Title

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Lighting and visual comfort performance of commercially available tubular daylight devices

Luís L. Fernandes, Cynthia M. Regnier

Abstract

Tubular daylight devices (TDDs) require a much smaller roof opening than conventional skylights and, because of their highly reflective tube, they can deliver daylight farther away from the building envelope. This can provide lighting energy savings, increasing resilience in new and existing buildings. Different types and configurations are available amongst commercially available TDDs, including domes/diffusers with varying optical properties and the diameter of the TDD. This paper presents a comprehensive experimental evaluation of the lighting and visual comfort performance of multiple configurations of commercially available TDDs, varying dome type (prismatic and clear), diffuser type (Fresnel and prismatic), and diameter (53 and 35 cm), under a range of environmental conditions (different times of day/year, sky cover). Based on illuminance measurements, estimated lighting energy use is also presented. Results indicate that, for clear sky, light levels increase and energy use decreases with solar altitude (e.g., 16 Wh/m^2 daily energy use intensity on a high maximum daily solar altitude (MDSA) day and 34 Wh/m^2 on a low MDSA day) and TDD diameter (e.g., 34 Wh/m^2 and 69 Wh/m^2 for 53 cm and 35 cm TDDs, respectively, for low MDSA). The daily illuminance profile is more rounded for prismatic domes and has higher peaks for clear domes; this translates into a somewhat higher average daily useful daylight illuminance (DUDI) for prismatic domes (86%) when compared to clear domes (80%). No clear impact of diffuser type was apparent. Measurements indicated no discomfort glare for any of the conditions tested.

Keywords

Daylighting; tubular daylight devices; light pipes; tubular skylights; experimental study; visual comfort

Abbreviations and symbols

DUDI	daily useful daylight illuminance
$E_{average}$	average horizontal illuminance
$E_{setpoint}$	assumed horizontal illuminance setpoint
EUI_{daily}	estimated daily energy use intensity from electric lighting
EUI_t	estimated energy use intensity from electric lighting for timestep t

HDR	high dynamic range
LPD	lighting power density
MDSA	maximum daily solar altitude
N_{all}	total number of timesteps used in DUDI calculation
N_{useful}	in DUDI calculation, number of timesteps for which the average horizontal daylight illuminance in the space is in the useful range of between 100 lx and 2 klx
P	lighting system power fraction
P_t	lighting system power fraction for timestep t
TDD	tubular daylight device

1 Introduction

1.1 Background

The use of daylight to offset energy use with electric lighting is one of the available approaches for helping to reduce carbon emissions caused by energy use in buildings. Core sunlighting comprises several techniques for bringing daylight – and particularly direct sunlight – deeper into buildings than what is achievable with conventional openings like windows and skylights, and in a way that makes use of this light while minimizing glare. Sunlight can be collected on the roof or on exterior walls, sometimes undergoing some level of concentration. The collected light can then be transported via highly efficient optical fibers or ducts/guides with interior mirrored surfaces, and delivered to interior spaces via a variety of diffusing devices. In many devices, these diffusers mimic the appearance and light diffusing characteristics of electric lighting luminaires. While this can seem counterintuitive – people usually like the distinctiveness of daylight – it can also be a way to avoid the main drawbacks of daylight (at least as delivered through conventional ways such as windows and skylights): glare, e.g., when the orb of the sun is directly visible to occupants, or thermal discomfort, e.g., when sunlight falls directly on occupants. Malet-Damour et al. (Malet-Damour et al., 2020) provide a recent, comprehensive review of the array of options for different core sunlighting system components.

1.2 Tubular daylight devices

While systems can include solar concentrating dishes and optical fibers, or mirrored arrays and mirrored ducts, the most common core sunlighting system is the tubular daylight device (TDD). TDDs are widely available commercially, with products marketed worldwide by large, established companies (Carter, 2014; Malet-Damour et al., 2020). From top to bottom, TDDs are comprised of a light-transmitting dome, a reflective tube of varying length and shape, and a diffuser. The dome admits daylight into the TDD, and it can be made of simple, clear polymer, or have some light-redirecting features. The tube is made of a highly reflective material, in order to minimize light losses as much as possible. The tube can curve and bend in order to accommodate the building's architectural features. This increases flexibility regarding where the TDD delivers daylight, as tubes can bring daylight horizontally or vertical to areas far from the building envelope that would not be reachable by conventional skylights or windows. Finally, at the point of delivery, the tube connects to a diffuser. Diffusers can be chosen with a variety of optical properties, with some closer to what would be expected from a conventional, fluorescent luminaire, and others aimed at producing a livelier, more "daylight-like", appearance. Carter (Carter, 2014) provides a thorough review of the features, physical performance and economics of TDDs. More recently, Li et al. (Li et al., 2021) review the methodologies available for estimating daylight and energy performance of TDDs. Kim and Kim (Kim and Kim, 2010) provide a detailed review of models for TDD performance analysis and design as well as of different types of systems and several case studies. Malet-Damour (Malet-Damour et al., 2019) provides a detailed review of the prior literature on TDD research.

While purely theoretical models for calculating TDD performance exist in the literature (Laouadi and Atif, 2001; Selkowitz and Johnson, 1989; Shuxiao et al., 2015), experimental measurements under real sky can be more realistic in both the assessment of TDD performance and providing the basis for mathematical and/or computational models. Of the experiments reported in the research literature in the last two decades or so, several experimental studies were aimed at developing useful correlations and design methods for TDDs. Zhang et al. (Zhang et al., 2002) develop models for the daylight provision of light pipes based on laboratory measurements, performed in Edinburgh, Scotland, of TDDs of varying diameter. Carter (Carter, 2002) presents experimental results from laboratory and field measurements on light pipes of varying diameter conducted in Liverpool, England, and developing prediction methods for the luminous performance of such devices. Mohelnikova (Mohelnikova, 2009) used measurements of a TDD installed in a hallway to validate a theoretical model of tubular light guides. Lo Verso et al. (Lo Verso et al., 2011) use results from measurements and simulations to improve on previous models of TDD performance. Su et al. (Su et al., 2012) measured the luminous flux output, under real skies, of different sizes of commercially-available TDDs and developed a model for the luminous flux output of TDDs. Similarly, Patil et al. (Patil et al., 2018) validate existing models and propose new ones based on experimental measurements of horizontal illuminance in New Delhi. Malet-Damour et al. (Malet-Damour et al., 2017, 2016) also use measurements under real skies to validate models of the luminous performance of a TDD. Vasilakopoulou et al. (Vasilakopoulou et al., 2017) analyze the performance of a TDD in a test room, using a grid of horizontal illuminance sensors, in order to derive correlations between the magnitude and spatial distribution of indoor illuminance on one side and sky clarity or outdoor illuminance on the other.

Other laboratory evaluations were more generally aimed at investigating the various specific aspects of TDD performance, including (sometimes in the same study) both commercially available and prototype systems. Wu et al. (Wu et al., 2008) investigate two TDD types under clear sky during the winter in Beijing, comparing two different types of diffusers, frosted and prismatic, with the frosted diffuser having slightly improved performance over the prismatic one. Garcia Hansen et al. (Garcia Hansen et al., 2009) measured the performance of a TDD with a novel laser-cut dome. Kim and Kim (Kim and Kim, 2010) tested a TDD with a custom reflector placed inside a clear acrylic dome, and present results for clear and overcast sky at noon, for a 7x7 grid in a 6 x 6 x 4 m room in South Korea. In another study (Yun et al., 2010) conducted in the same facility, results for a commercially-available TDD were shown for various sky types and correlations are developed between indoor illuminance on one side and sky clarity and solar altitude on the other. Li et al. (Li et al., 2010) evaluated the light transmission efficiency and workplane illuminance delivered by TDDs in the hallway of a commercial building in Hong Kong. Annual potential lighting energy savings were estimated based on correlations between interior and exterior illuminance. Baroncini et al. (Baroncini et al., 2010) perform a 1:2 scale test of a novel light pipe concept, including two different types of diffusers. Detailed results on the differences in performance due to variation in the type of diffuser are not presented, however. Wu et al. (Wu et al., 2011) studied the influence of dust and condensation on the luminous performance of TDDs. Wu and Li (Wu and Li, 2012) measured the luminous performance of TDDs in two buildings in Beijing, also computing estimated lighting energy savings. Thakkar (Thakkar, 2013) measured the illuminance provided by TDDs with varying dome diameters while keeping the tube diameter constant. The effect of varying the position of a reflector inside the dome has been investigated by Azad and Rakshit (Azad and Rakshit, 2018) for New Delhi climate. Malet-Damour et al. (Malet-Damour et al., 2019) show spatial and temporal illuminance distributions for clear and overcast sky on Reunion Island, also studying the effects of adding and varying the position of a reflector inside the dome and of adding a cyclone-resistant subdome under the main dome. Recently, several researchers have investigated the circadian impacts of the light provided by TDDs (Jain et al., 2019; Malet-Damour and Fakra, 2021).

On the whole, this literature provides ample evidence on the luminous and lighting energy benefits of TDDs for an array of component types, latitudes and climates. However, many of these studies focused on a single component type (e.g., evaluating a novel dome versus a conventional one, or two types of novel diffusers), were constrained to a few consecutive days or weeks, and did not cover a representative range of conditions throughout the year. Additionally, none of them include measurements of visual comfort quantities. While some studies included horizontal illuminance measurements on a regular grid, many of them relied on a reduced number of illuminance sensors to derive horizontal illuminance trends.

The experiment presented in this paper provides a more comprehensive and systematic evaluation of the performance of commercially-available and commonly-used TDD configuration options than what is available in the literature to date. To that end, the experiment includes the main two types of TDD dome that are commercially available: (prismatic and clear), two commercially-available and commonly-used types of diffuser (prismatic and Fresnel), and two common diameters for TDDs (53 and 35 cm). These combinations were studied under a variety of sky types (from completely clear to completely overcast) and a variety of maximum daily solar altitude (MDSA, or solar altitude at solar noon) angles. TDD performance variables measured or estimated included horizontal illuminance on a regular grid, lighting energy use, and, for the first time in the literature, occupant visual comfort. The results of this study can inform the research community, as well as designers and potential users of these systems, on what they can expect from commercially available TDD systems in mid-latitude locations.

2 Methodology

2.1 Experimental design

The independent variables considered in this study included environmental variables and TDD-specific variables (Table 1). Environmental variables included sky cover – i.e., whether the sky was clear, partly cloudy or overcast – and MDSA, which varies with the time of year. TDD characteristics included the dome/tube diameter, the type of dome, and the type of diffuser.

The dependent variables for this experiment (Table 2) were the daily useful daylight illuminance (DUDI) (Huo et al., 2020), daily lighting energy use intensity (EUI), and daylight glare probability (DGP) (Wienold and Christoffersen, 2006). DUDI and EUI were calculated from measurements of horizontal daylight illuminance in the space lit by the TDD. DGP was calculated from luminance measurements of the same space.

Tests were performed under real sky conditions, and for a range of maximum solar altitudes aimed at spanning, as much as possible, the range of maximum solar altitude encountered in mid-latitude regions. The first set of measurements, for low maximum solar altitude, was performed in February and March 2018 using 53 cm TDDs. In order to identify whether major differences in performance could be expected between TDD component types, TDDs from two different major manufacturers were used, as well as two different dome and diffuser types. A narrower set of configurations was used in the subsequent tests with higher maximum solar altitude, in May and June 2018. These tests also introduced a new variable – TDD width – with a 35 cm TDD being included in the test configurations. In order to capture additional solar angles with 35 cm TDDs, additional tests were conducted in September 2018 and January 2019, including an additional test with one 53 cm TDD configuration that did not get sufficient time under clear skies during the previous low solar angle tests. More detail on the sequence of the tests and the particular combinations of configurations that were tested is shown in Section 2.5.

Table 1. Overview of independent variables considered in the experiment.

Category		**Values**
TDD configuration	dome type	clear

		prismatic
	diffuser type	prismatic
		Fresnel
	diameter	35 cm
		53 cm
Solar altitude	MDSA	low
		high
Sky cover		clear
		overcast
		partly cloudy

Table 2. Overview of dependent variables considered in this experiment.

Category	**Direct measurements**	**Calculated quantities**
Daylight availability	Horizontal illuminance	Daily useful daylight illuminance (DUDI)
		Lighting energy use intensity (EUI)
Visual comfort	Luminance mapping	Daylight Glare Probability (DGP)

2.2 Facility

The experimental evaluation of TDD performance was conducted at full-scale in a facility for testing whole-building integrated systems (FLEXLAB®, Lawrence Berkeley National Laboratory, 2022) in Berkeley, California, United States. This location, situated at a latitude of 38°N, has a warm-summer Mediterranean climate, with warm, dry summers and cool, wet winters. The experimental facility has a number of testbeds, each consisting of two identical test cells, that allow the evaluation of building technologies and systems – including systems that go through the building envelope such as TDDs – in a controlled environment. This experiment was conducted in one of these cells over the course of a year.

2.3 Experimental layout

In a 6.27 x 9.60 m test cell, a smaller 4.88 x 4.27 m enclosure was created using fire-rated foam boards that went all the way from the floor to the ceiling and were finished with the same paint (0.57 reflectance) that was used in the interior walls of the test cell. The 2.74 m high ceiling (0.74 reflectance) is a 61 x 61 cm grid of acoustic tiles, with two LED luminaires (which were kept powered off for the duration of the experiment) and two HVAC diffusers also present within the section of the ceiling that was within the test enclosure. The vertical boards creating the enclosure were fastened to the metal ceiling grid using magnets. The floor is covered with wall-to-wall carpet (0.14 reflectance) The size of the smaller enclosure was chosen to approximate the largest average floor area per 53 cm TDD in a typical commercial building installation, according to available manufacturer literature (Solatube, n.d.). The windows in the test cell were blocked using the same type of panel used for the interior partitions so that daylight was not measurable indoors. Inside the test enclosure, two types of instruments were placed: photometers measuring horizontal illuminance and high-dynamic-range (HDR) camera apparatuses in order to capture information about glare from a variety of viewpoints. Figure 1 shows the experimental layout and Figure 2 a view of the test enclosure. More detail on the instrumentation is provided below.

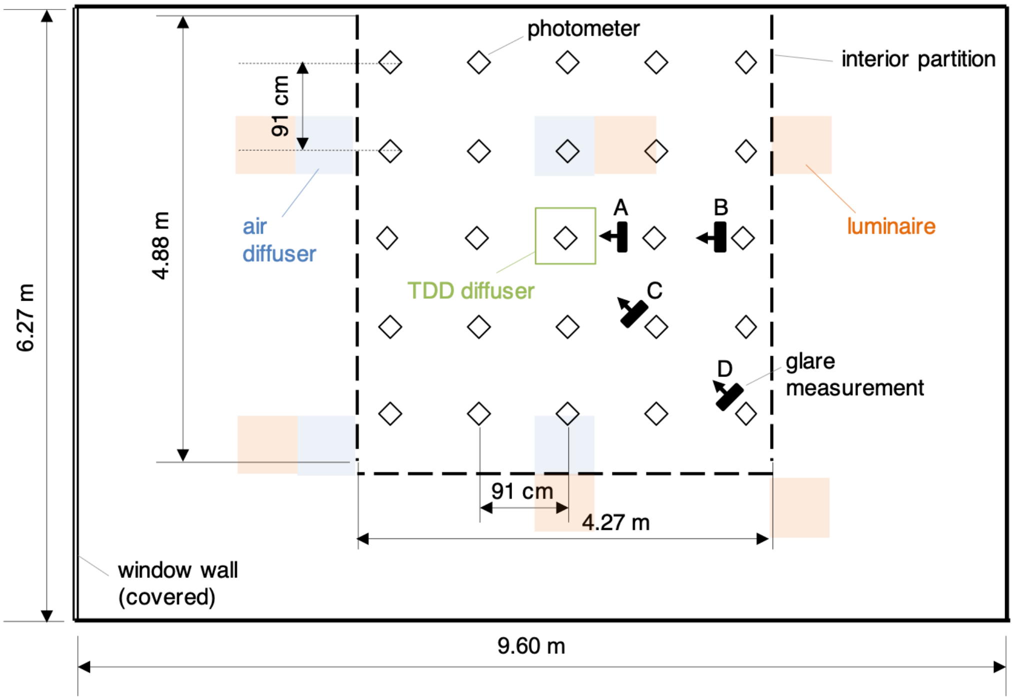

Figure 1. Experimental layout.

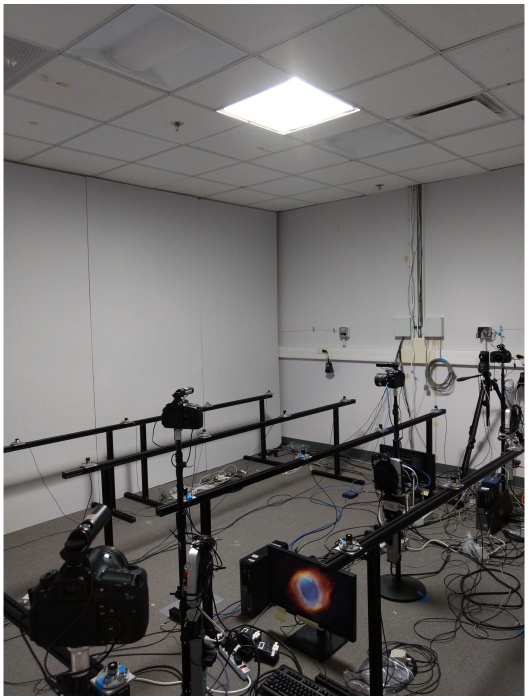

Figure 2. View of the test enclosure showing TDD diffuser on the ceiling, photometers mounted on horizontal rails, and equipment for measuring visual comfort.

2.4 Measurements

2.4.1 Exterior conditions

In order to evaluate sky cover, exterior global and diffuse horizontal irradiance were available from a weather station in a nearby research facility, situated approximately 300 m from the test cells.

2.4.2 Illuminance

Horizontal illuminance inside the space was measured using photometers (Licor LI-210R) (LI-COR Biosciences, n.d.), mounted 76 cm (30 inches) above the floor, and leveled using a bubble level built into the photometer base. Figure 3 shows one of these photometers mounted on a stand inside one of the test cells. Horizontal illuminance data was used for assessing light levels within the space.

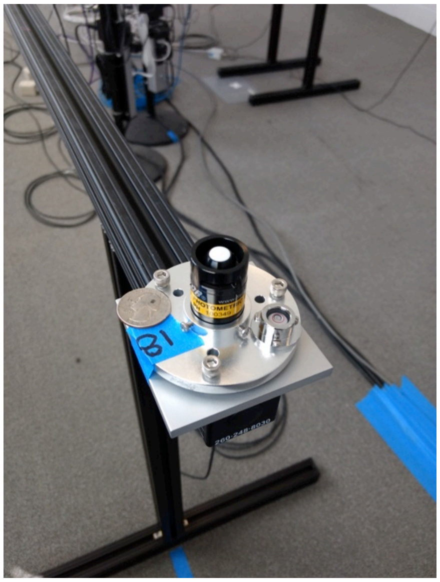

Figure 3. Photometer on stand inside test cell.

2.4.3 Visual comfort

Visual comfort was measured using high-dynamic-range (HDR) luminance mapping techniques and the DGP metric (Wienold and Christoffersen, 2006). HDR images were captured using Canon 60D (Canon USA, n.d.) and Canon 5D (Canon USA, n.d.) digital single-lens reflex cameras fitted with fisheye lenses and one Licor LI-210 photometer (LI-COR Biosciences, n.d.)(for measuring vertical illuminance), controlled by a computer running Mac OS (Figure 4) (Apple Inc, n.d.). These HDR images were processed in order to calculate a luminance map of the image, i.e., calculate the luminance for each image pixel.

Figure 4. Glare sensing apparatus.

The DGP metric represents a probability, between 0 and 1, that occupants of the space will experience glare when their eyes are at the position of the camera lens at the time that the HDR image was captured. Subjective ratings corresponding to DGP values are as follows: 0.30, 0.35, 0.40 and 0.45 are the thresholds for “just imperceptible glare” “just perceptible glare”, “just disturbing glare” and “just intolerable” glare. In general, it is desirable that DGP remains below 0.35, and that breaches above that level are of short duration and do not exceed 0.40.

2.5 TDD configurations

The TDDs used in the tests were manufactured by two different major manufacturers. Each 53 cm TDD was tested with two different domes – a clear dome and a prismatic dome (Figure 5) – and two different diffusers at the bottom – a prismatic diffuser and a Fresnel diffuser (Figure 6). A smaller, 35 cm TDD was also tested. It had a prismatic dome; two bottom diffusers were tested: a 61 x 61 cm Fresnel diffuser similar to its 53 cm equivalent, and a frosted round diffuser (Figure 7) 35 cm in diameter. Tests were conducted between February 2018 and January 2019, in order to cover a representative range of weather conditions and solar angles. The configurations tested and the test dates are shown in Table 3.

Figure 5. The two types of dome tested: clear (*left*) and prismatic (*right*).

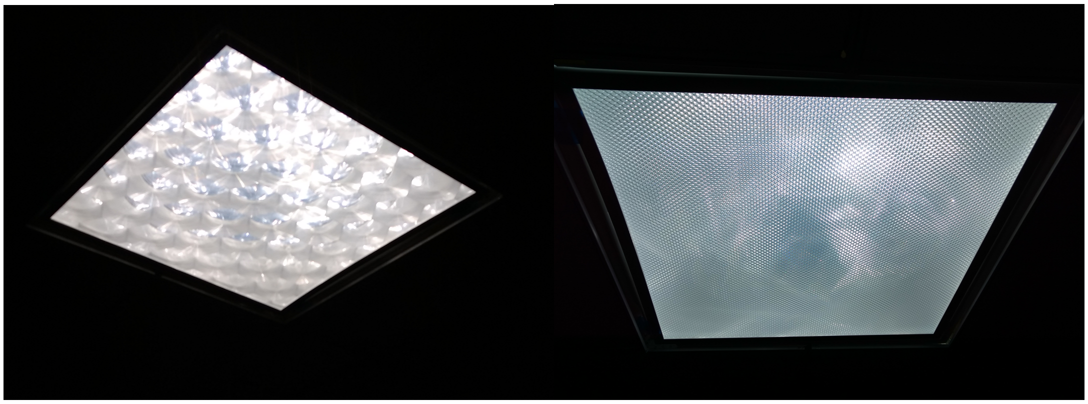

Figure 6. The two types of diffuser tested: prismatic (*left*) and Fresnel (*right*). Note that images are underexposed in order to show diffuser detail and aren't a good indicator of actual brightness.

Figure 7. Fourteen-inch frosted round diffuser.

Table 3. Test configurations and dates.

Configuration	Manufacturer	Dome	Diffuser	Diameter	Test dates
APP	A	Prismatic	Prismatic	53 cm	9 - 14 Feb 2018 19-21 May 2018

APF	A	Prismatic	Fresnel	53 cm	15 - 16 Feb 2018 22-23 May 2018 31 May - 3 Jun 2018 4 - 9 Jan 2019
ACP	A	Clear	Prismatic	53 cm	17 - 20 Feb 2018
ACF	A	Clear	Fresnel	53 cm	22 - 22 Feb 2018 26 - 29 May 2018
BPP	B	Prismatic	Prismatic	53 cm	24 - 26 Feb 2018
BPF	B	Prismatic	Fresnel	53 cm	27 - 28 Feb 2018
BCP	B	Clear	Prismatic	53 cm	7 - 9 Mar 2018
BCF	B	Clear	Fresnel	53 cm	10 - 11 Mar 2018 9 - 10 Jun 2018
35A	A	Prismatic	Fresnel	35 cm	5 Jun 2018 11 - 12 Sep 2018 25 - 30 Jan 2019
35B	A	Prismatic	Frosted	35 cm	7 Jun 2018 14 - 15 Sep 2018 11 - 24 Jan 2019

2.6 Calculations

2.6.1 Sky cover

The type of sky was classified according to the ratio between exterior direct normal irradiance and diffuse horizontal irradiance, using thresholds that, in previous research, have been found to be suitable classifying sky cover and/or controlling automated fenestration systems under the experiment's local climate (Fernandes et al., 2013). The sky was considered clear when this ratio was above 2, overcast when it was under 0.05, and partly cloudy in between.

2.6.2 Daylight availability

The ability of the TDDs to provide useful interior illumination was quantified using the daily useful daylight illuminance (DUDI), an extension, proposed in (Huo et al., 2020), of the useful daylighting illuminance (UDI) metric (Nabil and Mardaljevic, 2005). It was calculated by:

$$DUDI = \frac{N_{useful}}{N_{all}} \qquad (1)$$

where N_{useful}, is the number of timesteps for which the average horizontal daylight illuminance in the space is in the useful range of between 100 lx and 2 klx, and N_{all} is the total number of timesteps. In this paper, DUDI calculations were calculated for timesteps between 8 AM and 6 PM.

2.6.3 Estimated lighting energy use

The illuminance levels measured at the horizontal workplane were used to develop estimates of the electric lighting energy use for different TDD configurations. The method used was as follows:

1. For each timestep, lighting system power fraction P was calculated as:

$$P = \begin{cases} 0 \text{ if } E_{average} > E_{setpoint} \\ \frac{E_{setpoint} - E_{average}}{E_{setpoint}} \text{ if } 0 \leq E_{average} \leq E_{setpoint} \end{cases} \quad (2)$$

   where $E_{average}$ is the average horizontal illuminance, and $E_{setpoint}$ is the illuminance setpoint assumed for the lighting control system. An $E_{setpoint}$ value of 300 lx was used here[1].

2. Daily energy use intensity from electric lighting was calculated, for the hours between 8 AM and 6 PM, by

$$EUI_{daily} = \sum_{t=8\ AM}^{t=6\ PM} EUI_t = \sum_{t=8\ AM}^{t=6\ PM} P_t LPD \quad (3)$$

   where EUI_{daily} is the daily energy use intensity from electric lighting, EUI_t is the energy use intensity from electric lighting for timestep t, P_t is the lighting system power fraction for timestep t, and LPD is the installed lighting power density. An LPD value of 9.15 W/m^2 was used here[2].

3 Results

3.1 Sky conditions

Daytime (i.e., solar altitude above zero) sky conditions encountered throughout this study are shown in Figure 8 to Figure 10. The sky was clear for most of the daytime testing time (52%). The occurrence of partly cloudy sky was also significant (34%). The occurrence of overcast sky was lower but not insignificant (14%). Based on weather conditions, the test calendar for the different TDD configurations was continuously adjusted during the test periods with the goal of achieving at least one full day of testing with clear sky.

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[1] This is a commonly used horizontal illuminance setpoint in office spaces (David DiLaura et al., 2011).

[2] This value was based on the maximum lighting power allowance that the 2022 version of the California building energy code (California Energy Commission, 2022) allows for a 300 lx horizontal illuminance level, in a space with the same geometry as the space where measurements were performed.

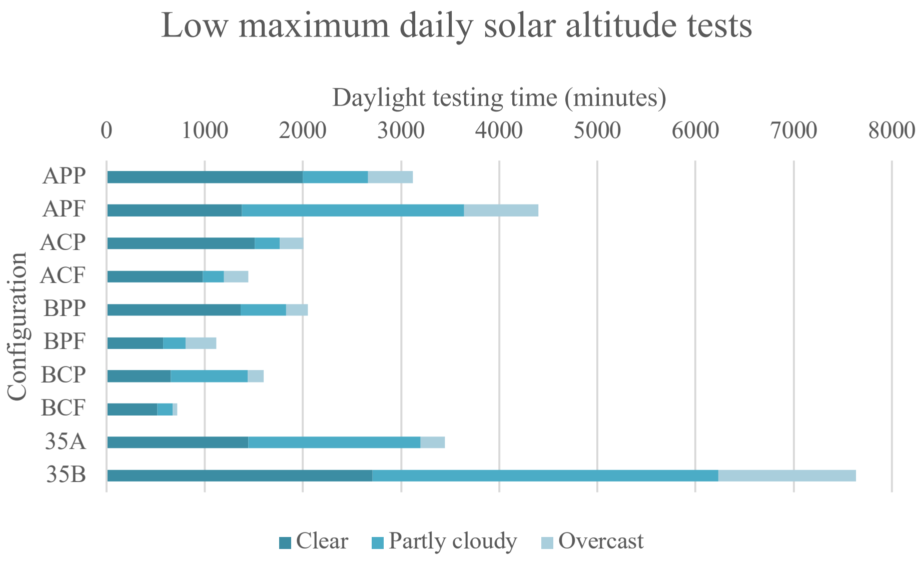


Figure 8. Occurrence of sky type by TDD configuration for low maximum solar altitude tests.

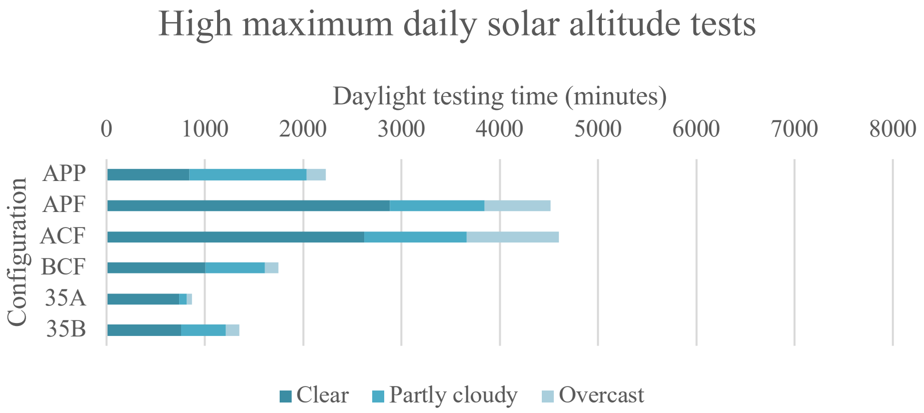


Figure 9. Occurrence of sky type by TDD configuration for high maximum solar altitude tests.

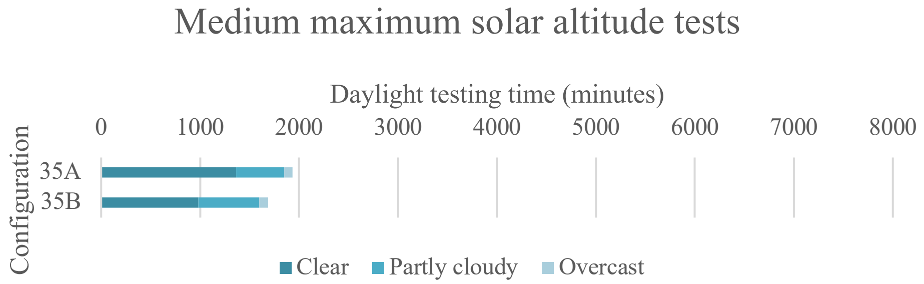


Figure 10. Occurrence of sky type by TDD configuration for medium maximum solar altitude tests.

3.2 Daylight illuminance

3.2.1 Behavior throughout the day

On a typical clear sky day, TDDs provided a significant amount of daylight to the interior space, rising in the morning, with a peak around mid-day and decreasing in the afternoon. For example, on a February day, a 53 cm TDD with prismatic dome and Fresnel diffuser provided an average illuminance of at least 200 lx between 9 AM and 4 PM, with individual illuminance values ranging from around 100 lx to more than 600 lx (Figure 11). As is to be expected, the amount of light provided when the sky was overcast was much lower (Figure 12). Under partly cloudy skies, performance tended towards intense variability in horizontal illuminance (Figure 13). DUDI for the three days shown in Figure 11 to Figure 13 is presented in Table 4.

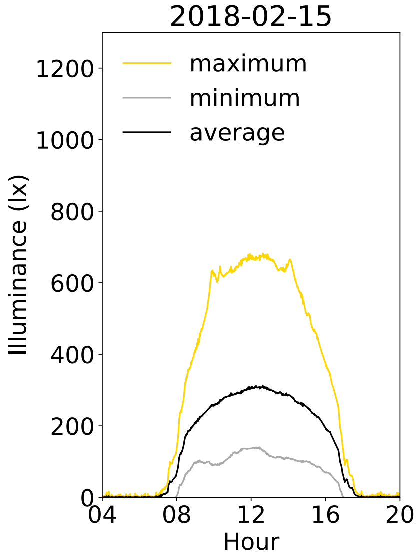


Figure 11. Average, maximum and minimum horizontal illuminance obtained with 53 cm TDD, prismatic dome and Fresnel diffuser (configuration APF) under clear sky in February (low MDSA).

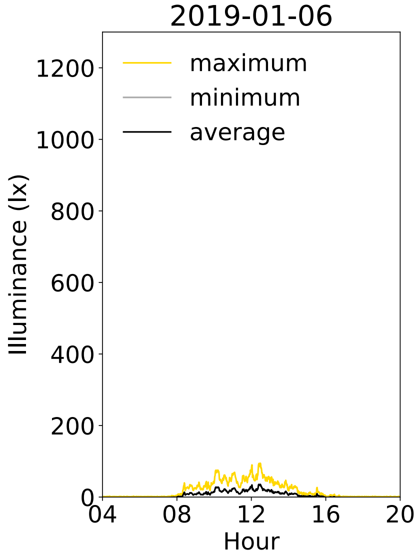


Figure 12. Average, maximum and minimum horizontal illuminance obtained with 53 cm TDD, prismatic dome and Fresnel diffuser (configuration APF) under overcast sky in January (low MDSA).

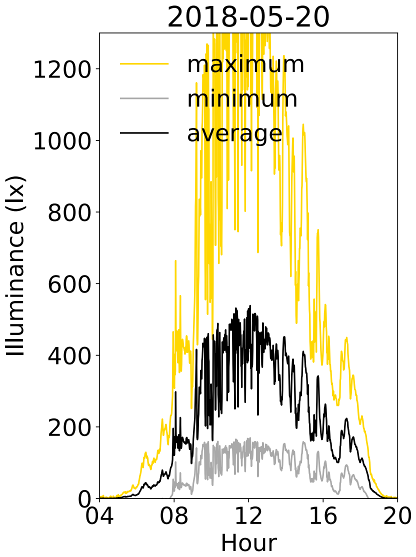


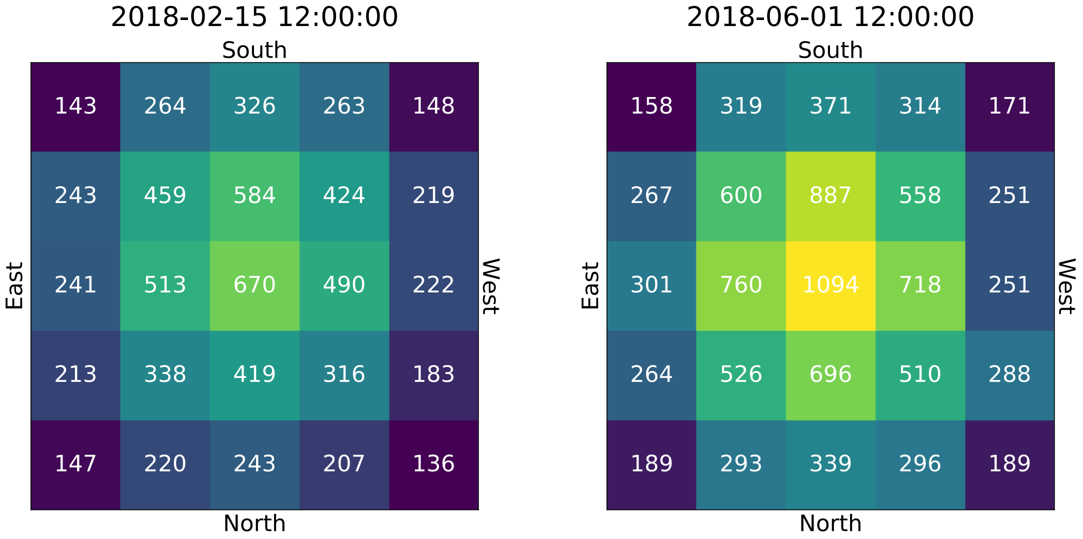
Figure 13. Average, maximum and minimum horizontal illuminance obtained with 53 cm TDD, prismatic dome and prismatic diffuser (configuration APP) under partly cloudy sky in May (high MDSA).

Table 4. DUDI for three days shown in Figure 11 to Figure 13.

Sky	Date	DUDI (8 - 18 h)
Clear	15 Feb	87%
Overcast	01 Jan	0%
Partly cloudy	20 May	100%

3.2.2 Spatial distribution

In the interior space illuminated by the TDD, horizontal illuminance at the workplane is consistently higher towards the center of the room. This is the case under clear sky (Figure 14). Similar trends were observed when the sky was overcast or partly cloudy (Figure 15).



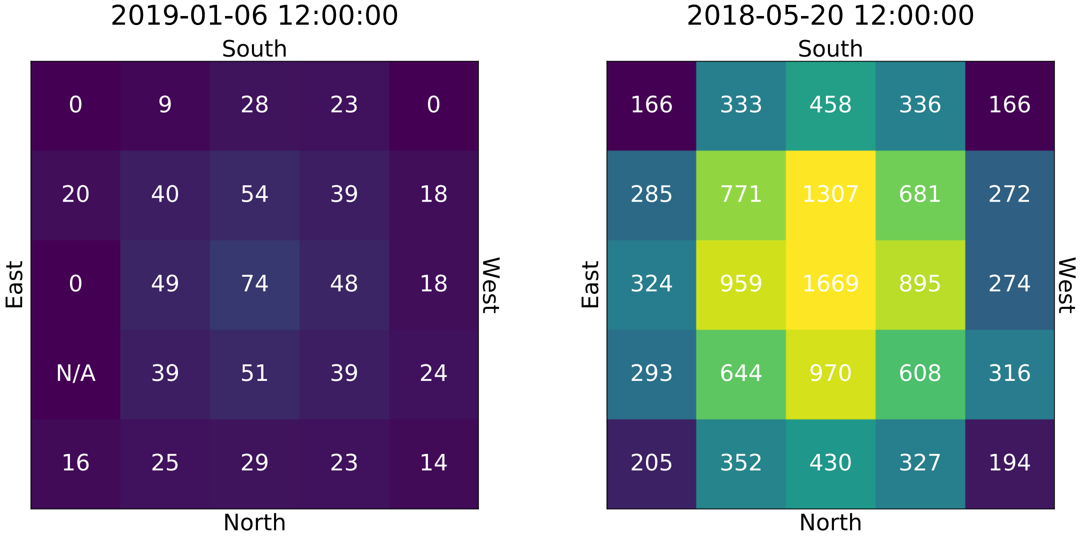
2018-02-15 12:00:00

143	264	326	263	148
243	459	584	424	219
241	513	670	490	222
213	338	419	316	183
147	220	243	207	136

2018-06-01 12:00:00

158	319	371	314	171
267	600	887	558	251
301	760	1094	718	251
264	526	696	510	288
189	293	339	296	189

Figure 14. Illuminance (lx) distribution within interior space obtained with 53 cm TDD, prismatic dome and Fresnel diffuser (configuration APF) under clear sky at noon during low (*left*) and high (*right*) maximum solar altitude tests. Illuminance increased towards the center of the room.



2019-01-06 12:00:00

0	9	28	23	0
20	40	54	39	18
0	49	74	48	18
N/A	39	51	39	24
16	25	29	23	14

2018-05-20 12:00:00

166	333	458	336	166
285	771	1307	681	272
324	959	1669	895	274
293	644	970	608	316
205	352	430	327	194

Figure 15. Illuminance (lx) distribution within interior space obtained with 53 cm TDD, prismatic dome and Fresnel diffuser (configuration APF) under overcast sky at noon during low maximum altitude test (*left*). Illuminance (lx) distribution within interior space obtained with 53 cm TDD, prismatic dome and prismatic diffuser (configuration APP) under partly cloudy sky at noon during low maximum altitude test. Illuminance increased towards the center of the room (*right*).

3.2.3 Effect of maximum daily solar altitude

During tests with high MDSA, horizontal illuminance tended to be higher. This was especially evident in the behavior of maximum illuminance, but also in average illuminance as well, even if less markedly so (Figure 16). Under clear sky, data from the days shown in Figure 16 indicates that DUDI is higher for high MDSA tests, but still high for low MDSA tests (97% versus 86%, respectively – see Table 5).

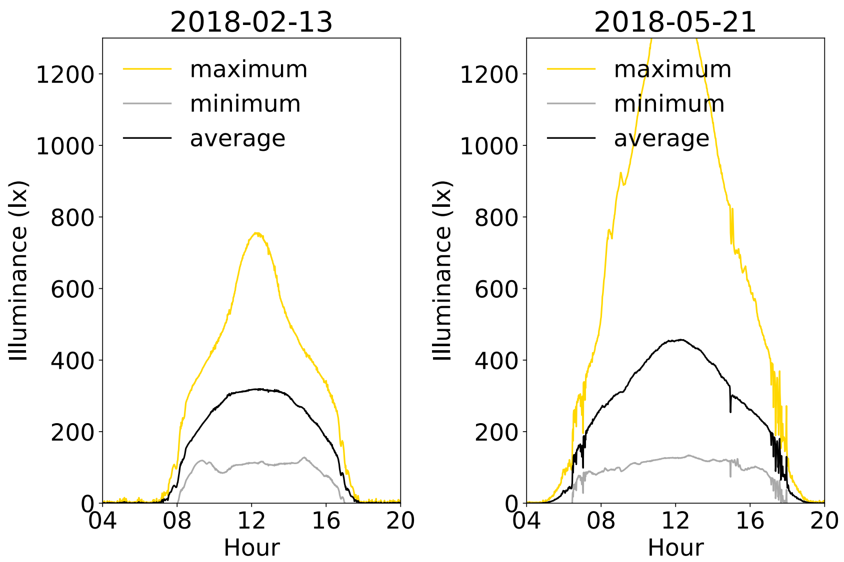


Figure 16. Average, maximum and minimum horizontal illuminance obtained with 53 cm TDD, prismatic dome and prismatic diffuser (configuration APP) under clear sky for (*left*) low and (*right*) high maximum daily solar altitude tests.

Table 5. DUDI for days shown in Figure 16.

MDSA	**Date**	**DUDI (8 - 18 h)**
Low	13 Feb	86%
High	21 May	97%

3.2.4 Effect of TDD diameter

Results for 35 cm TDDs showed similar illuminance profiles throughout the day as obtained with 53 cm TDDs. The main difference in the results was that illuminance levels were lower than with the larger diameter devices for both low and high MDSA tests (Figure 17). When examining DUDI results, however, it appears that a reduction in TDD diameter has minimal to moderate impact for high MDSA (97% and 90% for 53 cm and 35 cm TDDs, respectively), and a significant impact for low MDSA (86% and 26% for 53 cm and 35 cm TDDs, respectively) (Table 5 and Table 6).

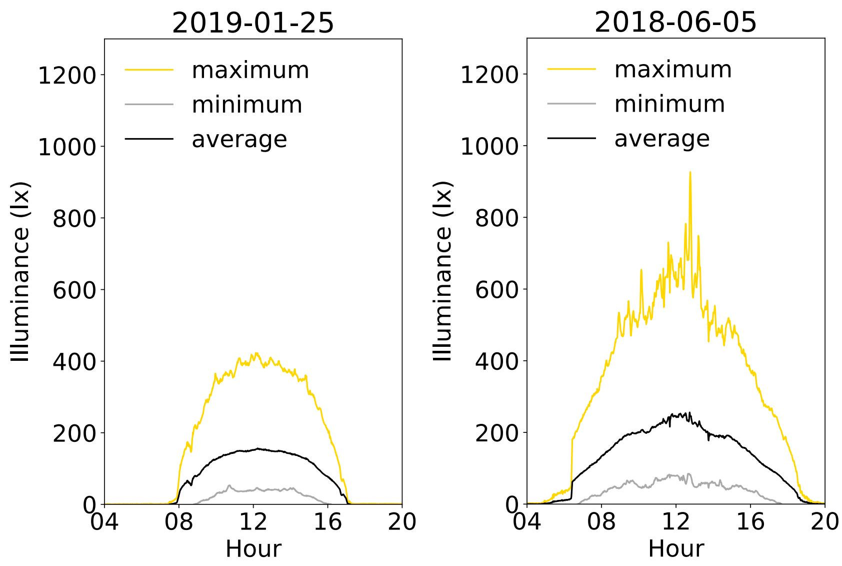


Figure 17 Average, maximum and minimum horizontal illuminance obtained with 35 cm TDD, prismatic dome and square Fresnel diffuser (configuration 35A) under clear sky for low and high maximum daily solar altitude tests.

Table 6. DUDI for days shown in Figure 17.

MDSA	Date	DUDI (8 - 18 h)
Low	25 Jan	26%
High	05 Jun	90%

3.2.5 Effect of dome and diffuser types

3.2.5.1 Dome

For days with low MDSA and clear sky, the daily profile tended to be more rounded for prismatic domes than for clear domes both in terms of average and minimum illuminance (Figure 18). This translates into somewhat higher average DUDI for prismatic domes when compared to clear domes (86% versus 80%, respectively, as shown in Table 7). Maximum illuminance tended to be more variable for clear domes than for prismatic domes. For high MDSA, trends were not as clear, although higher variability and more profiles with more peaks were observed for clear domes than for prismatic domes (Figure 19). Average DUDI results are virtually identical between the two types of domes (98% and 97% for prismatic and clear domes, respectively). In general, results appear to support the assertion that prismatic domes provide more even illuminance levels throughout the day than clear domes. Clear domes generally, but not necessarily always, achieve higher average, maximum, and minimum illuminance at some point during the day than prismatic domes.

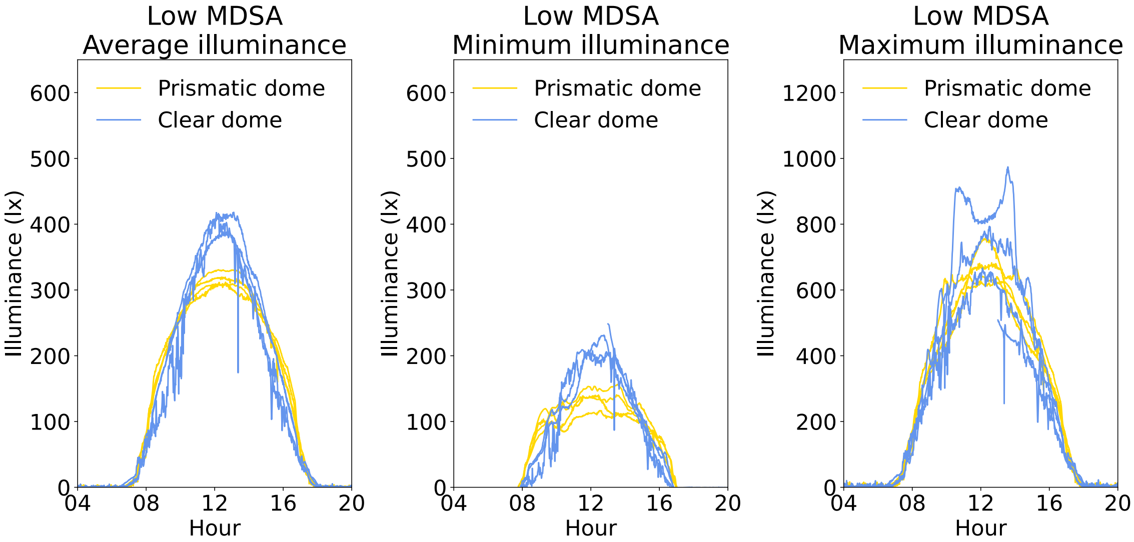


Figure 18. Daily profiles of average, minimum, and maximum illuminance obtained with prismatic and clear domes on low maximum solar altitude days with clear sky. Note that for one of the clear dome curves (configuration BCP) the sky was not clear until around 1 PM; data is plotted only for the clear sky part of the day.

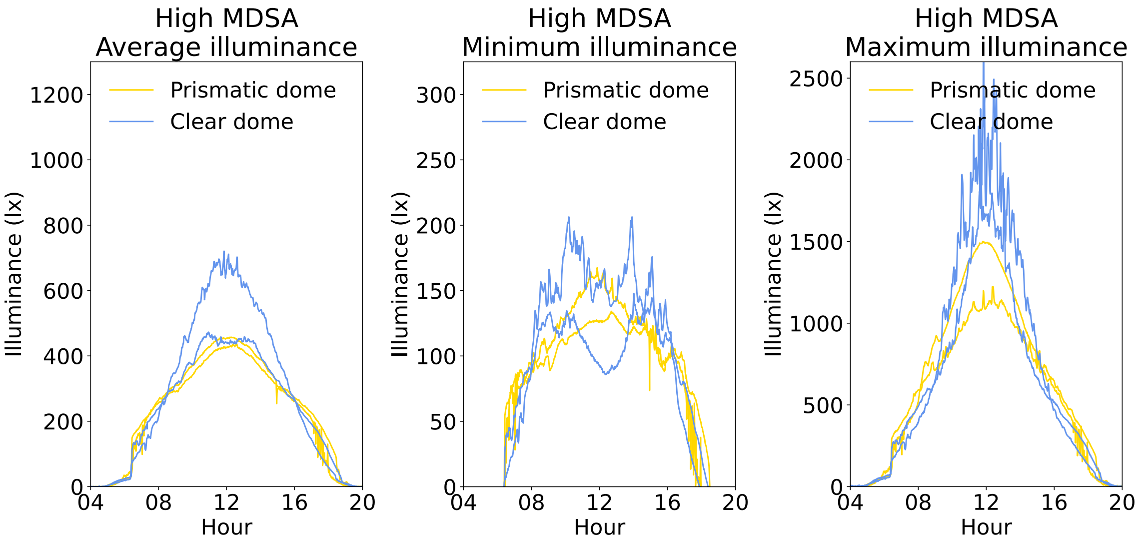


Figure 19. Daily profiles of average, minimum, and maximum illuminance obtained with prismatic and clear domes on high maximum solar altitude days with clear sky.

Table 7. Average DUDI for the same low and high MDSA days shown in Figure 18 and Figure 19. For clear domes and low MDSA, the incompletely clear day that was only partly plotted in Figure 18 was not included in the DUDI calculation.

Dome	MDSA	DUDI (8 - 18 h)
Prismatic	Low	86%
Clear	Low	80%
Prismatic	High	98%
Clear	High	97%

3.2.5.2 Diffuser

Results obtained under clear sky with low maximum solar altitude did not appear to show any clear trend related to which diffuser was used, whether regarding the magnitude, shape, or variability of the daily illuminance profiles (Figure 20). As a result, subsequent high MDSA tests did not include the full range of dome and diffuser combinations that were included in the low MDSA tests. Similarly to low MDSA results, for high MDSA no clear trend was observed (Figure 21). Average DUDI results (Table 8) appear to indicate minimal differences in daylight delivery between the two diffusers (97% and 98% for high MDSA, 85% and 83% for low MDSA, for prismatic and Fresnel diffusers, respectively).

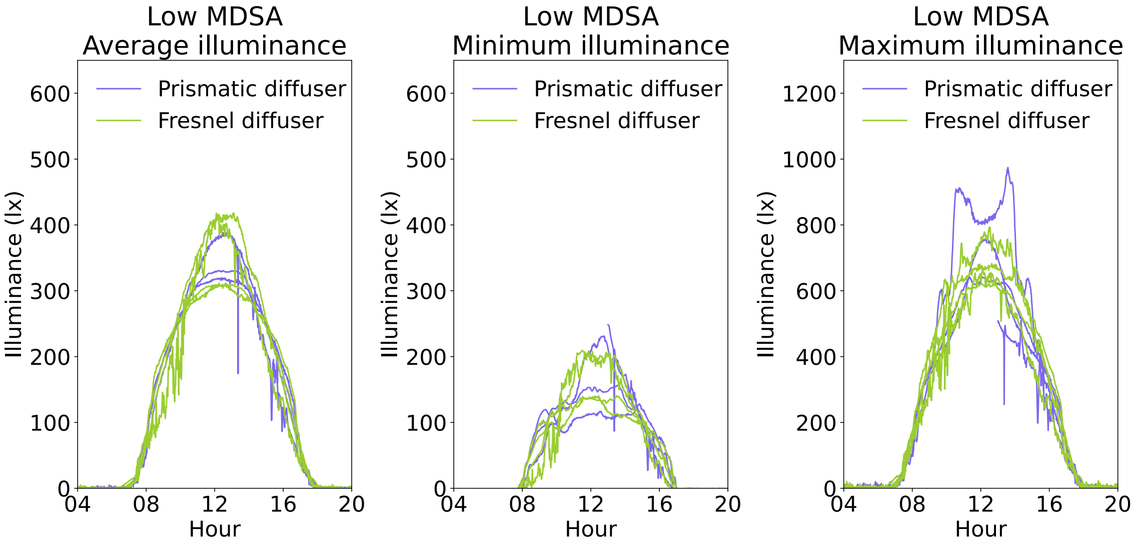


Figure 20. Daily profiles of average, minimum, and maximum illuminance obtained with prismatic and Fresnel diffusers on low maximum solar altitude days with clear sky. Note that for one of the prismatic diffuser curves (configuration BCP) the sky was not clear until around 1 PM; data is plotted only for the clear sky part of the day.

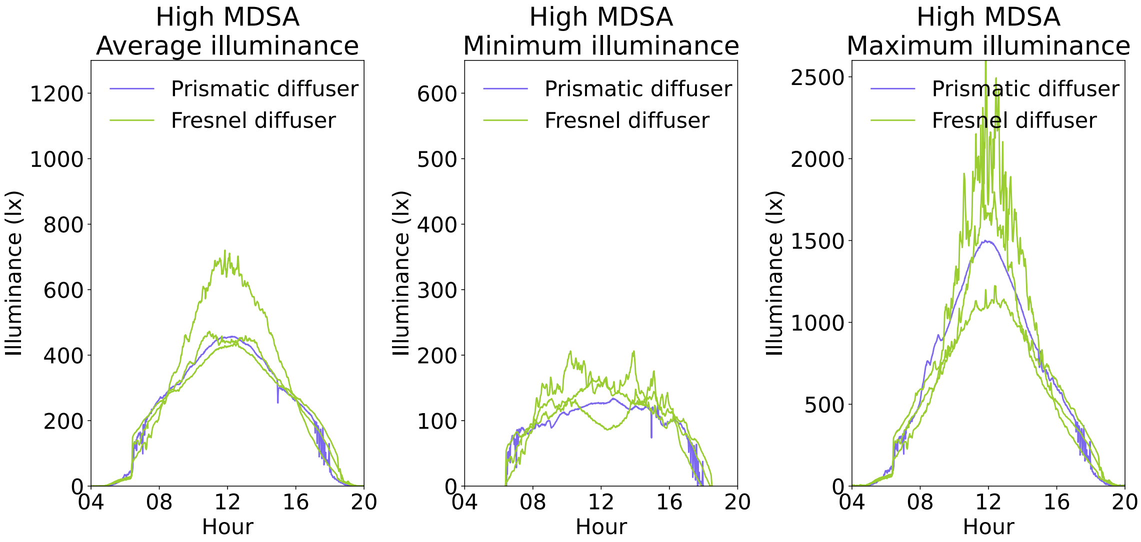


Figure 21. Daily profiles of average, minimum, and maximum illuminance obtained with prismatic and Fresnel diffusers on high maximum solar altitude days with clear sky.

Table 8. Average DUDI for the same low and high MDSA days shown in Figure 20 and Figure 21. For prismatic diffusers and low MDSA, the incompletely clear day that was only partly plotted in Figure 20 was not included in the DUDI calculation.

Diffuser	MDSA	DUDI (8 - 18 h)
Prismatic	Low	85%
Fresnel	Low	83%
Prismatic	High	97%
Fresnel	High	98%

3.3 Estimated lighting energy use

3.3.1 Behavior throughout the day

In terms of lighting energy use, for clear sky days there was a clear trend of decreasing energy use as the sun rises in the sky, followed by an increase as the sun lowers towards the horizon (Figure 22). During overcast days energy use generally stayed at high levels throughout the day, especially for low MDSA (Figure 23). Variability was significant during days with partly cloudy sky (Figure 24). Daily energy use was clearly higher for overcast days than for clear days (Table 9).

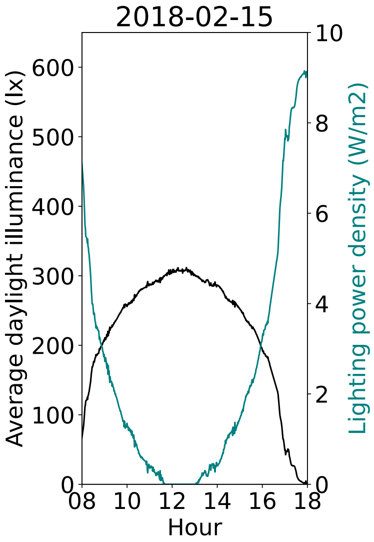


Figure 22. Average illuminance and lighting power density obtained with 53 cm TDD, prismatic dome and Fresnel diffuser (configuration APF) under clear sky in February.

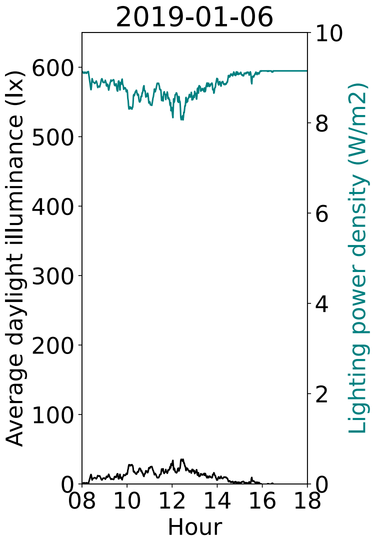


Figure 23. Average illuminance and lighting power density obtained with 53 cm TDD, prismatic dome and Fresnel diffuser (configuration APP) under overcast sky in January

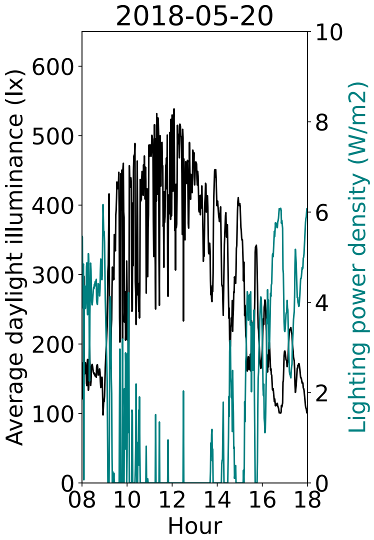


Figure 24. Average illuminance and lighting power density obtained with 53 cm TDD, prismatic dome and prismatic diffuser (configuration APP) under partly cloudy sky in May.

Table 9. Daily energy use intensity for days shown in Figure 22 to Figure 24.

Sky	Date	Daily EUI (8 - 18 h) Wh/m^2
Clear	15 Feb	33
Overcast	01 Jan	97
Partly cloudy	20 May	25

3.3.2 Effect of maximum solar altitude

For days with clear sky, energy use decreased to zero at some point during the day, independently of MDSA (Figure 25). The main difference is that, for low MDSA, the daily duration of lowest energy use is shorter. This results in higher daily energy use for low MDSA (Table 10).

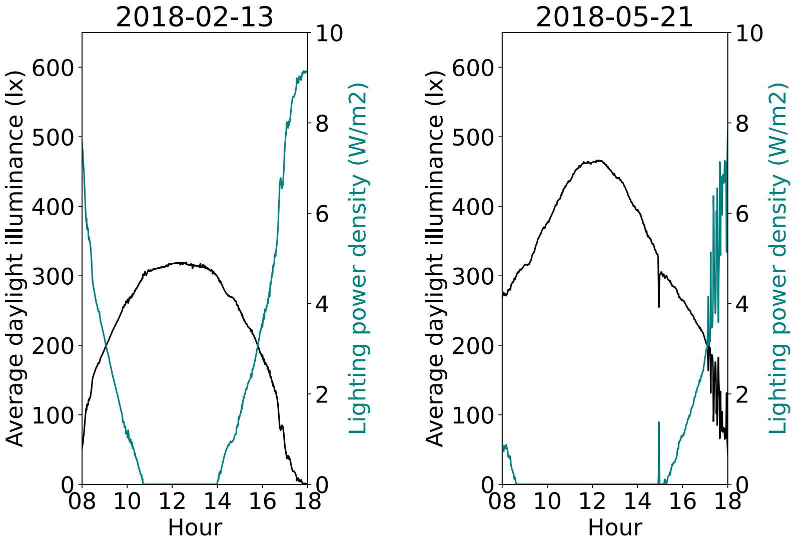


Figure 25. Average illuminance and lighting power density obtained with 53 cm TDD, prismatic dome and prismatic diffuser (configuration APP) under clear sky for low and high maximum solar angle tests.

Table 10. Daily energy use intensity for days shown in Figure 25.

MDSA	Date	Daily EUI (8 - 18 h) Wh/m^2
Low	13 Feb	34
High	21 May	16

3.3.3 Effect of TDD diameter

While still significant and reaching instantaneous levels of less than 2 W/m^2, estimated lighting energy use for the 35 cm TDD was higher than for 53 cm TDDs (Figure 26). When comparing daily EUI values between Table 10 and Table 11 and, reducing TDD diameter approximately represents a doubling of daily EUI for low MDSA (34 and 69

Wh/m^2 for 53 and 35 cm TDDs, respectively), and near tripling for high MDSA (16 and 45 Wh/m^2 for 53 and 35 cm TDDs, respectively).

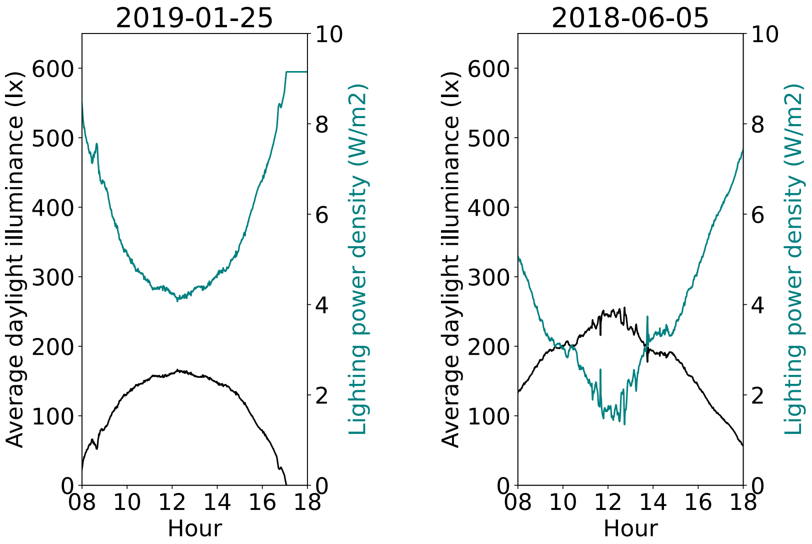


Figure 26. Average illuminance and lighting power density obtained with 35 cm TDD, prismatic dome and square Fresnel diffuser (configuration 35A) under clear sky for low and high maximum solar angle tests.

Table 11. Daily energy use intensity for days shown in Figure 26.

MDSA	Date	Daily EUI (8 - 18 h) Wh/m^2
Low	25 Jan	69
High	05 Jun	45

3.3.4 Effect of dome/diffuser type

3.3.4.1 Dome

When comparing the estimated daily lighting energy use profiles between prismatic and clear domes, similar trends emerge as for illuminance data. When MDSA is low, the profile tends to be slightly wider for prismatic domes and reach zero energy use for shorter periods (Figure 27). For high MDSA, profile differences between dome are not very evident. In terms of daily energy use, daily EUI results Table 12 indicate a consistent advantage of prismatic over clear domes, for both low (34 and 38 Wh/m^2 for prismatic and clear domes, respectively) and high MDSA (15 and 17 Wh/m^2 for prismatic and clear domes, respectively).

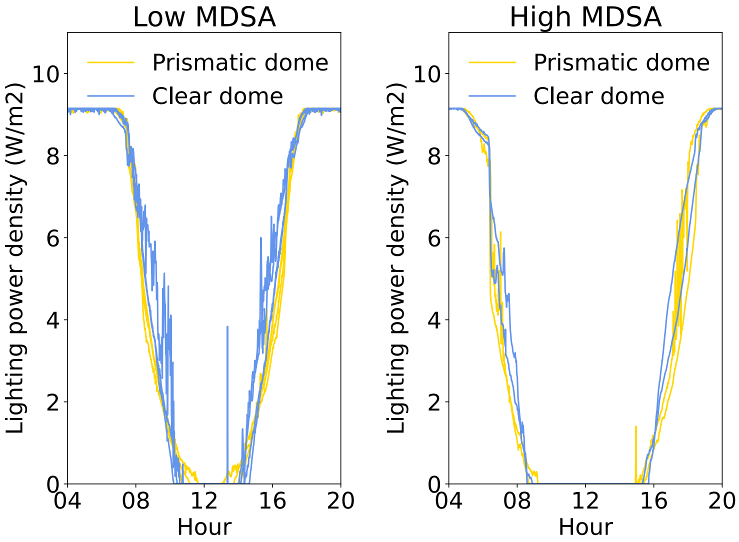


Figure 27. Lighting energy use profiles obtained with prismatic and clear domes on clear days for low and high MDSA. Note that for one of the low MDSA curves (configuration BCP) the sky was not clear until around 1 PM; data is plotted only for the clear sky part of the day.

Table 12. Average daily energy use intensity for days shown in Figure 27. For clear domes and low MDSA, the incompletely clear day that was only partly plotted in Figure 27 was not included in the EUI calculation.

Dome	**MDSA**	**Daily EUI (8 - 18 h) Wh/m^2**
Prismatic	Low	34
Clear	Low	38
Prismatic	High	15
Clear	High	17

3.3.4.2 Diffuser

Estimated daily lighting energy use profiles do not seem to indicate any clear effect of diffuser type on the daily lighting energy reduction profile (Figure 28). Daily EUI results (Table 13) suggest a slight but consistent advantage for prismatic over Fresnel diffusers for both low (34 and 36 Wh/m^2 for prismatic and Fresnel diffusers, respectively) and high MDSA (16 and 17 Wh/m^2 for prismatic and Fresnel diffusers, respectively).

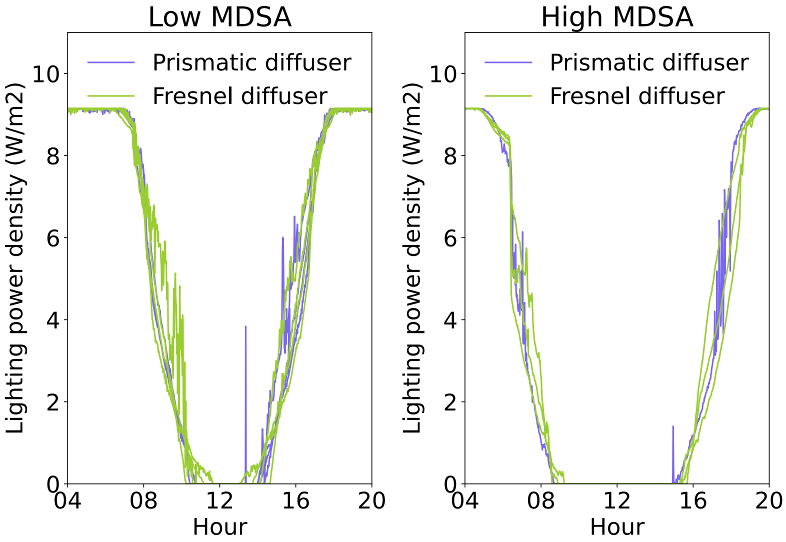


Figure 28. Daily lighting energy use profiles obtained with prismatic and Fresnel diffusers on clear days for low and high MDSA.

Table 13. Average daily energy use intensity for days shown in Figure 28. For prismatic diffusers and low MDSA, the incompletely clear day that was only partly plotted in Figure 28 was not included in the EUI calculation.

Diffuser	**MDSA**	**Daily EUI (8 - 18 h) Wh/m^2**
Prismatic	Low	34
Fresnel	Low	36
Prismatic	High	16
Fresnel	High	17

3.4 Visual comfort

3.4.1 Behavior throughout the day

Trends were similar to those observed for illuminance levels and lighting energy reduction. Under clear sky, DGP increases in the morning and decreases in the afternoon (Figure 29). In general, DGP levels peaked in the 0.2-0.3 range, indicating a low probability of visual discomfort from the TDD diffuser. Viewpoints B, and C tended to have spend longer periods near their maximum DGP value than viewpoints A and D. Measured DGP values were insignificant under overcast sky (Figure 30); on dark days ambient vertical illuminance levels were sometimes lower than the minimum for triggering the automated DGP measuring apparatus. As for what was shown earlier regarding horizontal illuminance, DGP variability was clearly higher on partly cloudy days, although without reaching problematic levels (Figure 31).

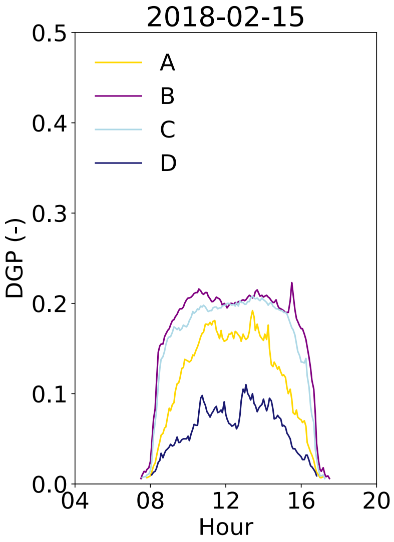


Figure 29. Daylight Glare Probability obtained with 53 cm TDD, prismatic dome and Fresnel diffuser (configuration APF) under clear sky in February.

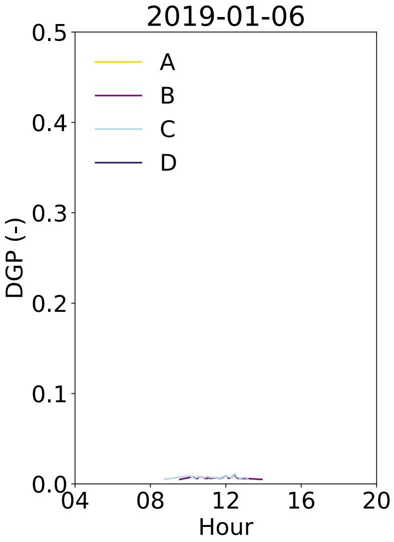


Figure 30. Daylight Glare Probability obtained with 53 cm TDD, prismatic dome and Fresnel diffuser (configuration APP) under overcast sky in January (note that there is no data from viewing positions A and D for this day due to the very low levels of ambient illuminance not being sufficient for triggering the automated DGP measurements.)

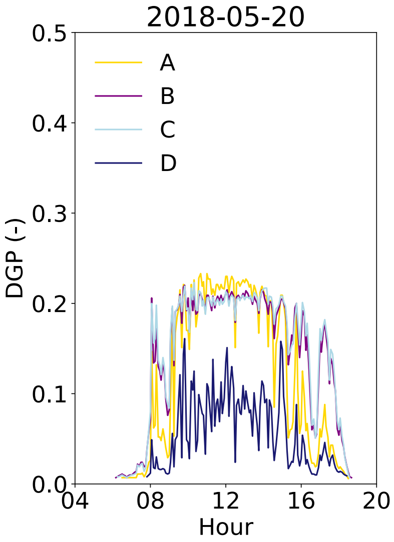


Figure 31. Daylight Glare Probability obtained with 53 cm TDD, prismatic dome and prismatic diffuser (configuration APP) under partly cloudy sky in May.

3.4.2 Effect of maximum daily solar altitude

Between low and high MDSA tests, the main difference is the duration of the peak in DGP, around 0.2, with results from high MDSA tests staying in the vicinity of that maximum value for longer periods, which is consistent with longer daytime hours (Figure 32). Another apparent trend, visible in Figure 32, is that, for viewpoint A, maximum DGP levels tended to be observably higher for high MDSA than for low MDSA. For other viewpoints, results suggest that DGP daily maxima is less affected by MDSA.

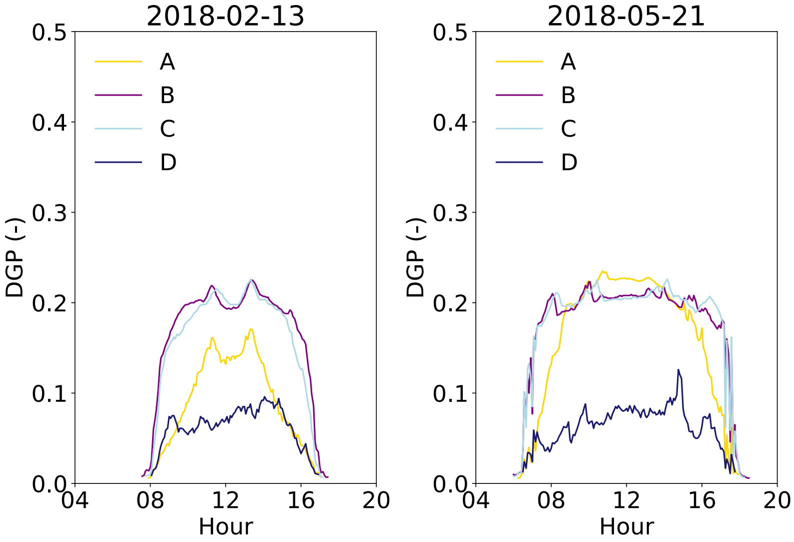


Figure 32. Daylight Glare Probability obtained with 53 cm TDD, prismatic dome and prismatic diffuser (configuration APP) under clear sky for low and high maximum solar angle tests.

3.4.3 Effect of TDD diameter

When compared with results for 53 cm TDDs, measurements done with the 35 cm TDDs resulted generally in even lower DGP values, especially for low MDSA (Figure 33). With high MDSA, maximum DGP values reached the vicinity of 0.2 but for shorter duration than with 53 cm TDDs. While there is more of an effect of MDSA on maximum daily

DGP for positions C and D than is observed for 53 cm TDDs, for 35 cm TDDs the effect for viewpoint A is still the greatest by far.

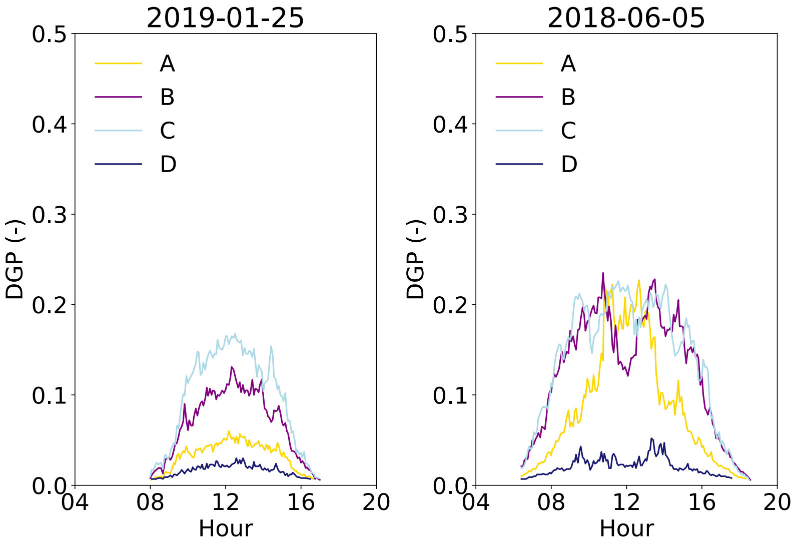


Figure 33. obtained with 35 cm TDD, prismatic dome and square Fresnel diffuser (configuration 35A) under clear sky for low and high maximum solar angle tests.

3.4.4 Effect of dome/diffuser type

3.4.4.1 Dome

For low MDSA tests under clear sky, measured DGP values were very similar between dome types for viewpoints B and C, with perhaps the prismatic domes resulting in a smoother, more rounded daily profile (Figure 34), i.e., without exhibiting sharp peaks shortly after sunrise or before sunset. For viewpoint A, results with clear domes appear slightly higher, peaking as high as 0.24, than with prismatic domes, which peak at 0.20. In viewpoint D, there was a significant difference in DGP levels between the two dome types, with the clear domes reaching peaks about twice as high (around 0.25) as the prismatic domes. For high MDSA tests (Figure 35), results were not too different, except for wider peaks for viewpoint A and, for viewpoint D, clear domes resulting in high variability (e.g., swings from about 0.1 to 0.3).

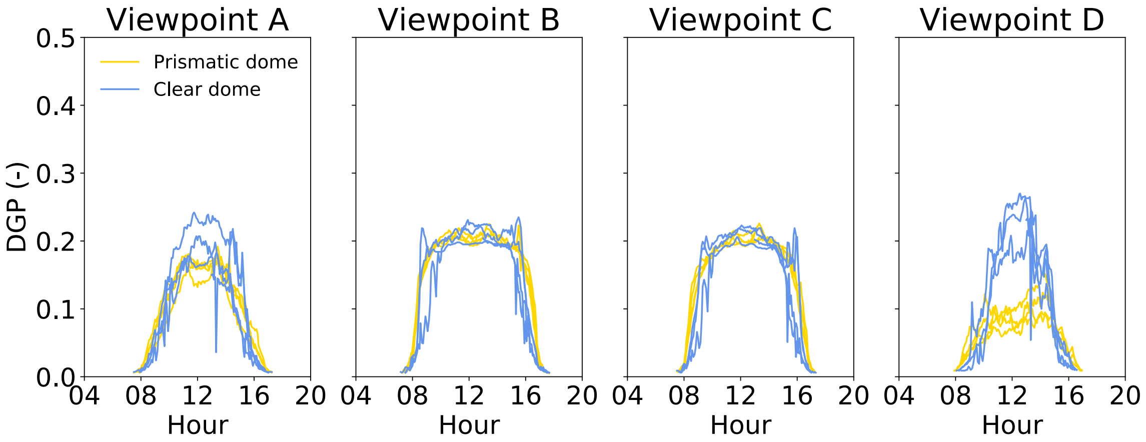


Figure 34. Daylight Glare Probability obtained with prismatic and clear domes on low maximum solar altitude days with clear sky. Note that for one of the clear dome curves (configuration BCP) the sky was not clear until around 1 PM; data is plotted only for the clear sky part of the day.

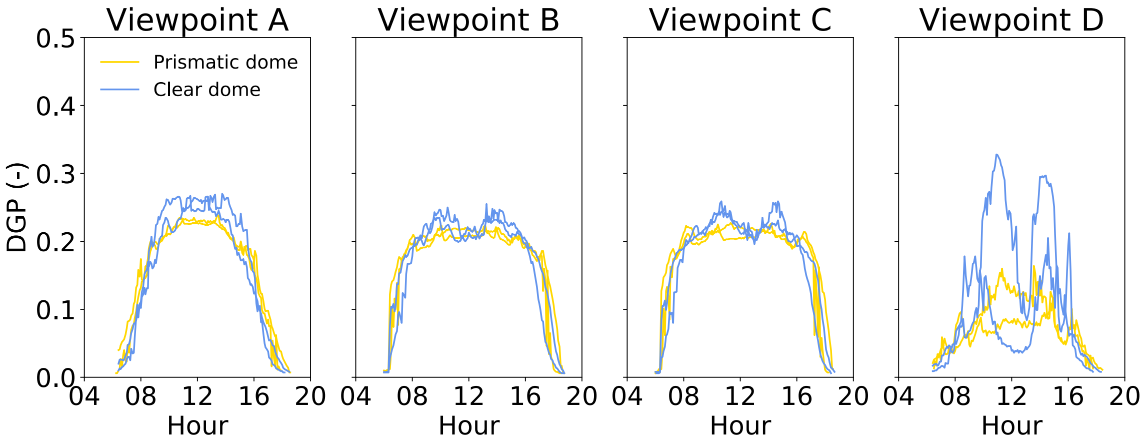


Figure 35. Daylight Glare Probability obtained with prismatic and clear domes on high maximum solar altitude days with clear sky.

3.4.4.2 Diffuser

No clear differences in visual comfort were observed that could be attributed to the diffuser type, either for low (Figure 36) or high MDSA (Figure 37).

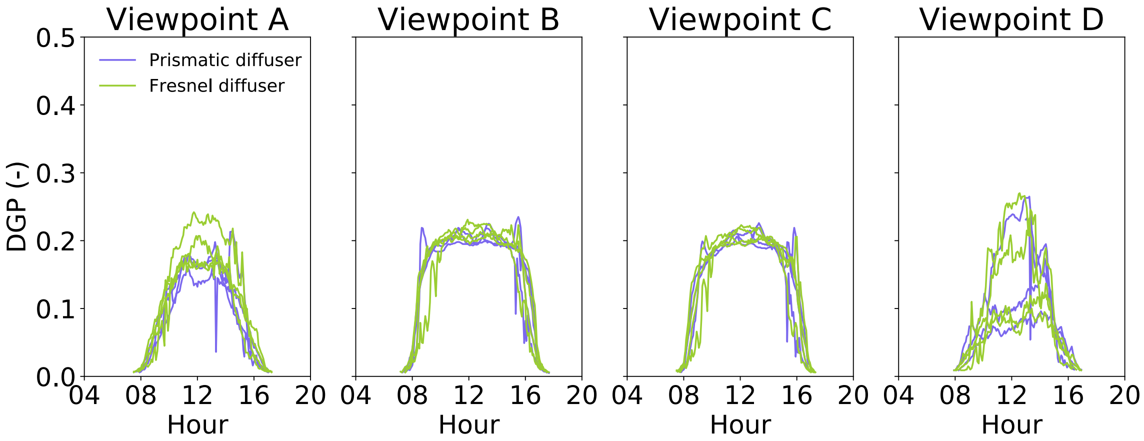


Figure 36. Daylight Glare Probability obtained with prismatic and Fresnel diffusers on low maximum solar altitude days with clear sky. Note that for one of the prismatic diffuser curves (configuration BCP) the sky was not clear until around 1 PM; data is plotted only for the clear sky part of the day.

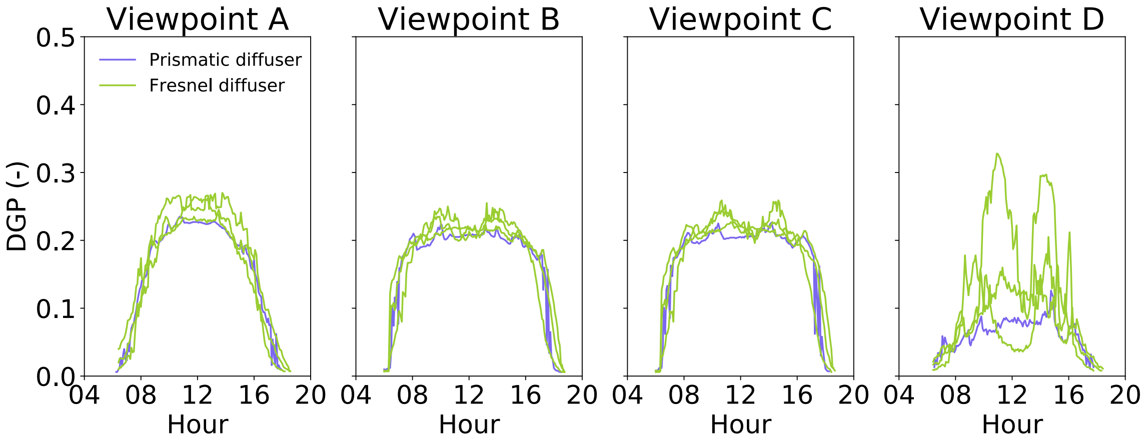


Figure 37. Daylight Glare Probability obtained with prismatic and Fresnel diffusers on high maximum solar altitude days with clear sky.

4 Discussion

4.1 Daylight illuminance

Results for daylight illuminance under clear sky showed the following trends:

- Illuminance increases until solar noon and decreases after that;
- Illuminance is highest below the TDD diffuser and decreases with horizontal distance from that point;
- Useful daylight illuminance increases with MDSA (e.g., for configuration APP, DUDI was 97% on a high MDSA day and 83% on a low MDSA day);
- Useful daylight illuminance increases with TDD diameter, with the effect more noticiable when MDSA is low (86% and 26% for 53 cm and 35 cm TDDs, respectively) than when MDSA is high (97% and 90% for 53 cm and 35 cm TDDs, respectively);
- Illuminance decreases when going from the center of the room towards the periphery;
- Large (53 cm diameter) TDDs can provide 300 lx average illuminance for a significant part of the day (DUDI always in excess of 80%).

Additionally, the following features were noticed regarding the type of TDD dome and diffuser:

- Clear domes tended to result in higher maximum daily illuminance and in a sharper curve;
- Prismatic domes tended to result in a more rounded daily illuminance; profile, with higher illuminance in the early morning and late afternoon than for clear domes;
- The two above trends translate into somewhat higher average DUDI for prismatic domes when compared to clear domes (86% versus 80%).
- No clear impact of diffuser type was observed; differences in DUDI between diffuser types appear to be minimal.

4.2 Estimated lighting energy use

Trends for estimated lighting energy use on clear sky days follow those mentioned above for daylight illuminance.

- Energy use decreases until solar noon and increases after that;
- Energy use increases as MDSA decreases (for APP configuration, 34 versus 16 Wh/m^2 for low and high MDSA, respectively);
- Reducing TDD diameter represents, approximately, a doubling of daily EUI for low MDSA (34 and 69 Wh/m^2 for 53 and 35 cm TDDs, respectively), and near tripling for high MDSA (16 and 45 Wh/m^2 for 53 and 35 cm TDDs, respectively);
- There is a consistent, if moderate, advantage of prismatic over clear domes, for both low (34 and 38 Wh/m^2 for prismatic and clear domes, respectively) and high MDSA (15 and 17 Wh/m^2 for prismatic and clear domes, respectively);
- Differences between diffusers are slight, and results suggest a slight advantage for prismatic over Fresnel diffusers, for both low (34 and 36 Wh/m^2 for prismatic and Fresnel diffusers, respectively) and high MDSA (16 and 17 Wh/m^2 for prismatic and Fresnel diffusers, respectively).

It should also be noted that the calculation method used in this paper for daily energy use is aimed at providing a useful general estimate of the potential differences in performance between different TDD configurations, based on the daylight levels that those configurations are able to deliver to the workplane. Actual energy use will depend on the particular specifications of the electric lighting system in use and also on the ability of a particular lighting control system to take advantage of the available daylight provided each TDD configuration. As this can vary significantly between lighting system configurations, the approach chosen for this experiment was to focus on the ability of TDDs to deliver daylight, as this is a more intrinsic characteristic of the TDDs themselves and, therefore, less dependent on the evolution of lighting technologies.

4.3 Visual comfort

Generally, the DGP levels measured during this experiment were consistently below 0.35, indicating a significant probability of visual comfort in spaces where daylight is provided by TDDs. Measured DGP levels tended to drop off with increasing horizontal distance from the diffuser, although that trend was not strict in the vicinity of the diffuser (i.e., DGP levels measured from viewpoint A were sometimes lower than for viewpoints B and C). With the exception of viewpoint A, the effect of MDSA on glare did not appear significant. A smaller TDD diameter appeared to reduce DGP levels. The effect of dome type did not appear significant, with the exception of viewpoint D. There was also no clear trend in DGP regarding the diffuser type. This was somewhat surprising because, anecdotally, Fresnel diffusers can produce brighter spots. While this can be considered to add visual liveliness to the interior environment, one might expect it to cause higher measured DGP whenever the diffuser is in the field of view. It is not clear why this was not observed. One possibility is that the images of the bright spots are small enough that their image is smaller than the pixels of the sensors used to measure DGP and therefore their luminance and spatial extent are not correctly captured by such equipment. Further research is needed to better understand this. It should also be noted that, at 0.2 and lower, measured differences between DGP values may not correspond to differences in perceived glare, as DGP's experimental validation has not focused on this range.

5 Conclusions

Experimental tests of TDD lighting and visual comfort performance were conducted for a comprehensive variety of TDD configurations, including different TDD diameters (53 and 35 cm), dome types (prismatic and clear), and diffuser types (Fresnel and prismatic). Tests took place at different times of the year (low and high MDSA) and under a variety of sky types (clear, overcast, partly cloudy). The results obtained provide quantitative detail about what performance one might expect from TDDs for a range of TDD configurations and environmental conditions.

Overall, results indicate that, for clear sky, light levels and potential lighting energy increase with solar altitude (e.g., for configuration APP, DUDI/EUI were 97%/16 Wh/m^2 on a high MDSA day and 83%/34 Wh/m^2 on a low MDSA day) and TDD diameter (e.g., 86%/34 Wh/m^2 and 26%/69 Wh/m^2 for 53 cm and 35 cm TDDs, respectively, on a low MDSA day; 97%/16 Wh/m^2 and 90%/45 Wh/m^2 for 53 cm and 35 cm TDDs, respectively, on a high MDSA day). Large (53 cm diameter) TDDs can provide 300 lx average illuminance for a significant part of the day (DUDI always in excess of 80%)

The daily illuminance profile is more rounded for prismatic domes and has higher peaks for clear domes; this translates into a somewhat higher average DUDI for prismatic domes when compared to clear domes (86% versus 80%). No clear impact of diffuser type was apparent in the results.

Measurements indicated no discomfort glare for any of the conditions tested.

6 Acknowledgements

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