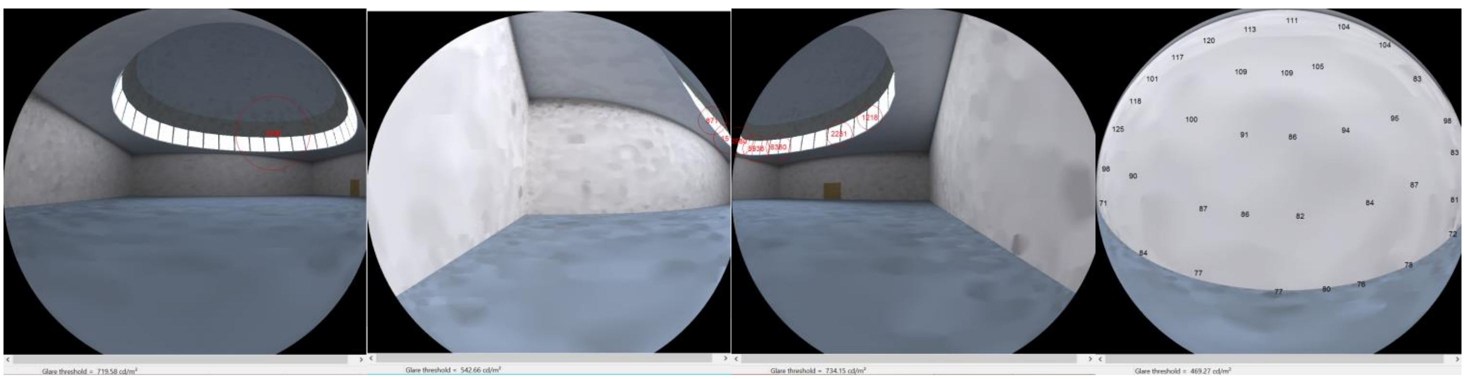
4. 21 Dec 8:00 am

Point A1:



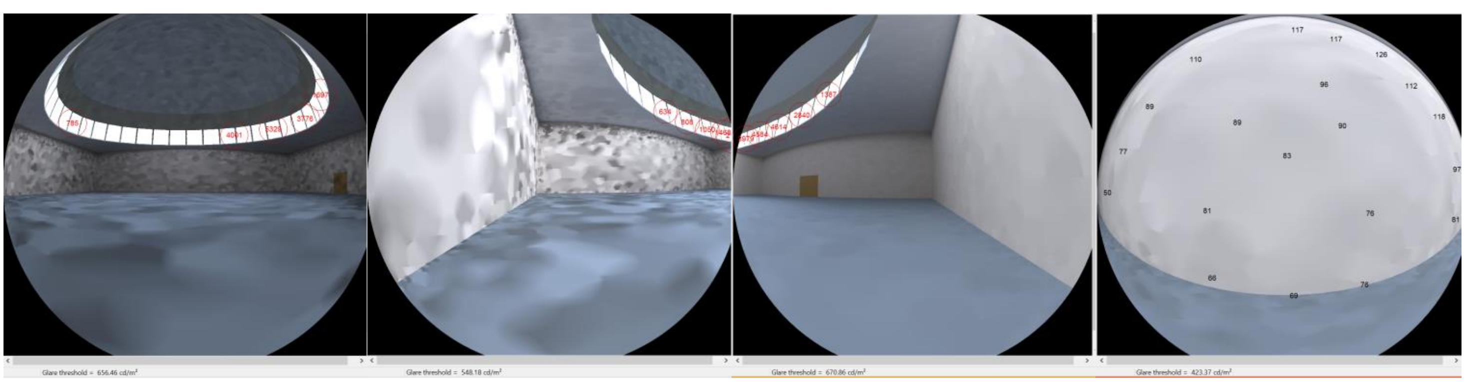
East **North** **South** **West**

Point A2:



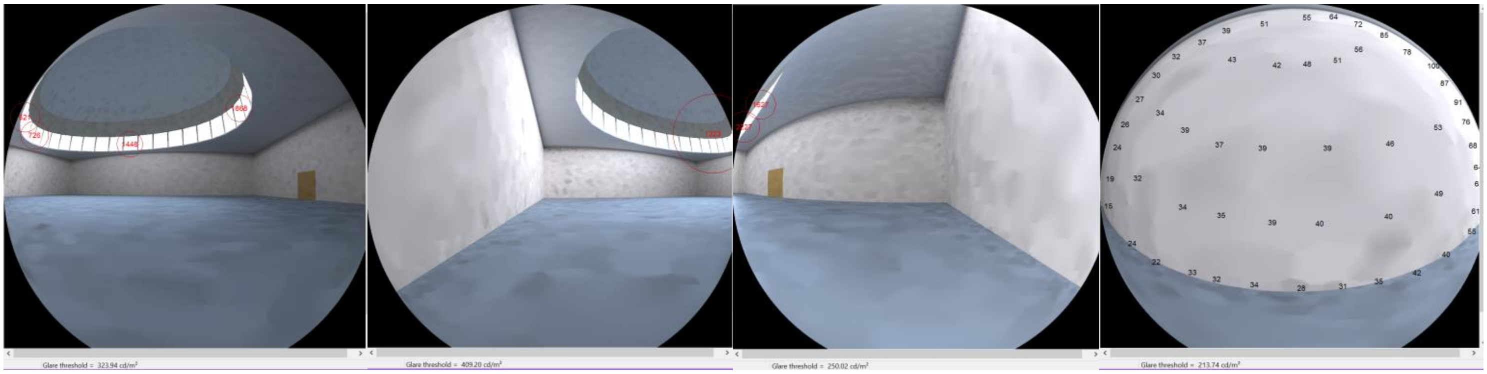
East **North** **South** **West**

Point A3:



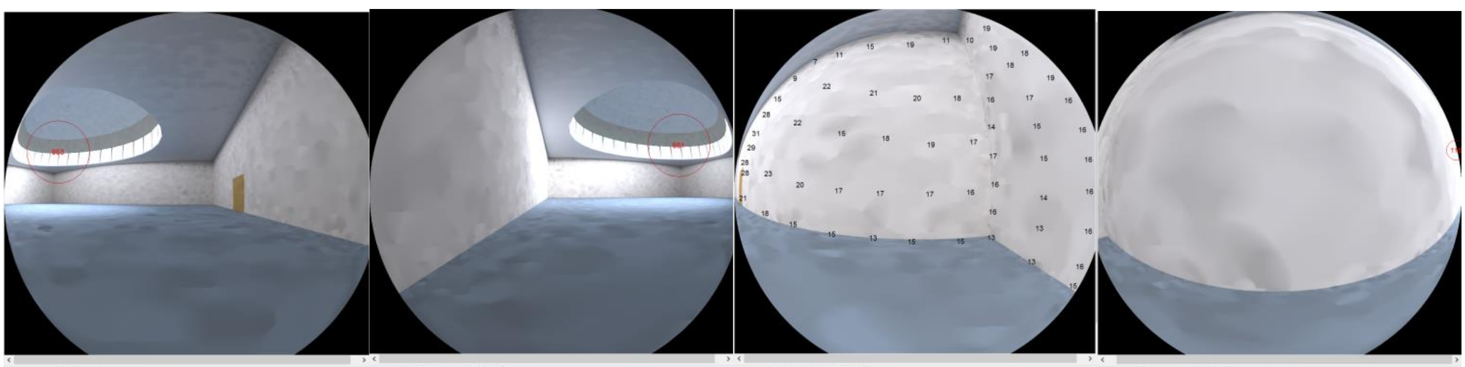
East **North** **South** **West**

Point A4:



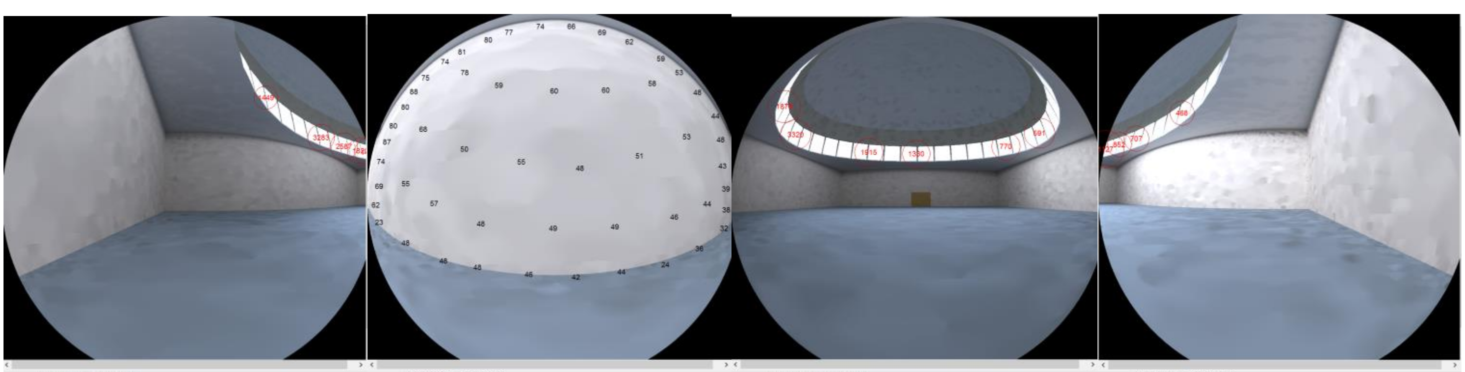
East **North** **South** **West**

Point A5:



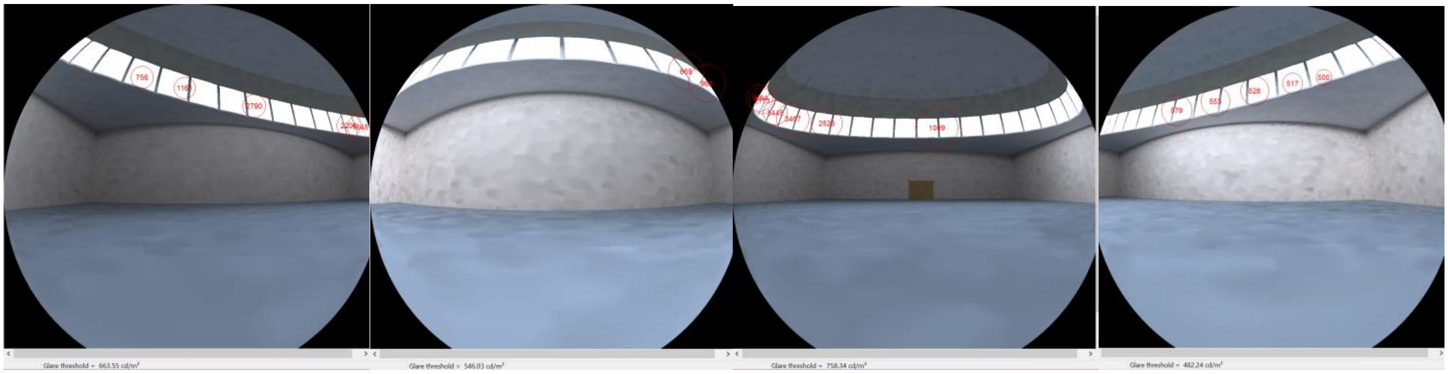
East **North** **South** **West**

Point B1:



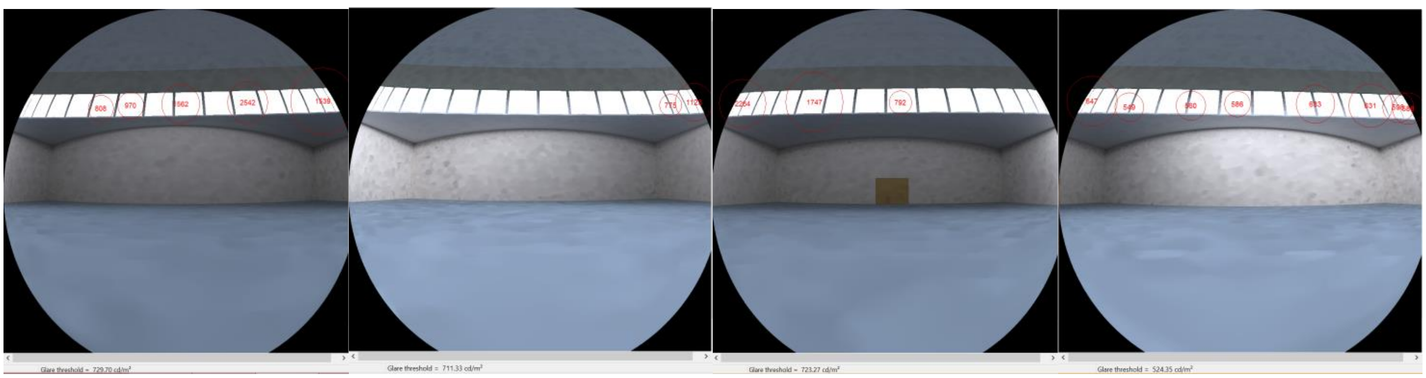
East **North** **South** **West**

Point B2:



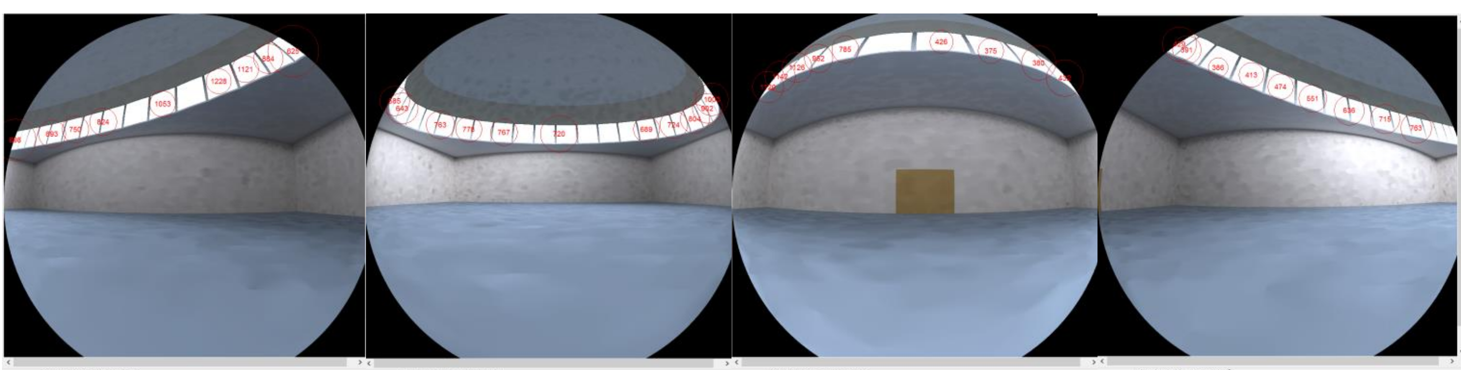
East **North** **South** **West**

Point B3:



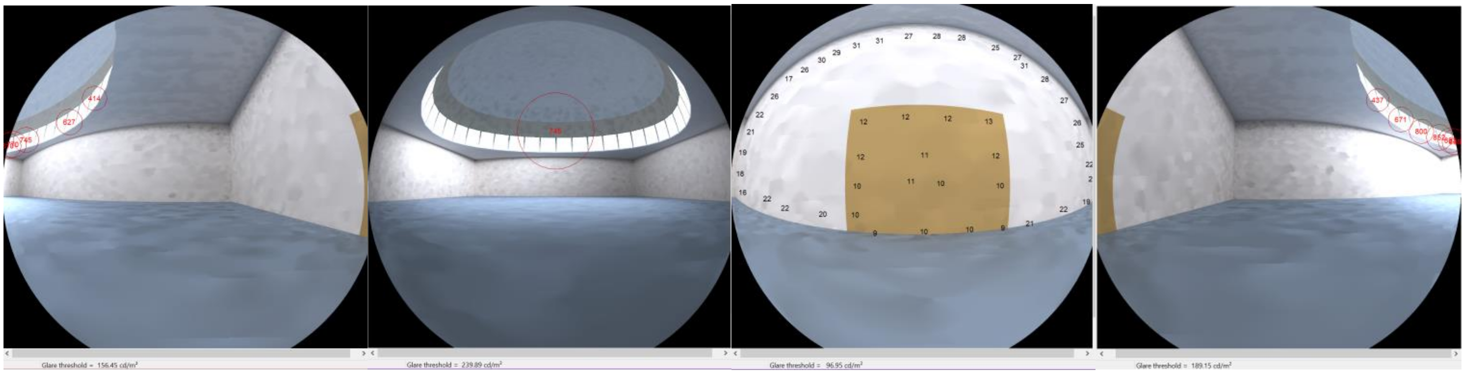
East **North** **South** **West**

Point B4:



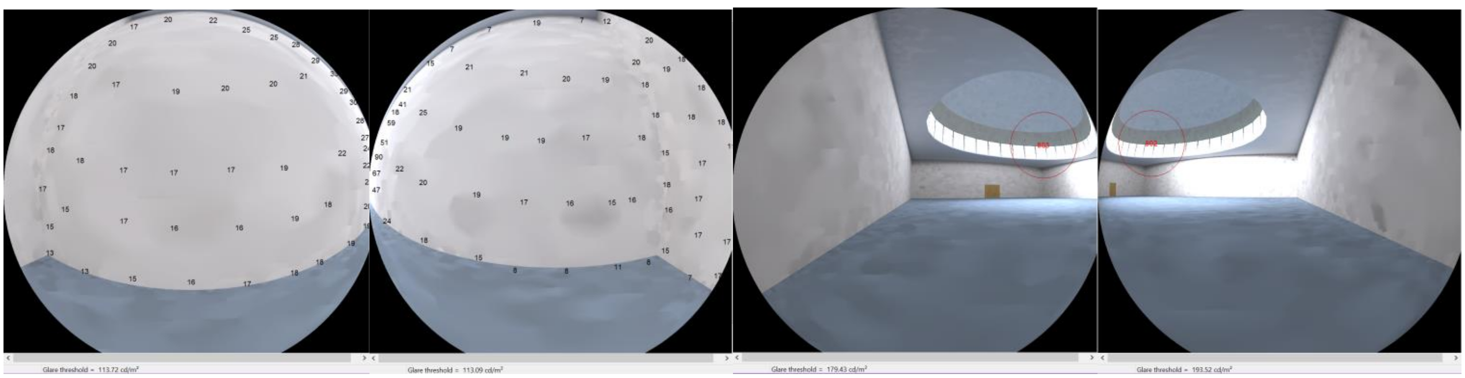
East **North** **South** **West**

Point B5:



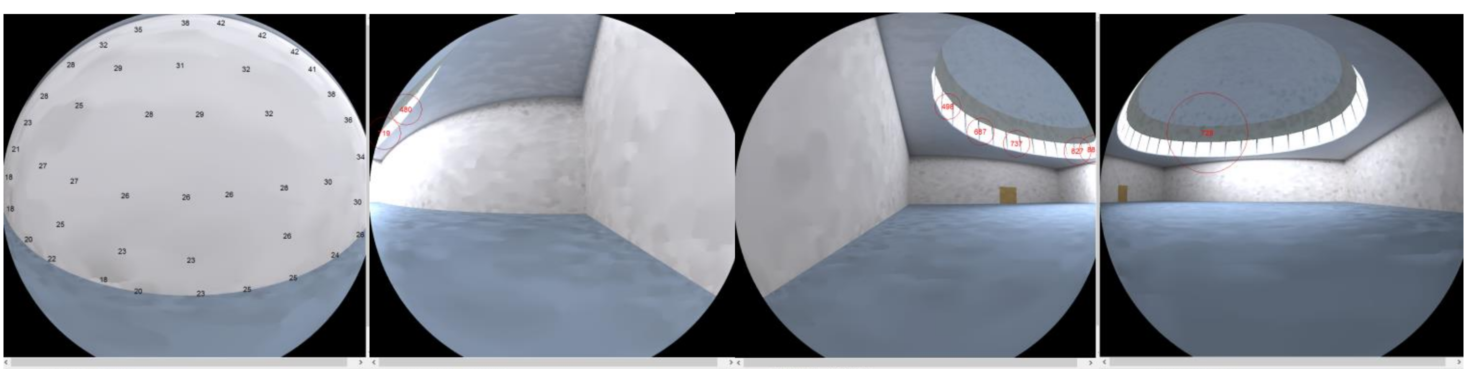
East **North** **South** **West**

Point C1:



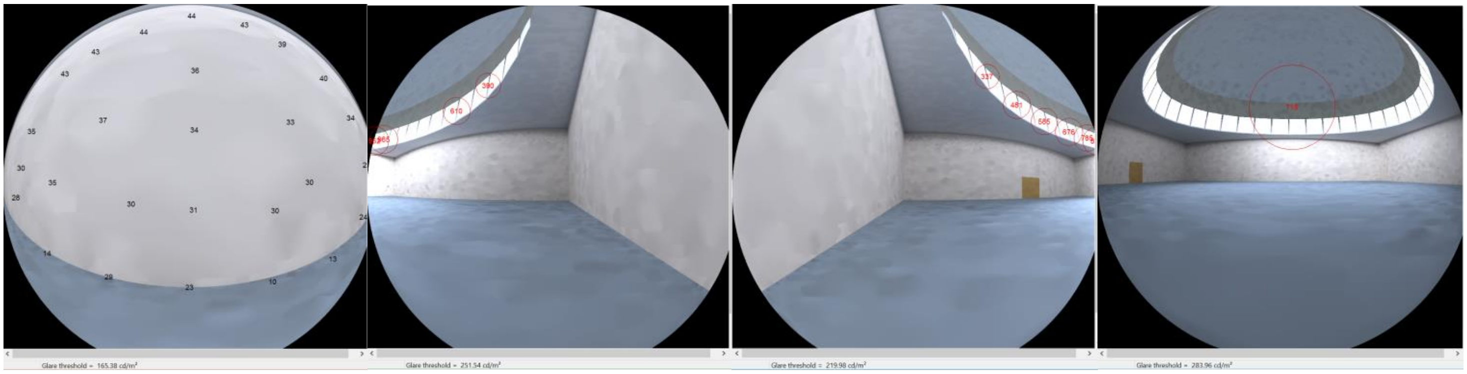
East **North** **South** **West**

Point C2:



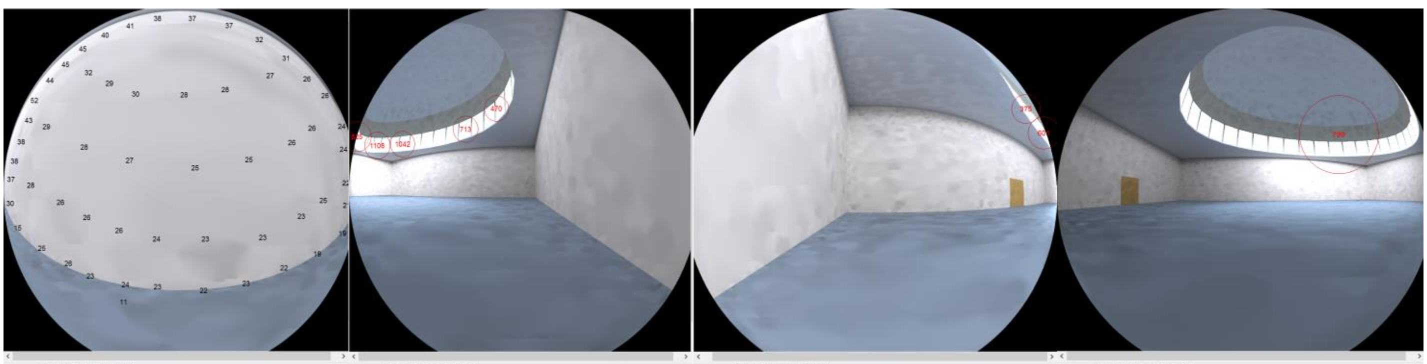
East **North** **South** **West**

Point C3:



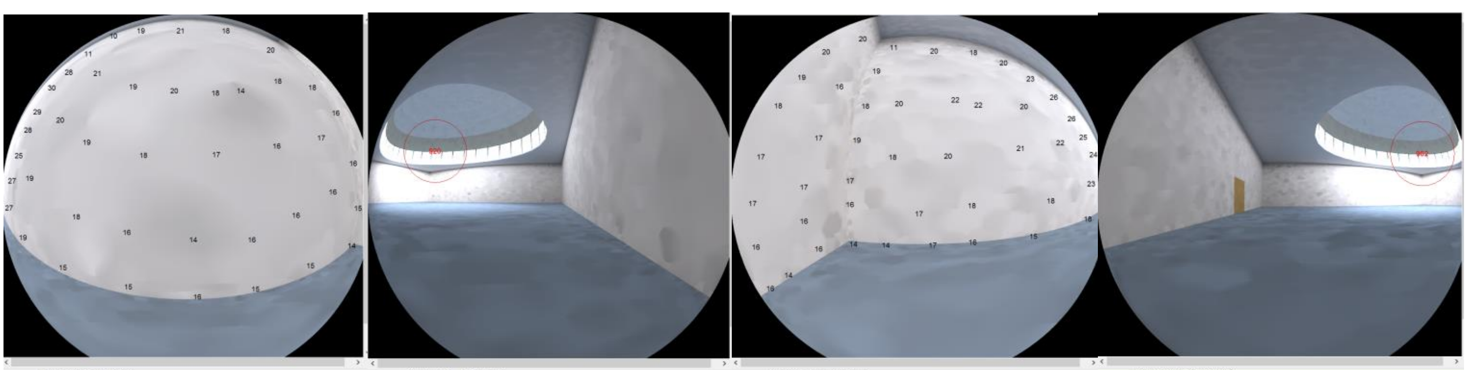
East **North** **South** **West**

Point C4:



East **North** **South** **West**

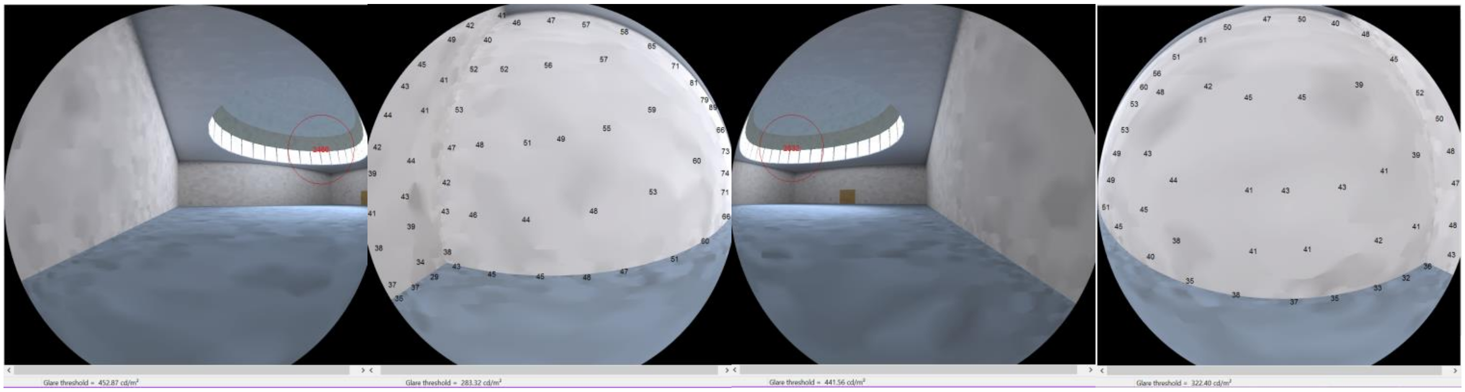
Point C5:



East **North** **South** **West**

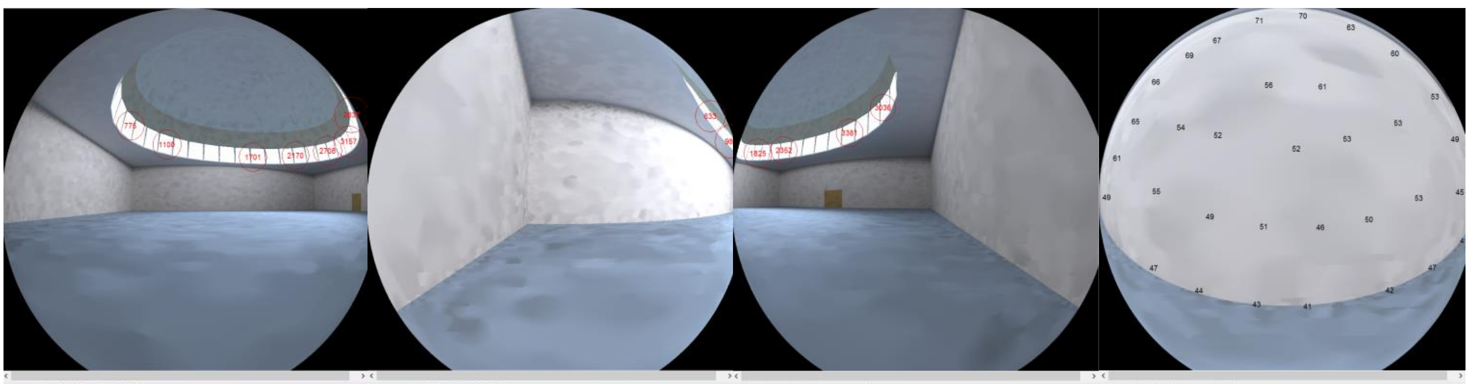
5. 21 Dec 12:00 pm

Point A1:



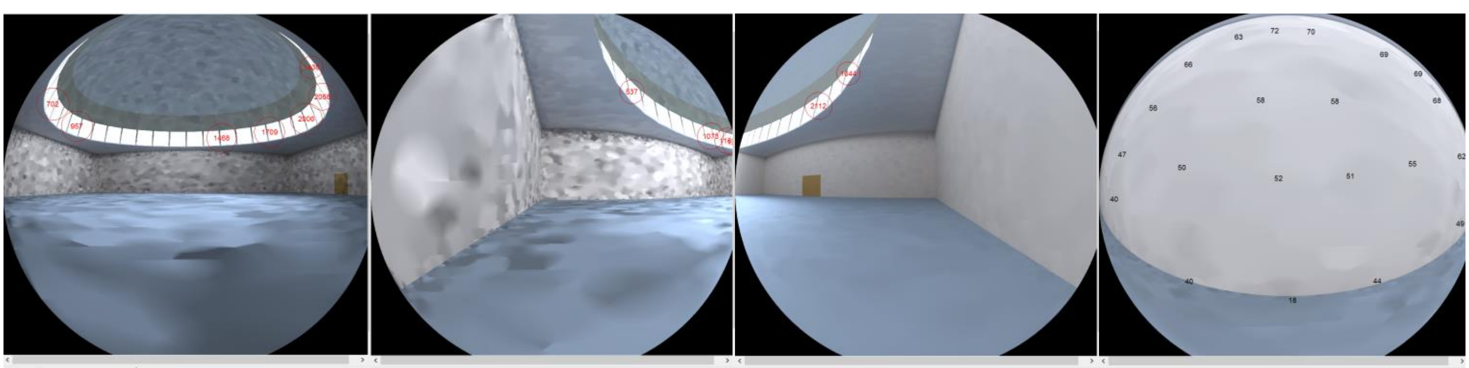
East **North** **South** **West**

Point A2:



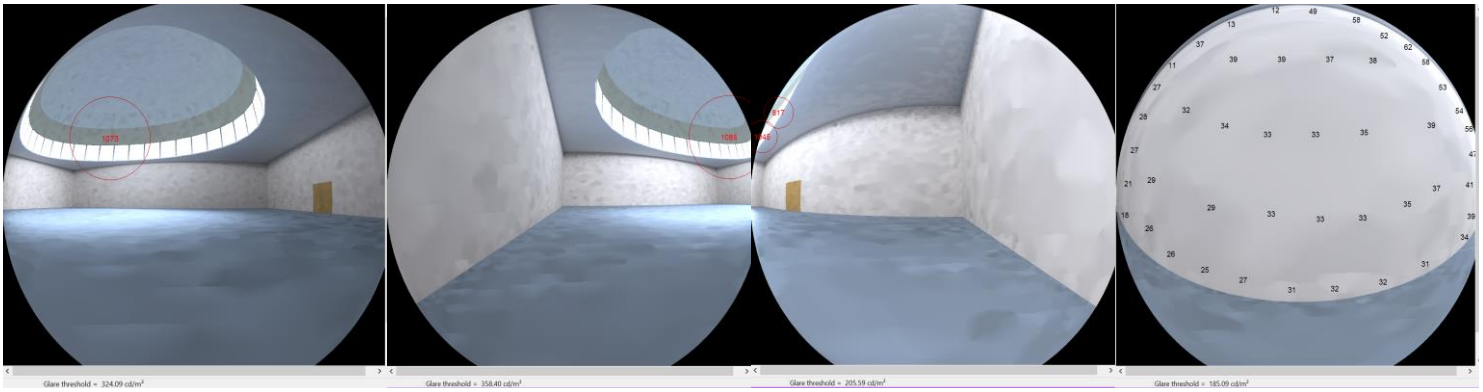
East **North** **South** **West**

Point A3:



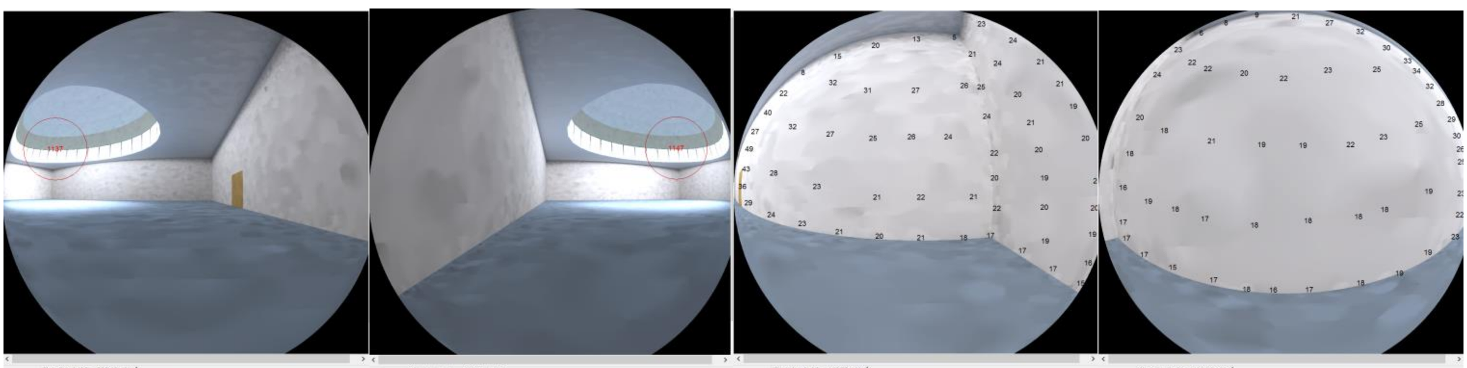
East **North** **South** **West**

Point A4:



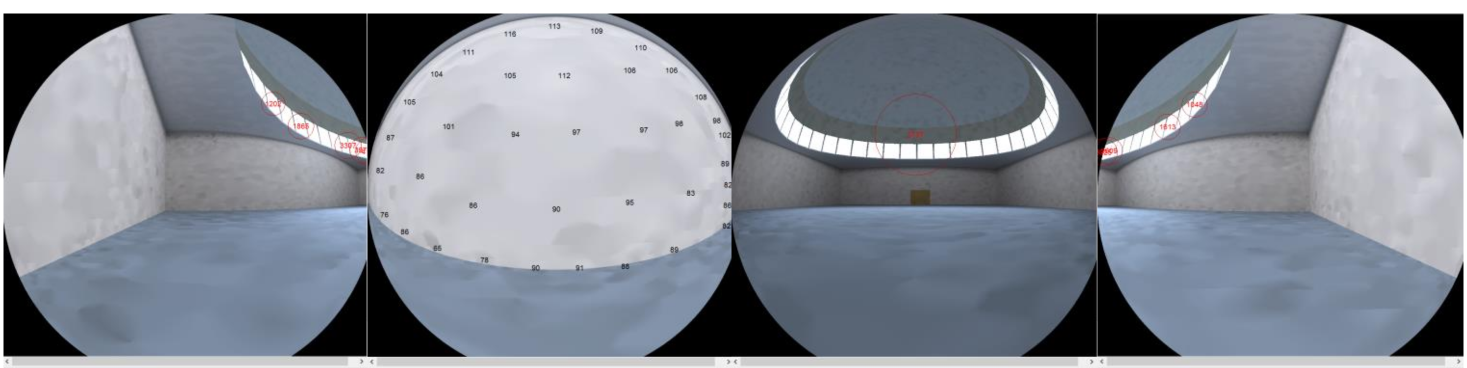
East **North** **South** **West**

Point A5:



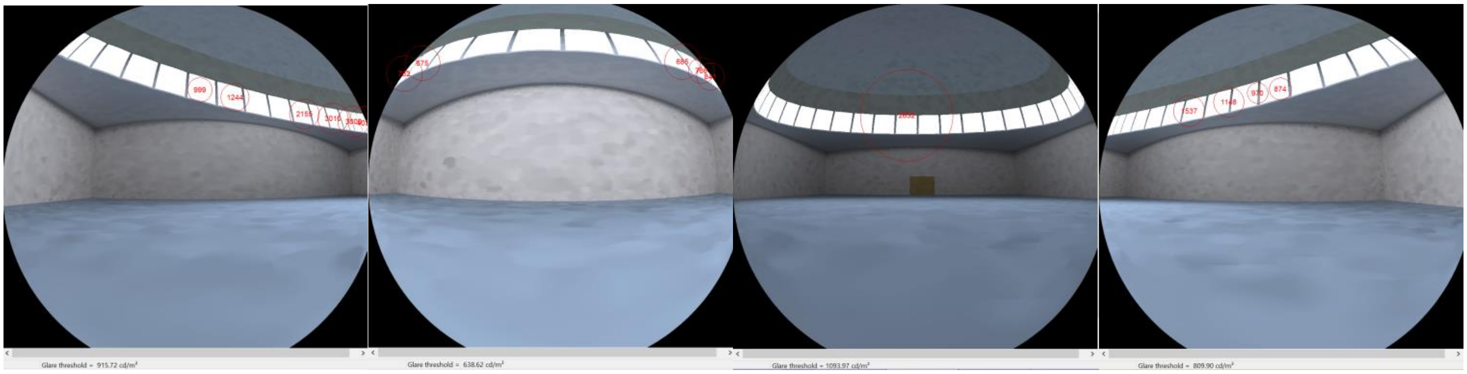
East **North** **South** **West**

Point B1:



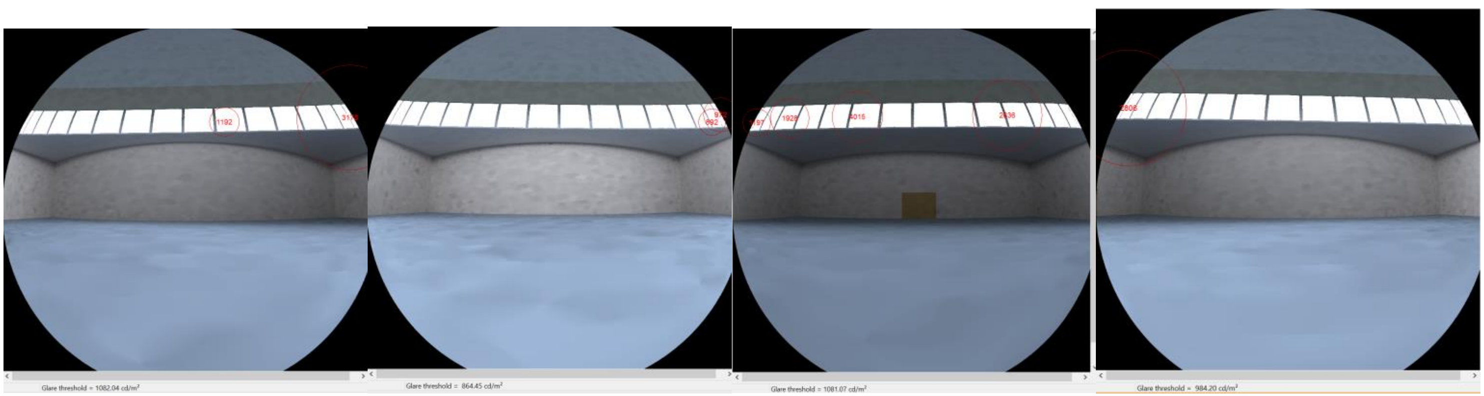
East **North** **South** **West**

Point B2:



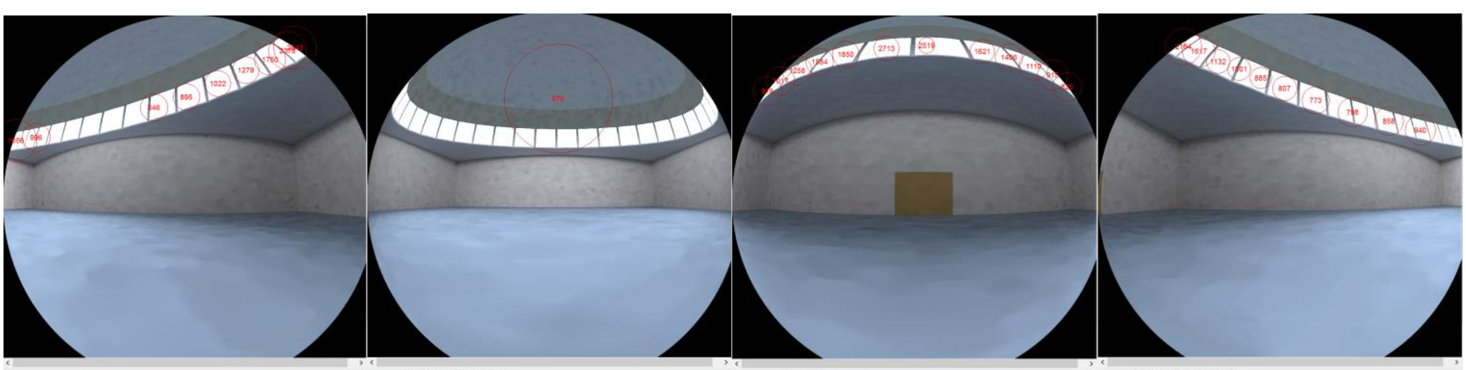
East **North** **South** **West**

Point B3:



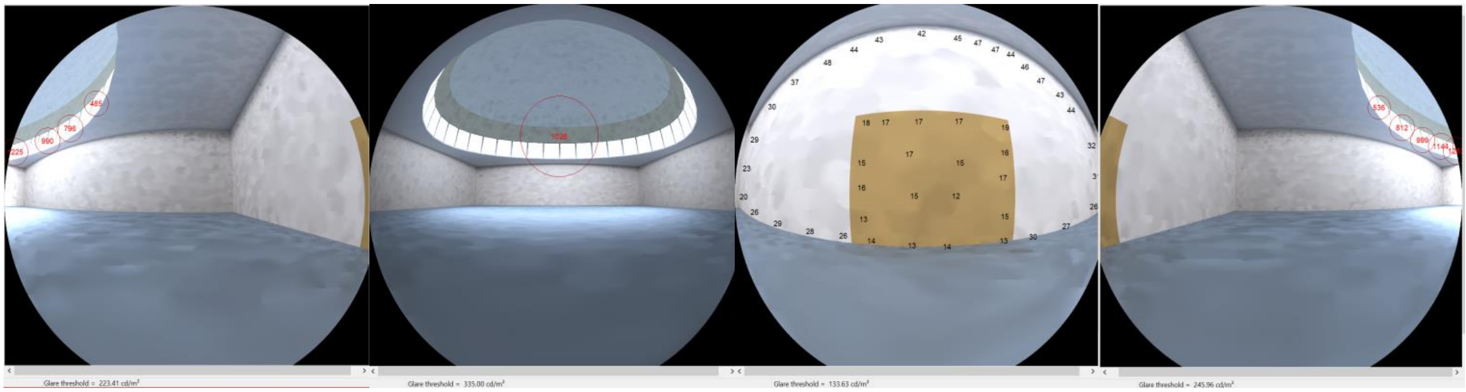
East **North** **South** **West**

Point B4:



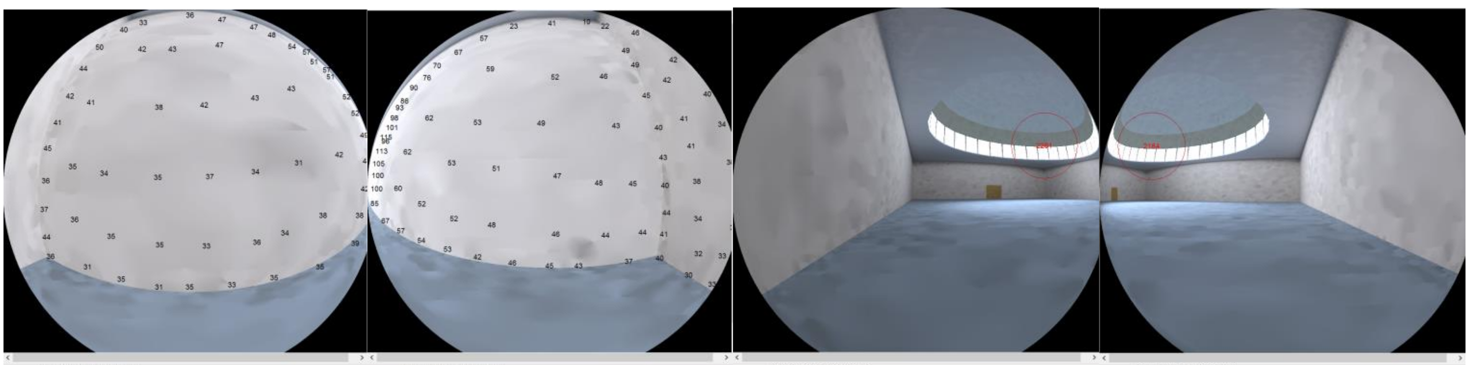
East **North** **South** **West**

Point B5:



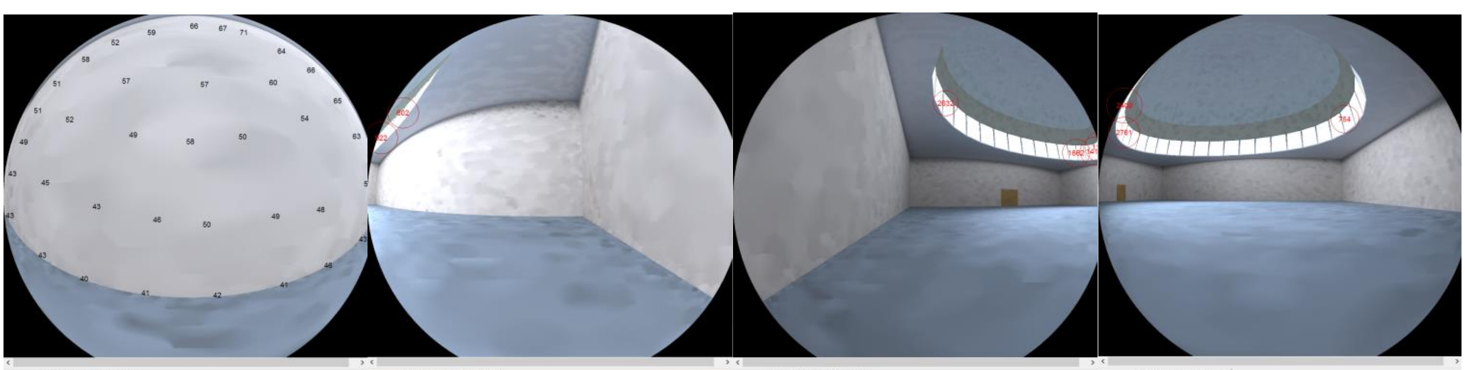
East **North** **South** **West**

Point C1:



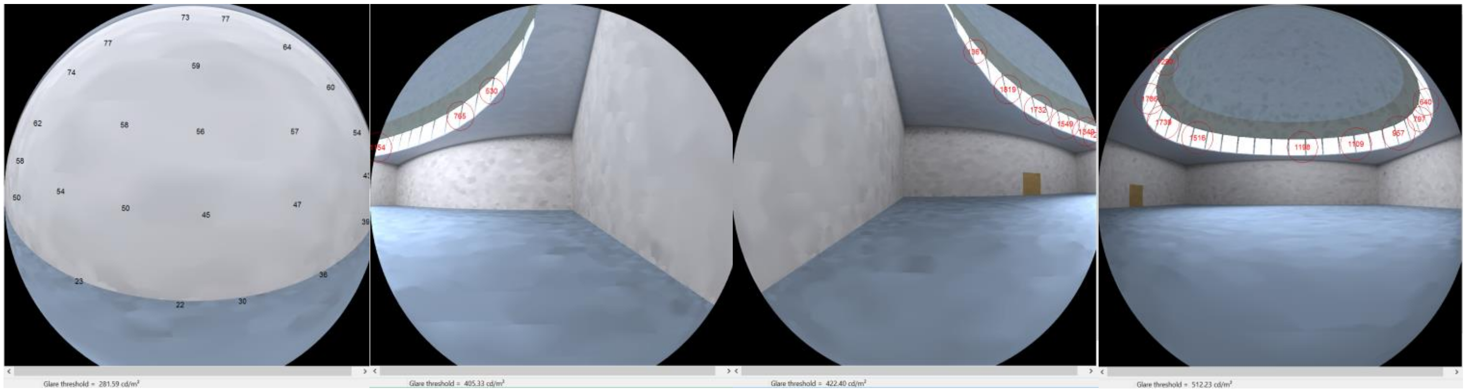
East **North** **South** **West**

Point C2:



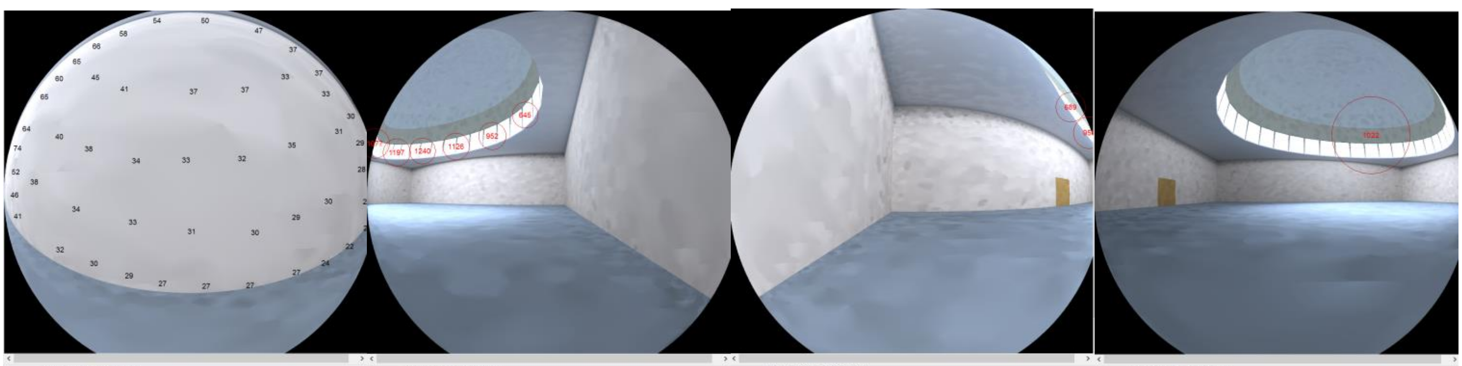
East **North** **South** **West**

Point C3:



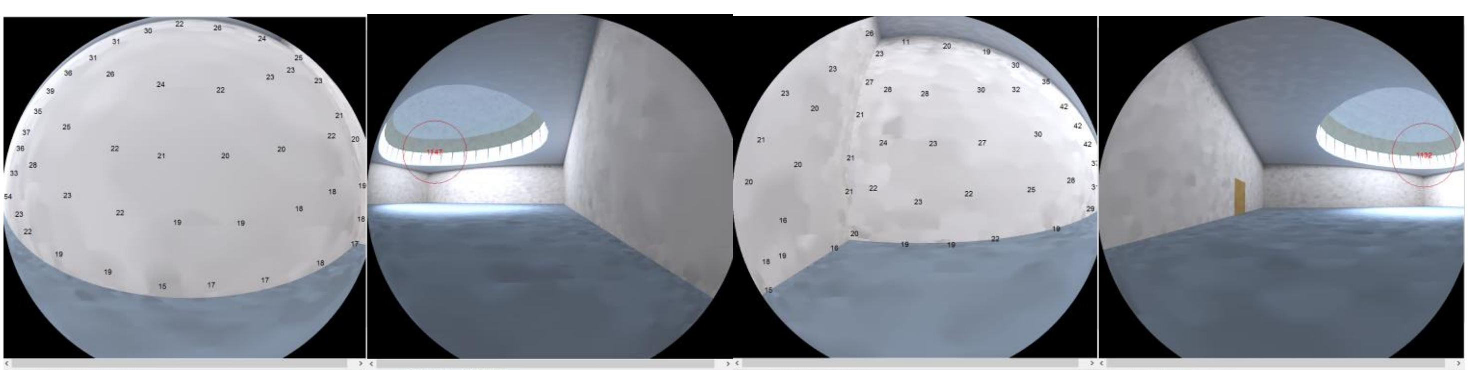
East **North** **South** **West**

Point C4:



East **North** **South** **West**

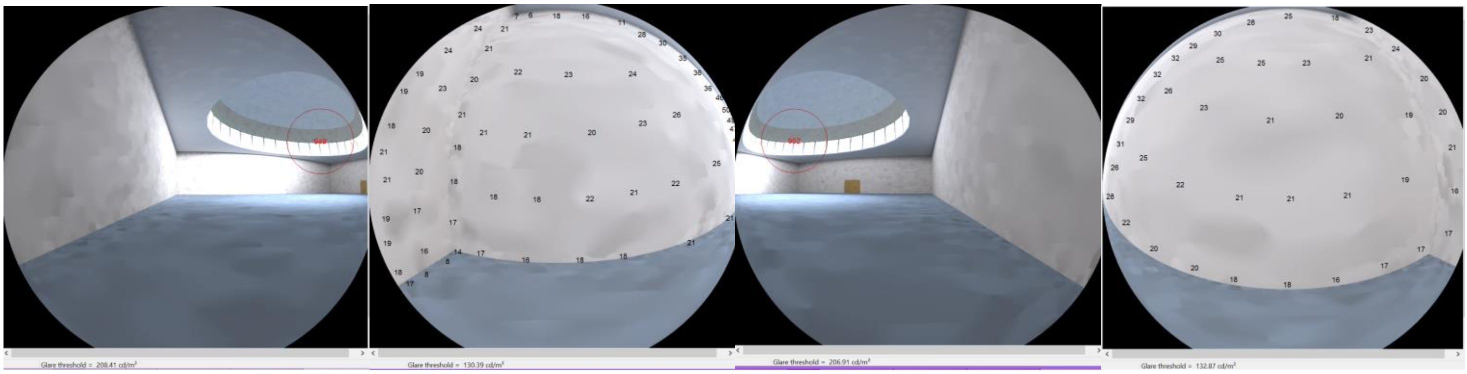
Point C5:



East **North** **South** **West**

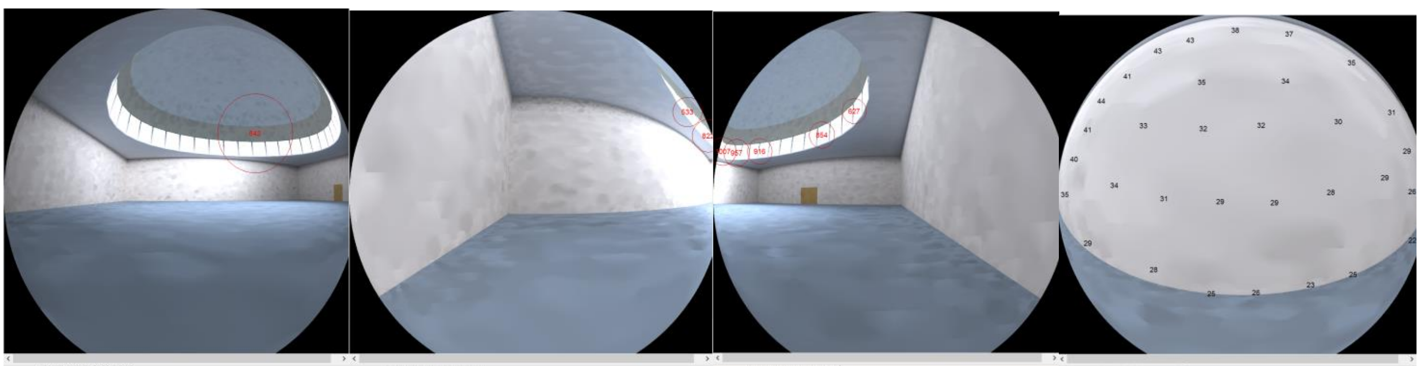
6. 21 Dec 4:00 pm

Point A1:



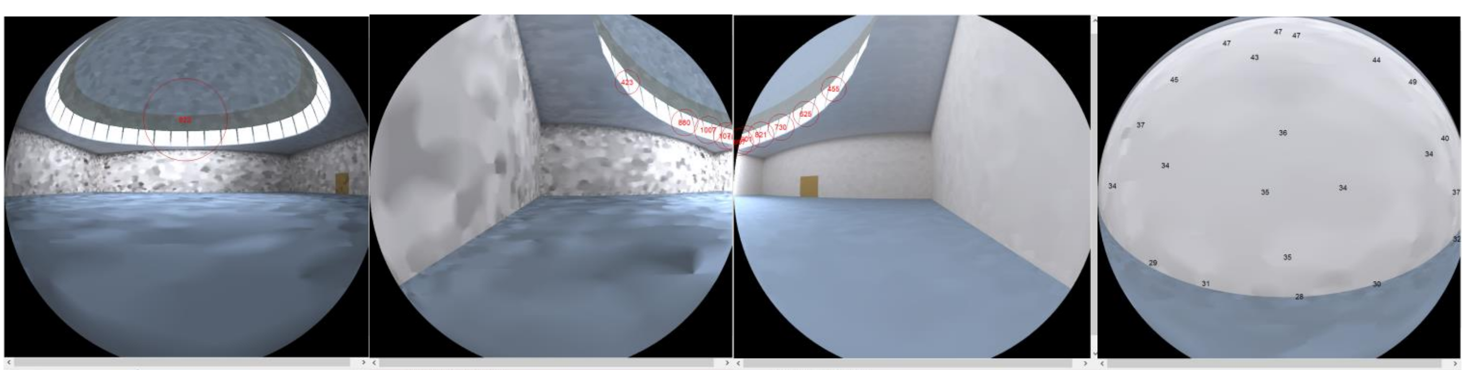
East **North** **South** **West**

Point A2:



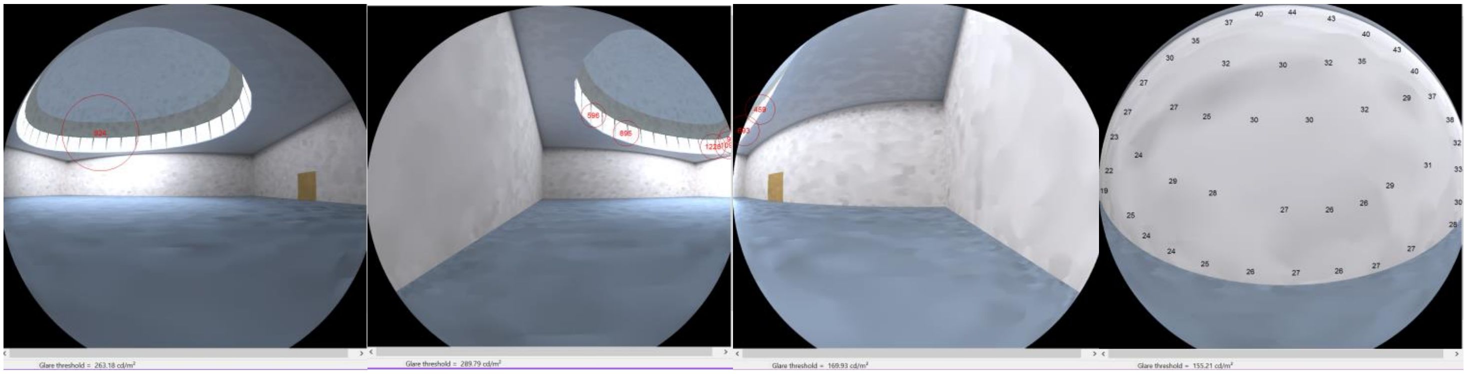
East **North** **South** **West**

Point A3:



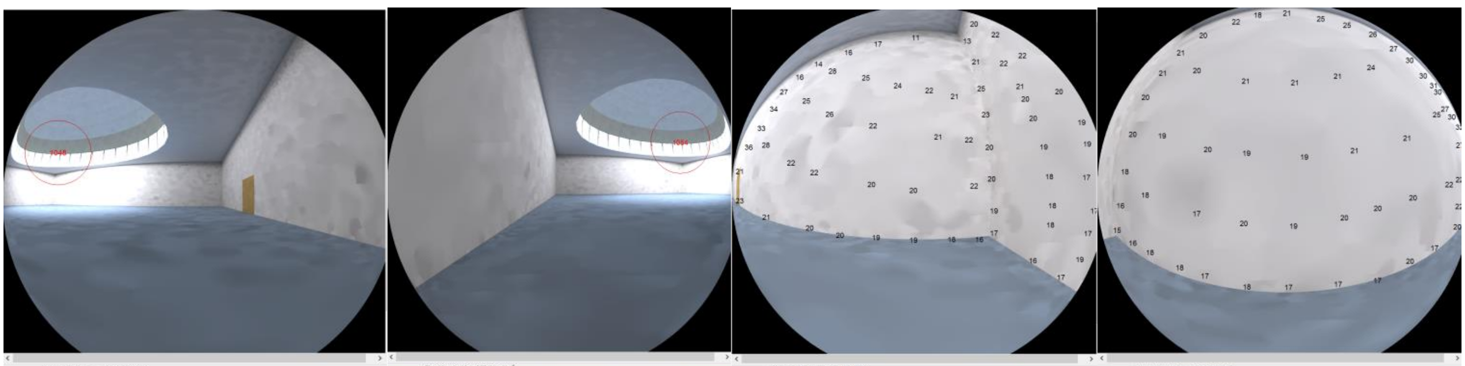
East **North** **South** **West**

Point A4:



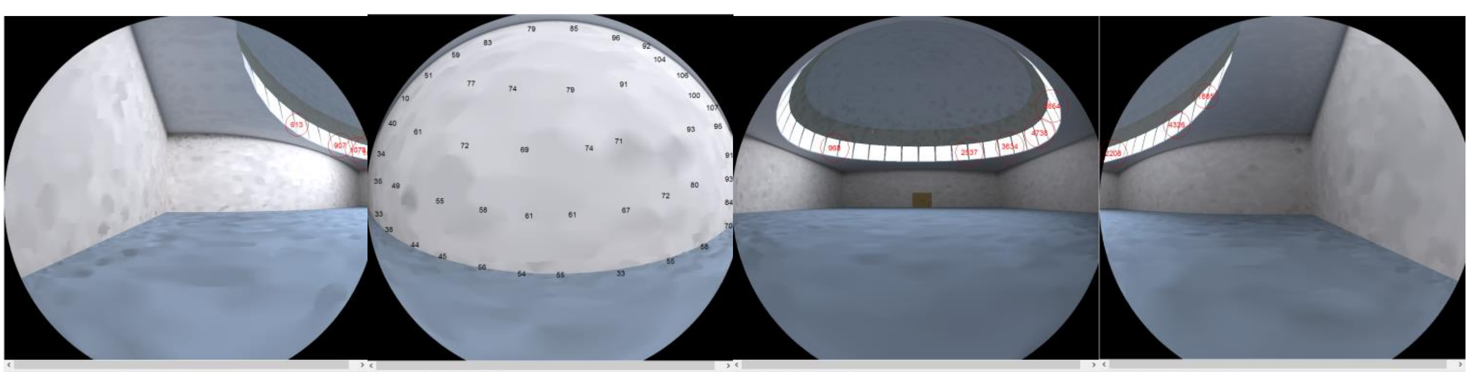
East North South West

Point A5:



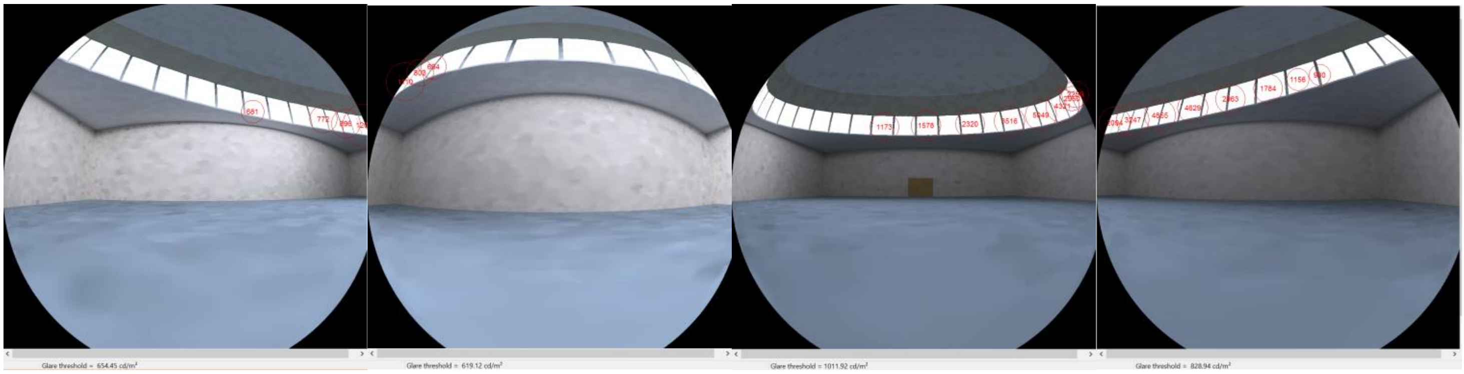
East North South West

Point B1:



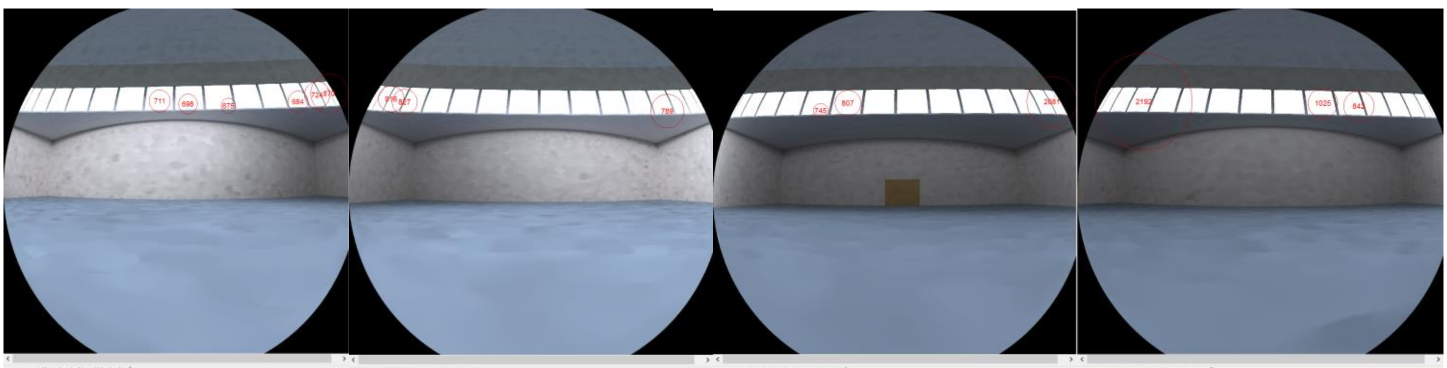
East North South West

Point B2:



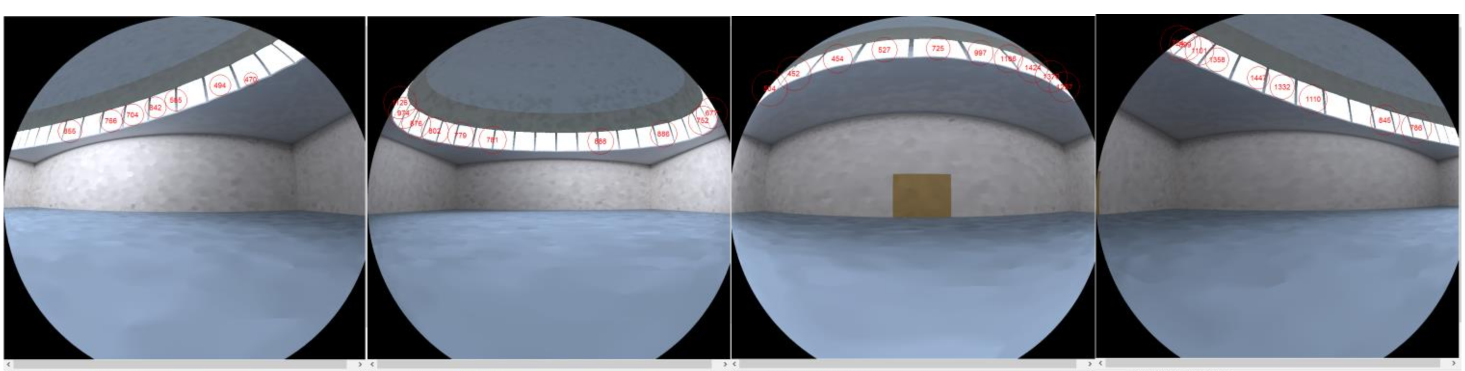
East North South West

Point B3:



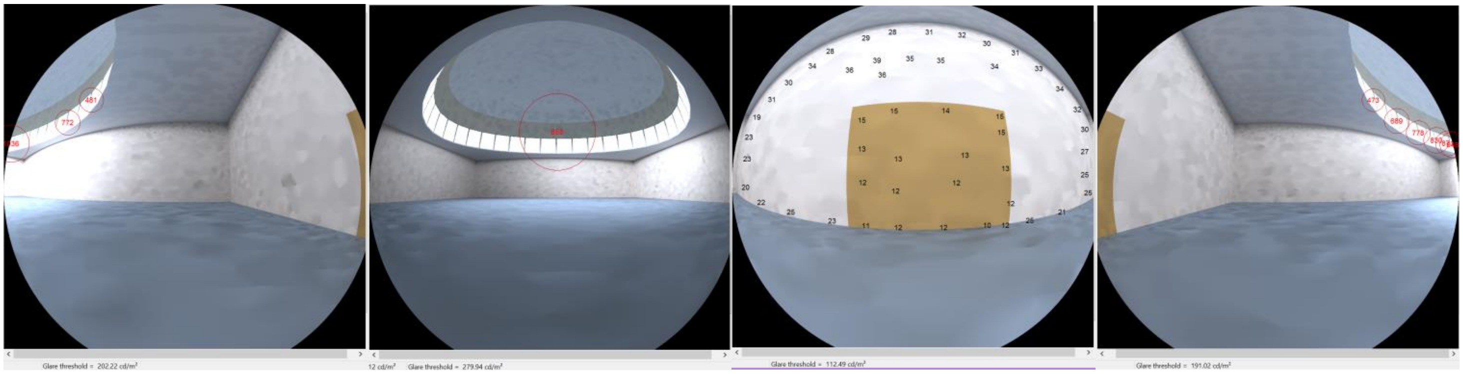
East North South West

Point B4:



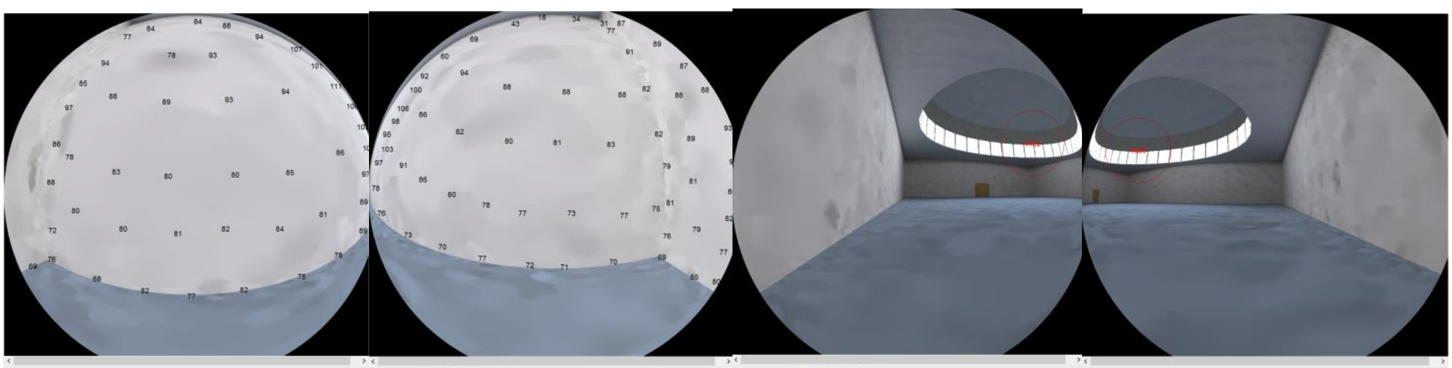
East North South West

Point B5:



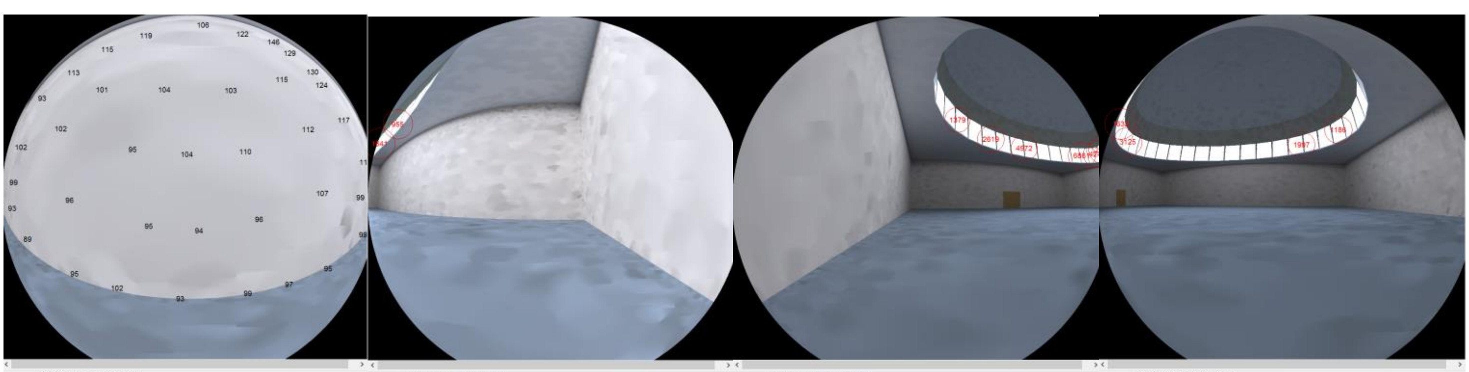
East North South West

Point C1:



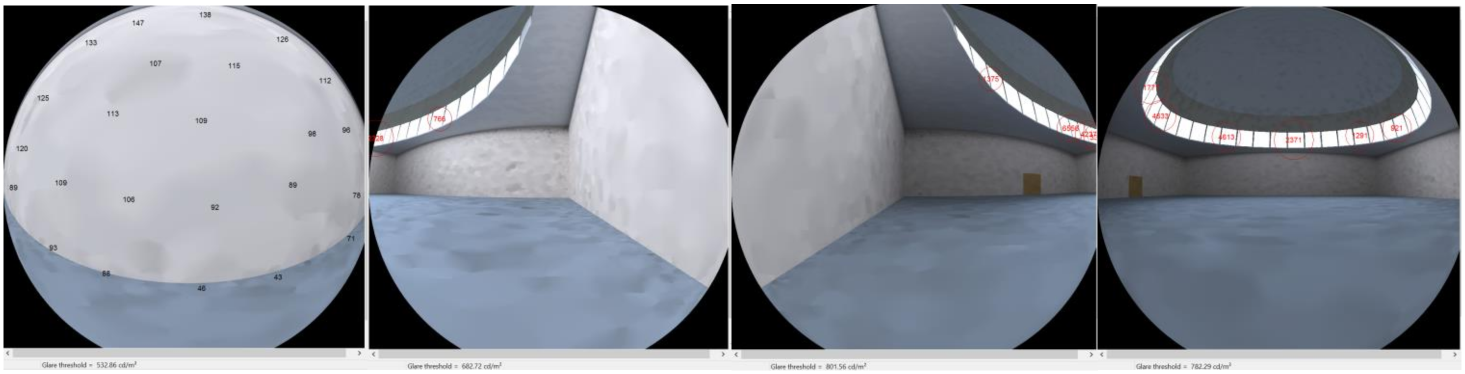
East North South West

Point C2:



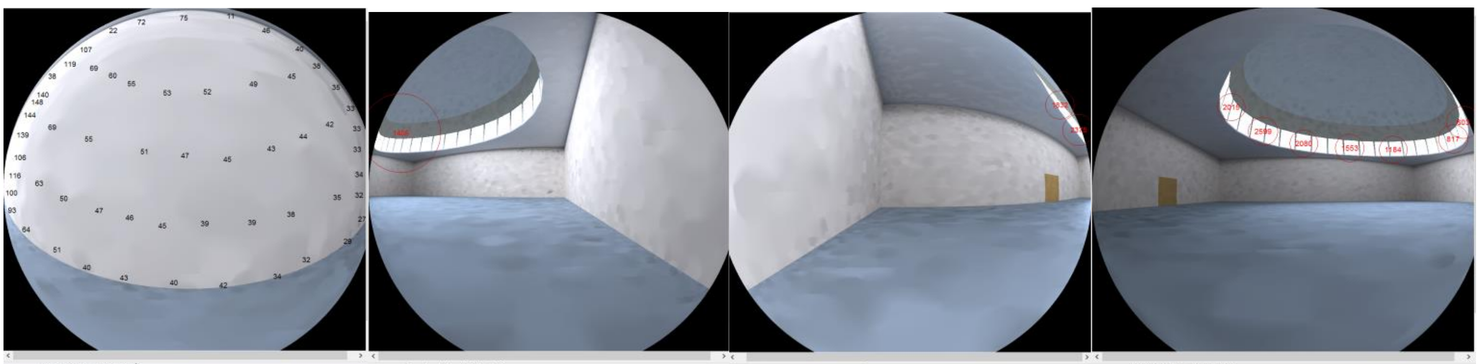
East North South West

Point C3:



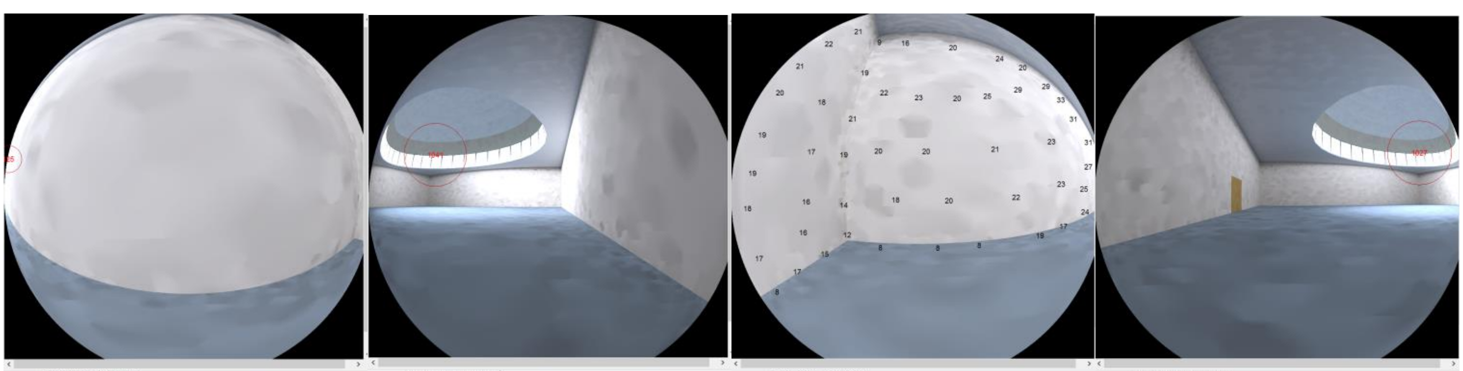
East **North** **South** **West**

Point C4:



East **North** **South** **West**

Point C5:



East **North** **South** **West**

Appendix D - Annual Variables Results (SDA and ASE)

Table 53: SDA and ASE results for (D=7 , H=2, S=10,15,25,100)

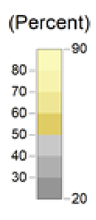
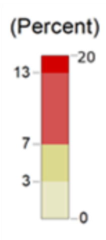
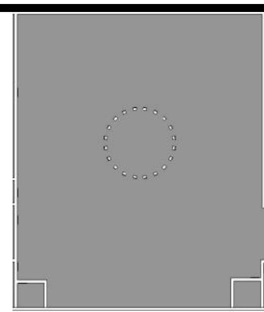
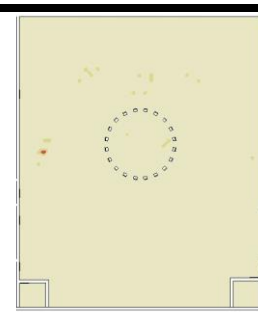
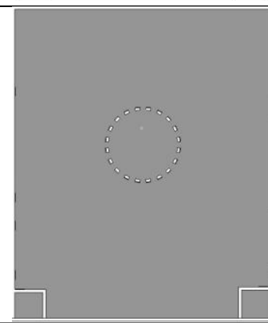
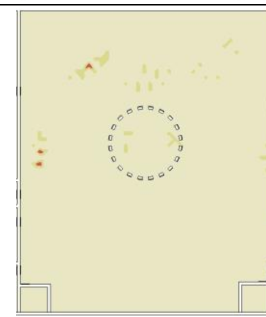
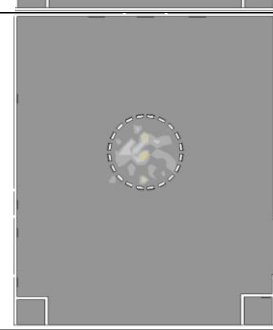
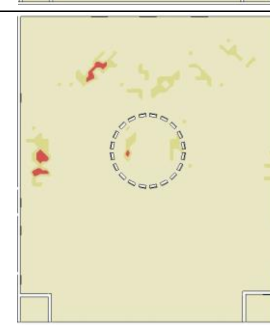
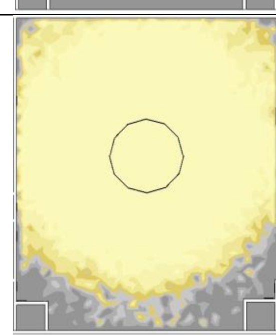
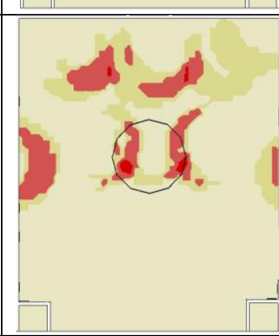
Date and Time: Annual				
Dome Diameter	Height of Drum	S windows in drum (W area/ D area)	SDA	ASE
7.0  	2.0 m (sill height = 0.3 m)	10%		
		15%		
		25%		
		100%		

Table 54: SDA and ASE results for (D=7 , H=3, S=10,15,25,100)

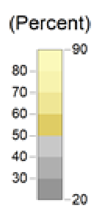
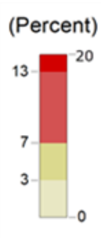
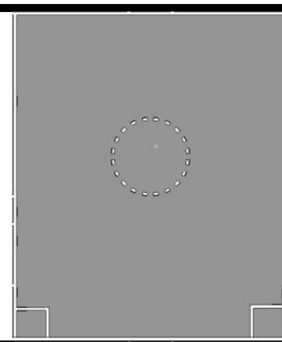
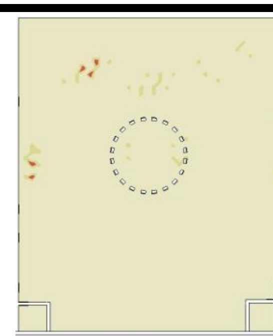
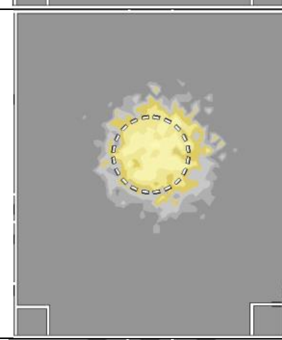
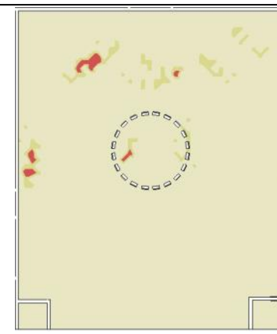
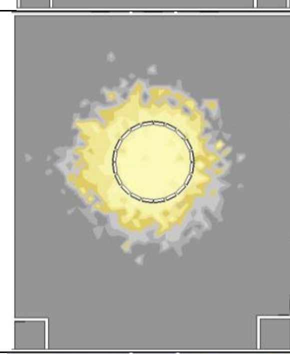
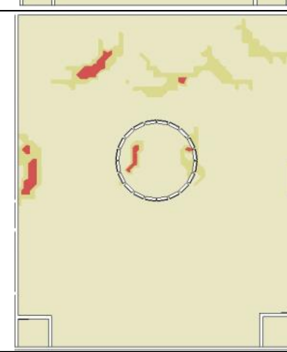
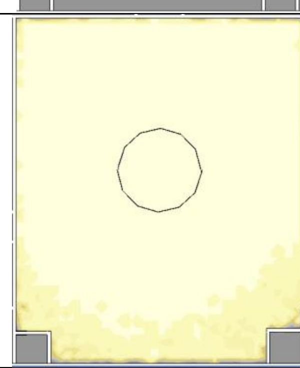
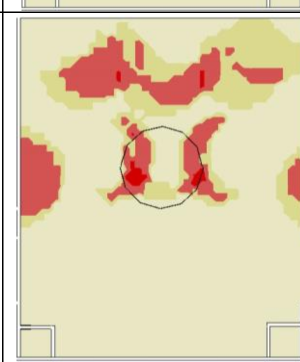
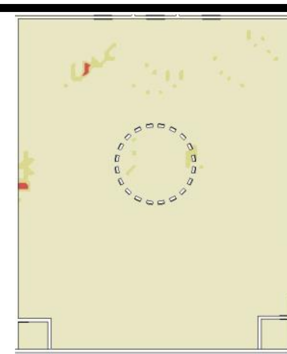
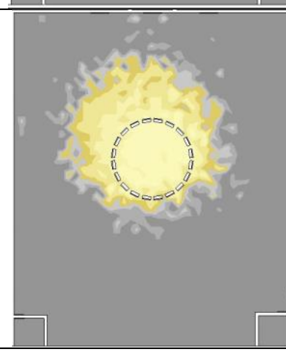
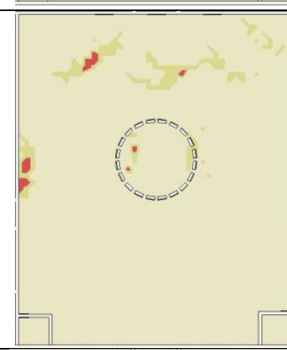
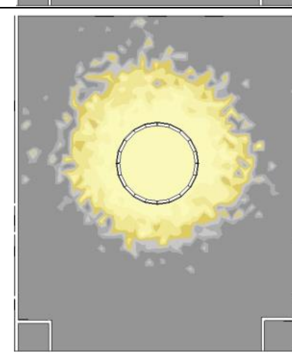
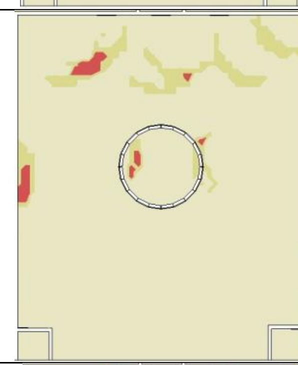
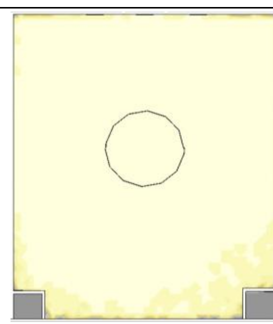
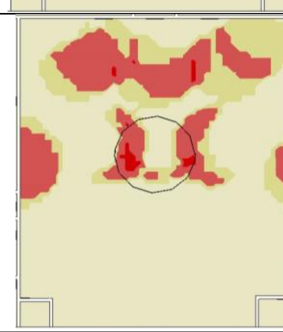
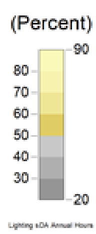
Date and Time: Annual				
Diameter	Height of Drum	S windows (W area/ D area)	SDA	ASE
7.0  	3.0 m (sill height = 0.8 m)	10%		
		15%		
		25%		
		100%		

Table 55: SDA and ASE results for (D=7 , H=4, S=10,15,25,100)

Date and Time: Annual				
Diameter	Height of Drum	S windows (W area/ D area)	SDA	ASE
7.0	4.0 m (sill height = 1.3 m)	10%		
		15%		
		25%		
		100%		



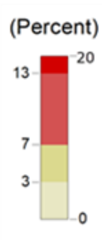


Table 56: SDA and ASE results for (D=14 , H=2, S=10,15,25,100)

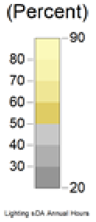
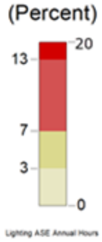
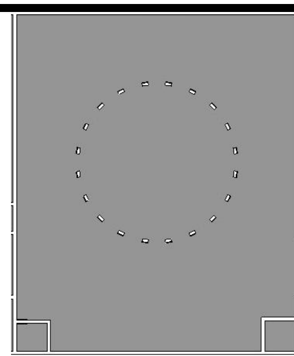
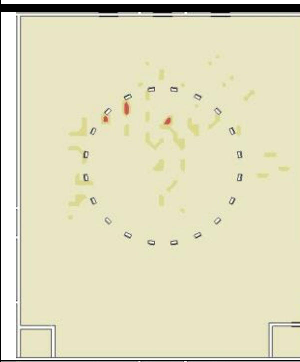
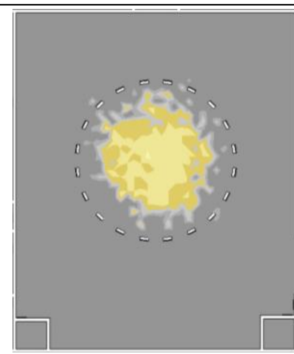
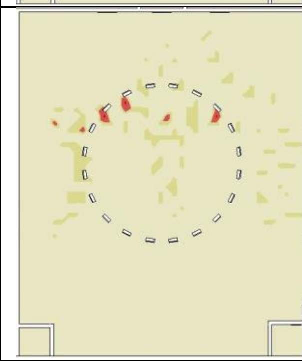
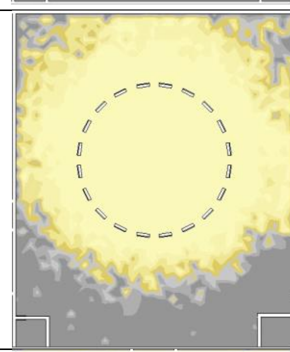
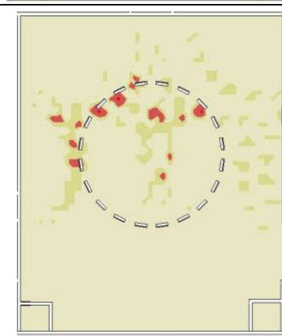
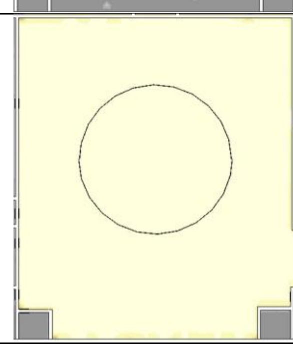
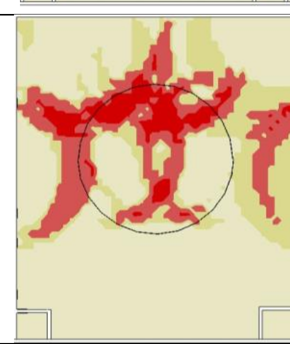
Date and Time: Annual				
Diameter	Height of Drum	S windows (W area/ D area)	SDA	ASE
14.0 (Percent)  (Percent) 	2.0 m (sill height = 0.3 m)	10%		
		15%		
		25%		
		100%		

Table 57: SDA and ASE results for (D=14 , H=3, S=10,15,25,100)

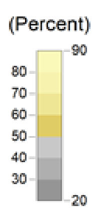
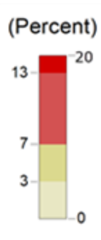
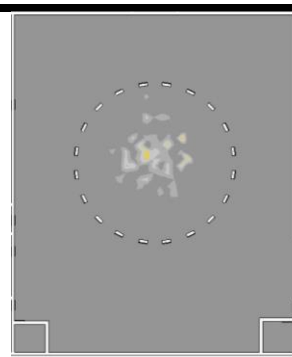
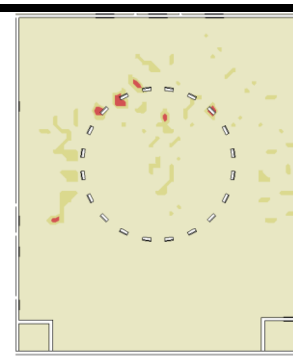
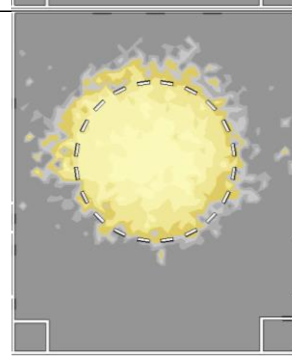
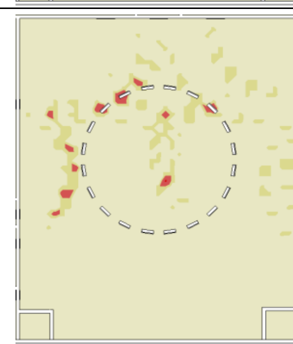
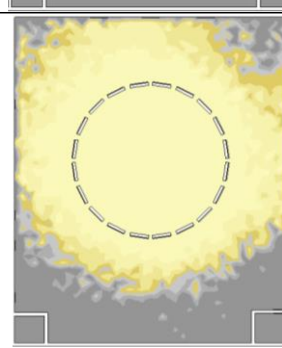
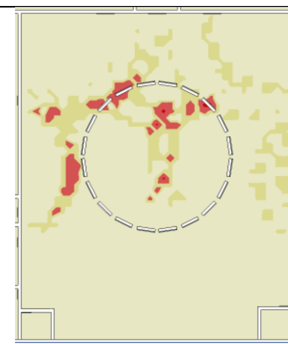
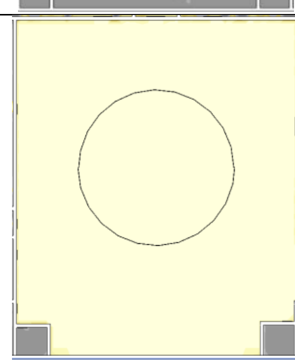
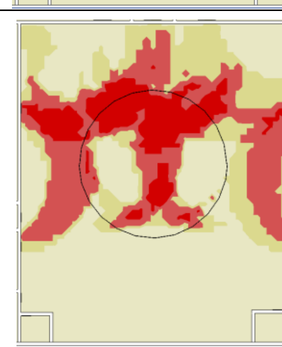
Date and Time: Annual				
Diameter	Height of Drum	S windows (W area/ D area)	SDA	ASE
14.0  	3.0 m (sill height = 0.8 m)	10%		
		15%		
		25%		
		100%		

Table 58: SDA and ASE results for (D=14 , H=4, S=10,15,25,100)

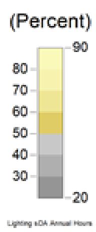
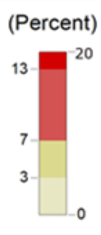
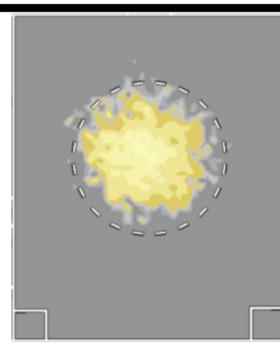
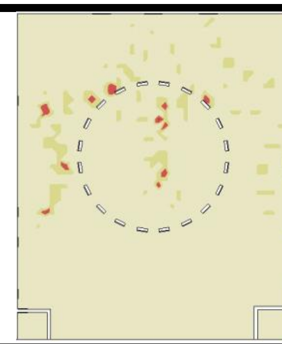
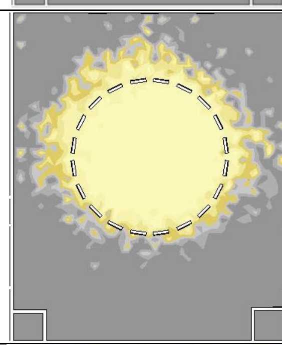
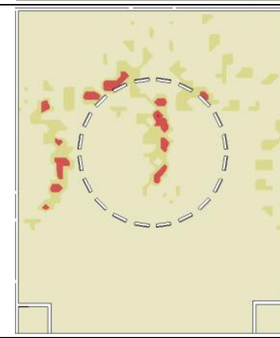
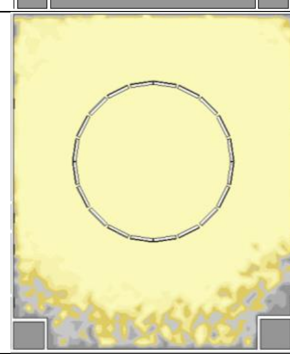
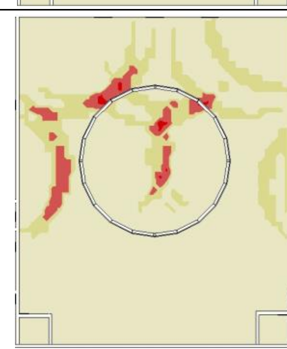
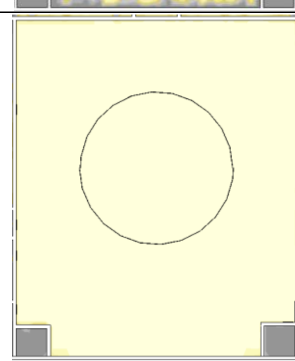
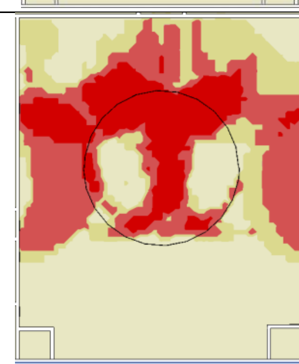
Date and Time: Annual				
Diameter	Height of Drum	S windows (W area/ D area)	SDA	ASE
14.0  	4.0 m (sill height = 1.3 m)	10%		
		15%		
		25%		
		100%		

Table 59: SDA and ASE results for (D=18 , H=2, S=10,15,25,100)

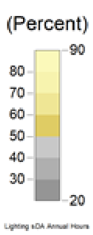
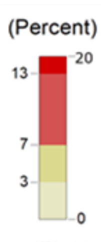
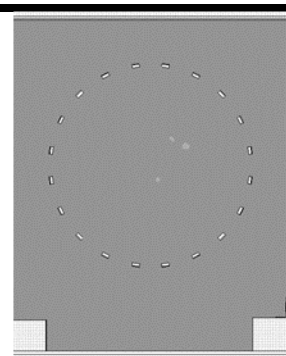
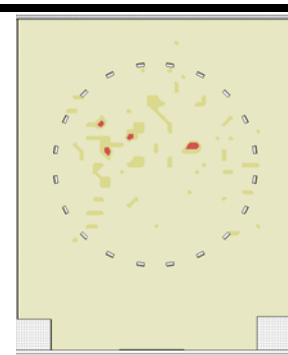
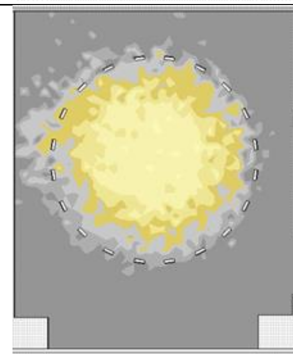
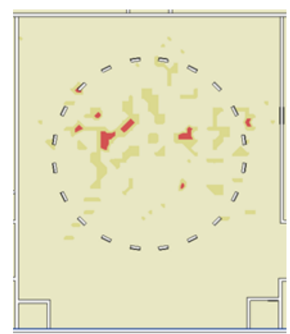
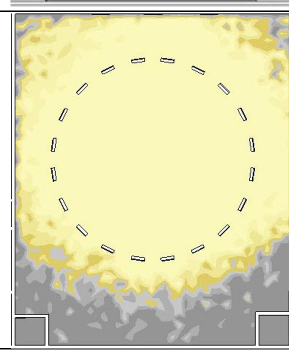
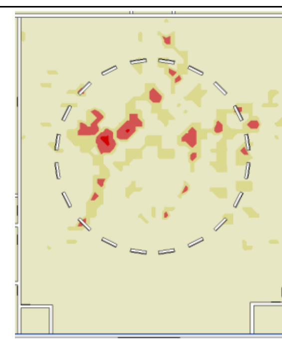
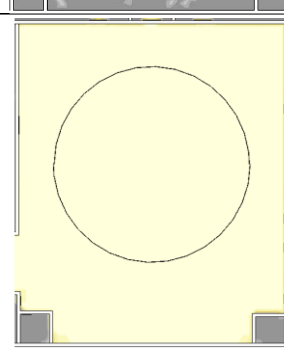
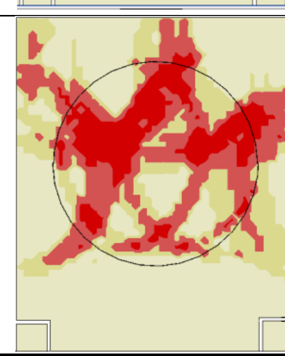
<table>
<tr><td colspan="5">Date and Time: Annual</td></tr>
<tr><td>Diameter</td><td>Height of Drum</td><td>S windows
(W area/ D area)</td><td>SDA</td><td>ASE</td></tr>
<tr><td rowspan="4">18.0

</td><td rowspan="4">2.0 m
(sill height = 0.3 m)</td><td>10%</td><td></td><td></td></tr>
<tr><td>15%</td><td></td><td></td></tr>
<tr><td>25%</td><td></td><td></td></tr>
<tr><td>100%</td><td></td><td></td></tr>
</table>

Table 60: SDA and ASE results for (D=18 , H=3, S=10,15,25,100)

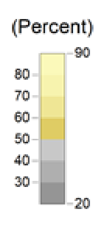
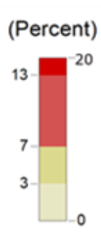
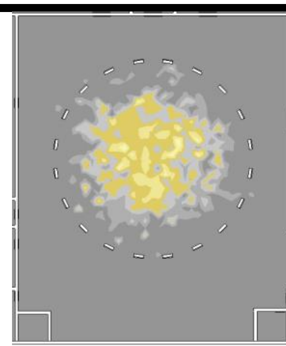
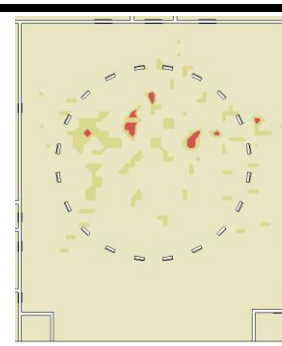
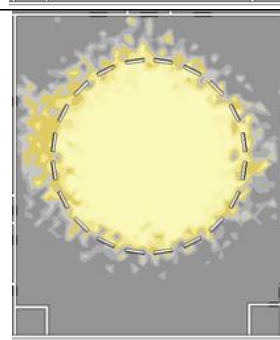
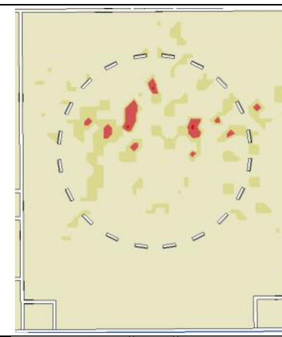
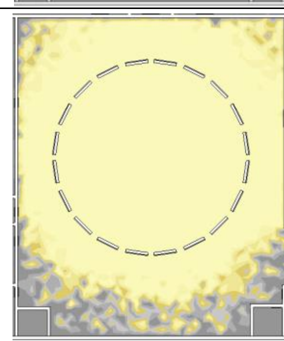
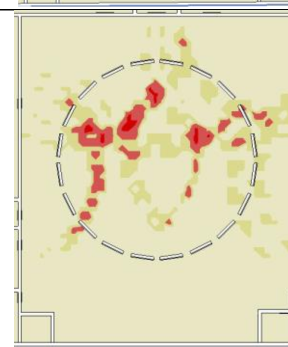
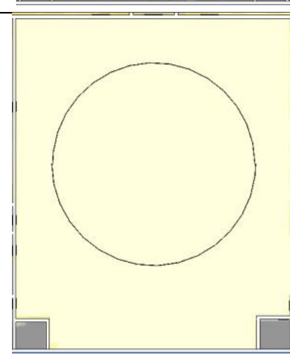
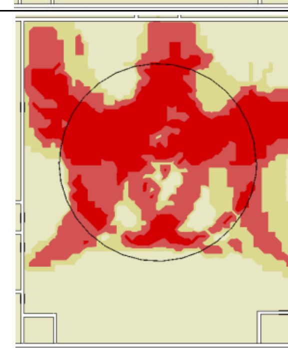
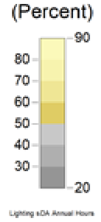
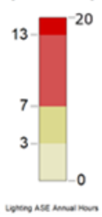
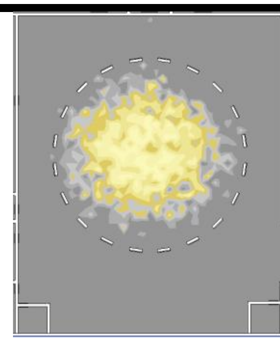
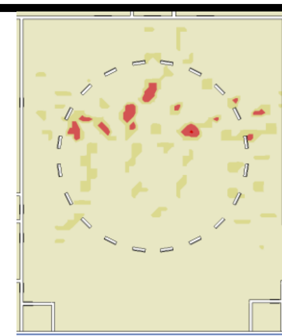
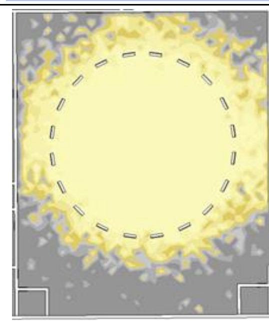
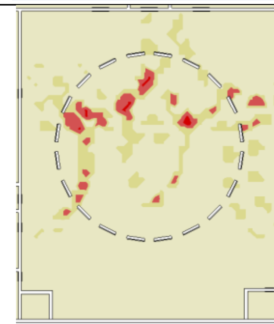
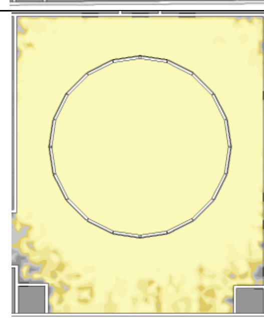
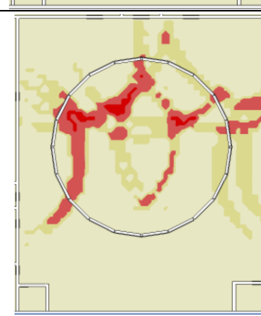
<table>
<tr><td colspan="5">Date and Time: Annual</td></tr>
<tr><td>Diameter</td><td>Height of Drum</td><td>S windows
(W area/ D area)</td><td>SDA</td><td>ASE</td></tr>
<tr><td rowspan="4">18.0

</td><td rowspan="4">3.0 m
(sill height = 0.8 m)</td><td>10%</td><td></td><td></td></tr>
<tr><td>15%</td><td></td><td></td></tr>
<tr><td>25%</td><td></td><td></td></tr>
<tr><td>100%</td><td></td><td></td></tr>
</table>

Table 61: SDA and ASE results for (D=18 , H=4, S=10,15,25,100)

Date and Time: Annual				
Diameter	Height of Drum	S windows (W area/ D area)	SDA	ASE
18.0 (Percent)  (Percent) 	4.0 m (sill height = 1.3 m)	10%		
		15%		
		25%		
		100%