Daylighting Performance Assessment Methods for High-rise Residential Buildings in a Dense Urban Environment

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A thesis submitted in partial fulfillment of the requirements
for the Degree of Doctor of Philosophy

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December 2005

ABSTRACT

The daylight provision in buildings is usually safeguarded by building regulations. A number of daylighting design and assessment methods are also recommended by the international standards, design guides and research reports. A review of published literature suggests that most of the building regulations and assessment methods are originally developed for low-rise building environment. They are either not suitable or difficult to be adopted in a dense urban environment like that in Hong Kong. Therefore, other methods have to be explored for buildings in a dense high-rise environment. This research study aims to develop daylighting design and assessment methods for high-rise residential buildings in a dense urban environment. The study uses Hong Kong as an example of a dense urban environment.

The thesis presents methods for both general and detailed evaluation of daylighting performance. For most of the building designs, only a general assessment of the daylighting performance is required, especially at the early design stages. However, a detailed evaluation of the daylighting environment of a space provides useful information for the annual energy performance analysis, such as the energy saving potential for integrated daylighting and electrical lighting control.

For general evaluation, the thesis discusses the use of several performance metrics: indoor average daylight factors for indoor daylighting, the external vertical daylight factor on windows for skylight availability to a room, and probable sunlight duration on windows as an indicator for sunshine availability. Calculation methods for indoor average daylight factors, vertical daylight factor on windows and probable sunlight

duration were developed for buildings in a high-rise urban context. The calculations of average daylight factors and vertical daylight factor use the concept that the external view of the window is divided azimuthally into 36 segments, so that the exterior environment can be defined by 36 pairs of altitude angles describing the obstructions to daylight from the sky. As for the calculation of probable sunlight duration, a sky map of annual cumulative probable sunlight duration was constructed. The sky map presents the amount of probable sunlight from every portion of the sky hemisphere. A set of criteria for general daylighting performance assessment was developed using the data obtained from a questionnaire survey conducted in two residential building estates in Hong Kong.

Two metrics are proposed for use in the detailed daylighting performance evaluation methods; they are the exterior vertical illuminance and the annual daylight exposure received at the external surface of a window. A year's profile of exterior vertical illuminance can be reorganized to evaluate the number of hours in a year for which the illuminance falls into the range of useful daylight. It provides a realistic measure of the true daylighting performance of a window. It also provides useful information for visual comfort and energy saving analysis. If the annual total daylight availability of a window has to be evaluated, the annual daylight exposure can be calculated. The methods of evaluation of these two performance metrics are elaborated in the thesis.

As Hong Kong is one of the cities with very high building density, its regulatory control of daylighting in buildings is of great value to other urbanized areas. The performance-based approach, which is recently accepted as an alternative measure for regulatory control of daylighting in buildings, is reviewed in the thesis. It uses the vertical daylight factor at the centre of the window pane as the assessment parameter. The thesis discusses a new method called the orthographically projected area method which can be used for a fast evaluation of the vertical daylight factor at the window.

The main contribution to knowledge of this work is the development of workable calculation methods for the evaluation of daylighting performance for residential buildings in a dense high-rise urban environment. These calculation methods offer clear procedures of daylighting performance assessment so that the building design for natural light can be optimized. The input parameters can be easily manipulated geometrically during the early design stages. The results of the study can help the building developers, architects, engineers, lighting designers, building environment assessors as well as legislators to set up an effective daylighting assessment scheme for high-rise buildings in a densely packed building environment.

ACKNOWLEDGEMENTS

I would like to express my most sincere appreciation and gratitude to my chief supervisor, Dr. T. M. Chung, Department of Building Services Engineering, the Hong Kong Polytechnic University for his professional guidance and suggestions throughout the PhD study, as well as for his indispensable support to my personal development. The invaluable support from Professor John Burnett, my co-supervisor, must also be acknowledged.

I would like to thank all those who have assisted with this research study, in particular Mr. Ho, the Principal of the Sai Kung Central Lee Siu Yam Memorial School, and Mr. To Tak Tung. My thanks are also extended to Dr May Fan, Department of English, the Hong Kong Polytechnic University for her guidance on writing this thesis. Last but not the least, I am especially grateful to my parents for their unconditional affection and support.

CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written nor material which has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

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CONTENTS

Chapter 3 Review of daylighting design and assessment methods

Chapter 4 Research Methodology

Chapter 5 Development of general evaluation methods of daylighting performance

LIST OF TABLES

Chapter 7

Chapter 8

LIST OF FIGURES

Chapter 5

Chapter 6

Chapter 7

Chapter 8

LIST OF ABBREVIATIONS

BEPAC	Building Environmental Performance Analysis Club
BIPV	Building Integrated Photovoltaics
BRE	Building Research Establishment
BREEAM	BRE’s Environmental Assessment Method
BRS	Building Research Station
BSI	British Standards Institution
CASD	Census and Statistic Department
CIBSE	Chartered Institution of Building Services Engineers
CIE	International Commission on Illumination
HK-BEAM	Hong Kong Building Environmental Assessment Method
HKSAR	Hong Kong Special Administrative Region
IDMP	International Daylight Measurement Programme
IESNA	Illuminating Engineering Society of North America
LEED	Leadership in Energy and Environmental Design
PV	Photovoltaic
RHP	Rectangular horizontal plane
RIBA	Royal Institute of British Architects
SARS	Severe Acute Respiratory Syndrome
TRY	Test reference year
WMO	World Meteorological Organization

LIST OF SYMBOLS

		Unit
δ	Azimuth angle of an obstruction or ground patch	°
ϕ	Azimuth angle of a segment or sky patch	°
$\phi_{d,h,m}$	Solar azimuth at minute m of hour h on day d	°
ϕ_L	Azimuth angle defining the limit of the visible sky at the left of the line of sight	°
ϕ_R	Azimuth angle defining the limit of the visible sky at the right of the line of sight	°
ϕ_s	Solar azimuth	°
ϕ_{win}	Window azimuth	°
$\phi_{obs(\delta,\lambda)}^{sun}$	Solar azimuth angle relative to $obs(\delta,\lambda)$	°
ϕ_{ref}^{sun}	Solar azimuth angle relative to the reference point	°
γ	Altitude angle of a sky patch	°
$\gamma_{d,h,m}$	Solar altitude at minute m of hour h on day d	°
γ_s	Solar altitude	°
λ	Altitude angle of an obstruction or ground patch	°
θ	Limiting obstruction angle	°
Θ	Vertical angle subtended at the centre of window by the visible sky	°
θ_H	Altitude angle defining the upper limit of visible sky	°
θ_L	Altitude angle defining the lower limit of visible sky	°
$\theta_H^{obs(\delta)}$	Altitude angle defining the upper limit of external obstruction at azimuth angle of δ	°

$\theta_L^{obs(\delta)}$	Altitude angle defining the lower limit of external obstruction at azimuth angle of δ	°
$\theta_H^{sky(\phi)}$	Altitude angle defining the upper limit of visible sky at azimuth angle of ϕ	°
$\theta_L^{sky(\phi)}$	Altitude angle defining the lower limit of visible sky at azimuth angle of ϕ	°
ρ	Area weighted mean reflectance of all indoor surfaces	-
ρ_b	Average reflectance of obstructing building	-
ρ_{back}	Area-weighted average reflectance in the back half of a room	-
ρ_{cw}	Average reflectance of the ceiling and upper walls above the mid-height of the window (not including the window wall)	-
ρ_{fw}	Average reflectance of the floor and lower walls below the mid-height of the window (not including the window wall)	-
ρ_g	Average reflectance of the ground	-
ρ_o	Effective reflectance of the cavity between the building and the ground	-
$\sum_{\text{annual}} G_p$	Annual cumulative solar normal illumination energy density for the pth sky patch	lm·hr/m^2
$\sum_{\text{annual}} H_{sky(\phi,\gamma)}$	Annual cumulative luminance of $sky(\phi,\gamma)$	lm·hr/m^2·sr
A	Total area of all indoor surfaces	m^2
A_{fw}	Area of the floor and lower parts of the walls below the mid-height of the window (not including the window wall)	m^2
A_{win}	Window area	m^2

AIH_{ref}^{sky}	Annual skylight exposure received at the reference point	lm·hr/m^2
AIH_{ref}^{sun}	Annual sunlight exposure received at the reference point	lm·hr/m^2
$ASDF$	Annual sunlight duration factor	%
C	Illuminance ratio component on the window due to flux incident from above the horizontal	%
d/h	Space-to-height ratio	-
$D \times \rho_g$	Illuminance ratio component on the window due to flux incident from below the horizontal	%
$\overline{DF}_{all}$	Average daylight factor over all the interior room surfaces	%
$\overline{DF}_{wp}$	Average daylight factor on the working plane	%
DSC	Direct skylight component (expressed as a fraction)	-
$DSC^{sky(\phi)}$	Direct skylight component at the reference point due to the visible sky in the segment of azimuth angle ϕ (expressed as a fraction)	-
$dsc^{sky(\phi,\gamma)}$	Direct skylight coefficient of $sky(\phi,\gamma)$	-
$DSI_{gd(\delta,\lambda)}^{sky(\phi,\gamma)}$	Direct skylight illuminance at $gd(\delta,\lambda)$ due to $sky(\phi,\gamma)$	lx
$DSI_{obs(\delta,\lambda)}^{sky(\phi,\gamma)}$	Direct skylight illuminance at $obs(\delta,\lambda)$ due to $sky(\phi,\gamma)$	lx
$DSI_{ref}^{sky(\phi,\gamma)}$	Direct skylight illuminance at the reference point due to $sky(\phi,\gamma)$	lx
$DSI_{gd(\delta,\lambda)}^{sun}$	Direct sunlight illuminance at $gd(\delta,\lambda)$	lx
$DSI_{obs(\delta,\lambda)}^{sun}$	Direct sunlight illuminance at $obs(\delta,\lambda)$	lx
DSI_{ref}^{sun}	Direct sunlight illuminance at the reference point	lx

$DSIH_{ref}^{sun}$	Direct sunlight illumination energy density at the reference point	lm·hr/m^2
E_d	Diffuse horizontal illuminance due to the whole unobstructed sky	lx
E_{east}	Measured vertical illuminance at reference point facing east under real skies	lx
E_g	Global horizontal illuminance due to the whole unobstructed sky	lx
E_i	Interior horizontal illuminance	lx
E_n	Solar normal illuminance	lx
E_{west}	Measured vertical illuminance at reference point facing west under real skies	lx
E_d^{overcast}	Contribution of diffuse horizontal illuminance from overcast sky model	lx
$E_d^{\text{partly cloudy}}$	Contribution of diffuse horizontal illuminance from partly cloudy sky model	lx
f_o	Mixing factor of overcast sky	-
f_p	Mixing factor of partly cloudy sky	-
$gd(\delta,\lambda)$	Ground patch whose centre subtends an azimuth angle of δ from the normal to the reference plane and an altitude angle of λ above horizon	n/a
$grc^{sky(\phi,\gamma)}$	Ground reflected coefficient of $sky(\phi,\gamma)$	-
$GRI_{ref}^{gd(\delta,\lambda)sky(\phi,\gamma)}$	Ground reflected illuminance from $gd(\delta,\lambda)$ at the reference point due to $sky(\phi,\gamma)$	lx
$GRI_{ref}^{sky(\phi,\gamma)}$	Ground reflected illuminance at the reference point due to $sky(\phi,\gamma)$	lx
GRI_{ref}^{sun}	Ground reflected sunlight illuminance at the reference point	lx

$GRIH_{ref}^{sun}$	Ground reflected sunlight illumination energy density at the reference point	lm·hr/m^2
H	Height of building above the window head on the lowermost floor	m
H_W	Window head height above the floor	m
H_{win}	Height of window	m
H/W	Height of building to width of street ratio	-
K_s	Direct solar luminous efficacy	lm/W
K_d	Diffuse luminous efficacy	lm/W
K_s	Global luminous efficacy	lm/W
K_{oc}	Diffuse luminous efficacy for overcast sky	lm/W
L	Depth of an interior room	m
L_b	Average luminance of the obstructing building	cd/m^2
$L_{sky(\phi,\gamma)}$	Luminance value of $sky(\phi,\gamma)$	cd/m^2
L_z	Sky zenith luminance	cd/m^2
$L_{sky(\phi,\gamma)}^{\text{blended}}$	Luminance value of $sky(\phi,\gamma)$ of the blended sky model	cd/m^2
$L_{sky(\phi,\gamma)}^{\text{overcast}}$	Luminance value of $sky(\phi,\gamma)$ of the overcast sky model	cd/m^2
L_z^{overcast}	Zenith luminance of the overcast sky model	cd/m^2
$L_{sky(\phi,\gamma)}^{\text{partly cloudy}}$	Luminance value of $sky(\phi,\gamma)$ of the partly cloudy sky model	cd/m^2
$L_z^{\text{partly cloudy}}$	Zenith luminance of the partly cloudy sky model	cd/m^2
MBE	Mean bias error	%
$obs(\delta,\lambda)$	Obstruction patch whose centre subtends an azimuth angle of δ from the normal to the reference plane and an altitude angle of λ above horizon	n/a

OPA	Orthographically projected area of all obstructions above the horizontal at the base of a unit hemisphere	m^2
$OPAH^{sky(\phi,\gamma)}$	Orthographically projected area of $sky(\phi,\gamma)$ on a horizontal plane	m^2
$OPAH^{sky(\phi,\gamma)}_{gd(\delta,\lambda)}$	Orthographically projected area of $sky(\phi,\gamma)$ at the centre point of $gd(\delta,\lambda)$	m^2
$OPAV^{gd(\delta,\lambda)}_{ref}$	Orthographically projected area of $gd(\delta,\lambda)$ at the reference point	m^2
$OPAV^{obs(\delta,\lambda)}_{ref}$	Orthographically projected area of $obs(\delta,\lambda)$ at the reference point	m^2
$OPAV^{sky(\phi,\gamma)}_{obs(\delta,\lambda)}$	Orthographically projected area of $sky(\phi,\gamma)$ at the centre point of $obs(\delta,\lambda)$	m^2
$OPAV^{sky(\phi,\gamma)}_{ref}$	Orthographically projected area of $sky(\phi,\gamma)$ at the reference point	m^2
ORC_{above}	Obstruction reflected (above horizon) component (expressed as a fraction)	-
$orc^{sky(\phi,\gamma)}$	Obstructed reflected coefficient of $sky(\phi,\gamma)$	-
$ORC^{sky(\phi)}_{above}$	Obstruction reflected (above horizon) component at the reference point due to the obstruction in the segment of azimuth angle ϕ (expressed as a fraction)	-
$ORI^{obs(\delta,\lambda)sky(\phi,\gamma)}_{ref}$	Obstruction reflected illuminance from $obs(\delta,\lambda)$ at the reference point due to $sky(\phi,\gamma)$	lx
$ORI^{sky(\phi,\gamma)}_{ref}$	Obstruction reflected illuminance at the reference point due to $sky(\phi,\gamma)$	lx
ORI^{sun}_{ref}	Obstruction reflected sunlight illuminance at the reference point	lx
$ORIH^{sun}_{ref}$	Obstruction reflected sunlight illumination energy density at the reference point	lm·hr/m^2

$P_{d,h}$	Averaged bright sunshine duration for the hour h on the day d	hr
$P_{\phi\gamma}$	Annual cumulative probable sunlight duration for $sky(\phi,\gamma)$	hr
r_s	Non-parametric (Spearman's) rank order correlation coefficients	-
R^2	Coefficients of determination	-
RMSE	Root mean square error	%
S	Sky ratio	-
S_x	Depth of overhang	m
$S_{y,left}$	Depth of sidefin on the left of the line of sight	m
$S_{y,right}$	Depth of sidefin on the right of the line of sight	m
$sky(\phi,\gamma)$	Sky patch whose centre subtends an azimuth angle of ϕ from the south and an altitude angle of γ above horizon	n/a
SSDF	Summer sunlight duration factor	%
t	Window transmittance	-
TVI_{ref}^{sky}	Total vertical illuminance at the reference point due to the whole sky hemisphere	lx
$TVI_{ref}^{sky(\phi,\gamma)}$	Total vertical illuminance at the reference point due to $sky(\phi,\gamma)$	lx
TVI_{ref}^{sun}	Total vertical illuminance at the reference point due to the sun	lx
UVA	Unobstructed vision area	m^2
$V_{ref}^{gd(\delta,\lambda)}$	Visibility of the centre point of $gd(\delta,\lambda)$ at the reference point	-
$V_{ref}^{obs(\delta,\lambda)}$	Visibility of the centre point of $obs(\delta,\lambda)$ at the reference point	-

$V_{gd(\delta,\lambda)}^{sky(\phi,\gamma)}$	Visibility of the centre point of $sky(\phi,\gamma)$ at the centre point of $gd(\delta,\lambda)$	-
$V_{obs(\delta,\lambda)}^{sky(\phi,\gamma)}$	Visibility of the centre point of $sky(\phi,\gamma)$ at the centre point of $obs(\delta,\lambda)$	-
$V_{ref}^{sky(\phi,\gamma)}$	Visibility of the centre point of $sky(\phi,\gamma)$ at the reference point	-
$V_{gd(\delta,\lambda)}^{sun}$	Visibility of the sun at $gd(\delta,\lambda)$	-
$V_{obs(\delta,\lambda)}^{sun}$	Visibility of the sun at $obs(\delta,\lambda)$	-
V_{ref}^{sun}	Visibility of the sun at the reference point	-
$vsc^{sky(\phi,\gamma)}$	Vertical skylight coefficient of $sky(\phi,\gamma)$	-
VDF	Vertical daylight factor	%
W	Width of an interior room	m
W_{win}	Width of window	m
$WSDF$	Winter sunlight duration factor	%

CHAPTER 1
INTRODUCTION

1.1 Motivation

There is now increasing concern regarding building energy consumption and indoor environmental quality. Daylight is considered to be a renewable lighting energy resource which supports human activities and has positive effects on human health. Many research findings suggest that human should function better emotionally and physically under natural light in which the human bodies are designed to operate. In many countries, the daylight provision in a building is safeguarded by building regulations which aim to maintain the minimally acceptable living conditions. In some cities, the building density can be so high that the existing building regulations may not guarantee a satisfactory daylight performance. There are some daylighting design and assessment methods which are recommended by the international standards, design guides and research report. They all target to provide a better-than-minimum performance. However, a review of published literature suggests that most of the methods are developed for low-rise building environment. The external view of the window is usually assumed to be blocked by infinitely long obstruction so that it can be defined by an obstruction angle. This assumption is difficult to be applied to windows in a densely packed building environment where the skylines are usually irregular and complicated. It results in that some of the building designers may wrongly apply the obstruction angle assumption or even disregard the daylighting design of a building development. Therefore, new methods, which are suitable to be adopted in a dense urban environment, are in great demand. Apart from the daylighting design and assessment methods, suitable daylighting design criteria are also important for setting out the guidelines for daylighting design. Owing to the lack of data in a high-rise building environment, the architects and site layout planners usually adopt the general design criteria which are essentially developed for low terrace type buildings. The validity of the general design criteria has not been tested for use in locations with high building density. Therefore, alternative daylighting design methods and criteria have to be explored. In this research study, daylighting performance assessment methods were developed for high-rise residential buildings in dense urban environment. The methods offer clear procedures of daylighting performance assessment so that the building design for natural lighting can be optimized. The results of the study can help the building developers, architects, engineers, lighting designers, building environment assessors as well as legislators to set up an effective daylighting assessment scheme in a densely packed building environment.

1.2 Purpose of study

The intensity of daylight varies with time of a day and day of a year. A detailed evaluation of the daylighting environment of a space may include the daily illuminance level profile of every day in a year. This involves relatively more complicated calculations and larger amount of input parameters, but in return it provides useful information for annual energy performance analysis, like the energy saving analysis for integrated daylighting and electrical lighting control. For most building designs, however, a general evaluation of the daylighting performance of a space is already enough, especially at the preliminary design stage. The evaluation method should be able to assess the overall daylighting environment based on occupants' satisfaction. Besides, it should be simple and yet accurate. In order to develop suitable daylighting design methods and criteria for dense urban building environments, three objectives are set out:

Objective 1 - To review the parameters used for daylighting design and assessment and to find out suitable parameters for general and detailed evaluation of daylighting performance of a densely packed building development.

Objective 2 - To develop calculation methods and design criteria for the general evaluation parameters which are suitable to be used in a densely packed building development.

Objective 3 - To develop calculation methods for the detailed evaluation parameters which are suitable to be used in a densely packed building development.

To achieve the above objectives, the characteristics of Hong Kong, which is a city with very high building density, were first studied. Then the parameters and methods used for daylighting design and assessment were reviewed. A survey was conducted for the building standards, published journal papers, design codes and design guides. The principles, assumptions and limitations of each method were studied for evaluation of the suitability of the method to be adopted in a high-rise building environment. The review provides valuable background information for this research. Suitable parameters were selected for general and detailed evaluation of daylighting performance of a densely packed building development.

The next step of the research study was to develop the calculation methods for the selected parameters. The existing calculation methods were first studied. Then they were modified to be adopted in dense urban area. For the selected parameters which had no available calculation method, new methods were developed by studying various components of daylight and the effect of obstruction in a densely packed building environment. Some of the methods were based on the meteorological data and building environment in Hong Kong. However, the concepts and principles of the methods should be applicable to other cites where high-rise building blocks are closely packed in a limited land area. Calculation methods of the general evaluation parameters were first developed. In order to construct a set of daylighting design criteria, the relation between user satisfaction of a daylight environment and the numerical values of the assessment parameters was investigated by conducting a questionnaire survey. This survey aims to find out the critical values of the selected general evaluation parameters which result in different ratings of user satisfaction, so that a set of daylighting design criteria could be developed. After that, calculation methods of the detailed evaluation parameters were developed. The accuracy of the method was tested by computer simulations and measurements under real skies. The computer simulations were carried out by RADIANCE which is a backward raytracer based on a mixed stochastic and deterministic raytracing approach. A physical model was also constructed to measure the selected parameter under real skies. The calculation results were compared with the computer simulation results as well as the measurement results.

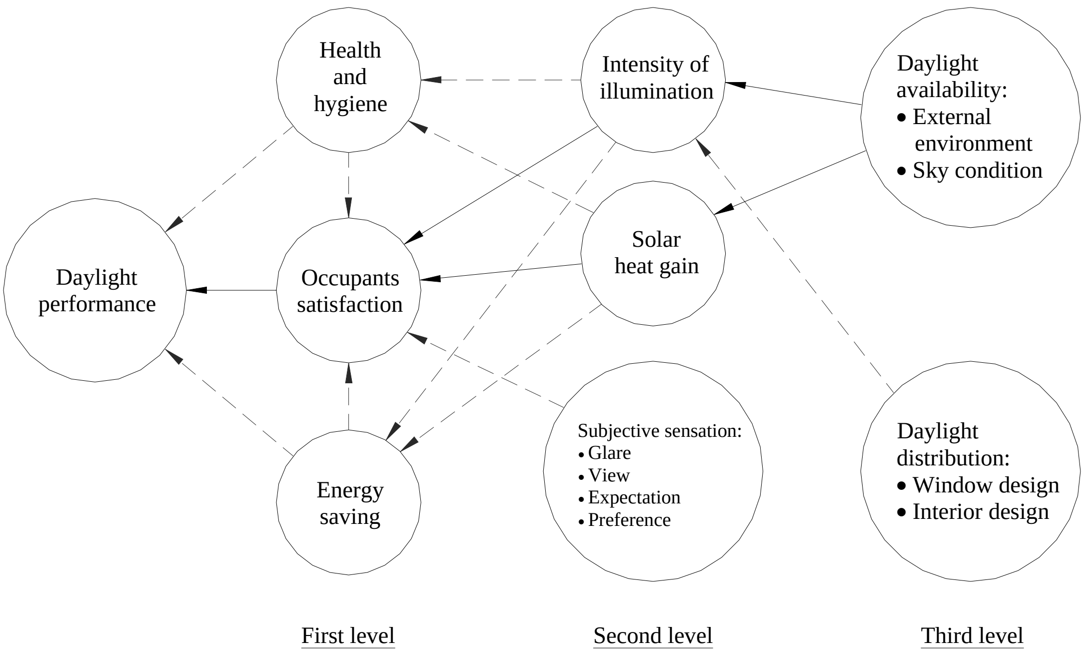
As Hong Kong is one of the cities with very high building density, its regulatory control of daylighting in buildings is of great value to other cities. Recently the Hong Kong government has accepted a performance-based approach as an alternative measure for regulatory control of daylighting in buildings. This approach may be applicable to other densely packed building environment. It could be adopted at the preliminary design stage. Therefore, this assessment method was also studied in this research.

1.3 Scope of study and hypothesis

Daylighting is an environmental system which is subjected to the photometry of natural light. Photometry is the only measurement science that is based on the human sense, which is probably the most complicated subject in the world science. There are many different approaches to assess human sense and daylight environment of an interior. In this thesis, the daylighting performance of an interior is hypothesized to be assessed at three levels which are shown in Figure 1.1. At the first level, the daylighting performance is assessed according to three factors: health and hygiene, occupants' satisfaction and energy saving. People spend most of their time inside a building. It is of utmost importance that the interior environment is safe and healthy. This factor of daylight performance should be regulated by the building laws which ensure the health and safety of people in and around buildings by imposing functional requirements for building design and construction. It is assumed that the existing building regulations are adequate to safeguard the daylight provision and therefore this factor is not the focus of this study. The next factor of daylight performance is the occupants' satisfaction. Occupants are the ultimate users of a building. The building services systems, including daylighting, should be designed to satisfy the requirements of the occupants. In this study, the occupants' satisfaction is considered to be the most critical factor in daylight performance assessment. As the earth is running out of natural resources and the environment is worsened by various kinds of pollution, the environmental issue would be the researchers' major concern. Energy saving is the third factor of daylight performance. As environmental conscious designs should be promoted, a daylighting design that saves energy and reduces electricity consumption should be recognized as better performance. In the development of the daylighting design and assessment methods, energy saving is taken into considerations, but the possible amount of energy saving by the daylighting design scheme is not the interest of this research.

At the second level, the focus is on the relationship between occupants' satisfaction and the three factors: intensity of illumination, solar heat gain and subjective sensations. The occupants' satisfaction is highly related to the intensity of illumination of an interior as it affects the visibility of the objects in a space. The second factor is solar heat gain. It affects the thermal comfort of the occupants, thus the occupants' satisfaction. Apart from the intensity of illumination and the solar heat gain, there are some other subjective sensations which affect the occupants' satisfaction. They include daylight glare, satisfaction to the view provided by the window as well as expectation and preference of an individual. The effect of these factors to the satisfaction of a daylight environment varies among different individuals. In this study, it is assumed that these factors have relatively less effects on the occupant's satisfaction in comparison with the intensity of illumination and solar heat gain. Therefore they are not the main concern of this study.

At the third level, the focus is on the relationship between intensity of illumination and the two factors: daylight availability at a window and daylight distribution in an interior, as well as the relationship between solar heat gain and these two factors. The daylight (sunlight and skylight) availability at a window is affected by the external environment of the window and the sky condition. The daylight distribution in an interior is affected by the window and interior designs. Both factors will influence the intensity of illumination and the solar heat gain of an interior. In a dense urban environment, daylight availability at the window is very important because without sufficient daylight on the window, the interior would not be well daylit even if the window and interior designs are excellent. Therefore, daylight availability at the external surface of the window is considered to be the main focus of this research study. It is hypothesized in this study that the daylight availability at a window will affect the intensity of illumination and solar heat gain of an interior, and therefore it will affect the occupants' satisfaction and finally it will determine the daylighting performance of a room.



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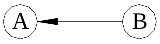
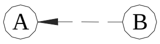


The influence of "B" on "A" is the focus of the study.



The influence of "B" on "A" is not the focus of the study.

Figure 1.1 The hypothetical model of this study

1.4 Importance of study

People spend most of their times in buildings. It is of utmost importance that the indoor environment is safe and comfortable. In order to promote a satisfactory interior daylight environment, daylighting design and assessment methods are aimed to be developed for high-rise buildings in dense urban environment. The study focuses on the methods for both general and detailed evaluation of daylighting performance. The methods encourage efficient use of daylight inside buildings. The outcomes of the research study offer clear procedures of daylighting performance assessment so that the building design for natural lighting can be optimized. The study offers simple and yet accurate methods for general evaluation of daylighting performance. The input parameters can be easily manipulated geometrically during the early design stages. The detailed daylighting performance evaluation method allows energy performance analysis of various energy conservation systems, like the integrated daylighting and electrical lighting control system, as well as the building integrated photovoltaic system.

The findings of the study help to build up an understanding of the relation between the subjective sensations to a daylight environment and the quantitative assessment parameters. Although some of the assessment methods were based on the meteorological data of Hong Kong, the concepts and principles of the methods should be applicable to other dense urban environment. The outcomes of the study could help the building developers, architects, engineers, lighting designers, building environment assessors as well as legislators to set up an effective daylighting assessment scheme for high-rise buildings in a densely packed building environment.

1.5 Organization of thesis

This thesis is organized into nine chapters. Chapter 1 is the introduction. Chapter 2 presents the general information of Hong Kong, including its weather, demographics, building environment and building regulations. The performance based approach, which is accepted by the Hong Kong government as an alternative measure for regulatory control of daylighting in buildings, is also introduced in this chapter. Chapter 3 gives a brief review of the daylighting design and assessment methods. The principles, assumptions and limitations of each method are presented. This chapter also gives a discussion on the selection of suitable parameters for general and detailed evaluation of daylighting performance of a densely packed building development. Chapter 4 explains the methodology for the development of the daylighting design and assessment methods. In chapter 5, calculation methods of the selected parameters described in chapter 3 for general evaluation of daylighting performance are presented. These general evaluation parameters include the average daylight factors, vertical daylight factor and probable sunlight duration. The development of daylighting design criteria for the vertical daylight factor and probable sunlight duration is presented in chapter 6. It was done by conducting a questionnaire survey which investigated the relation between user satisfaction of a daylight environment and the numerical values of the selected parameters. In chapter 7, calculation methods of the parameters selected in chapter 3 for detailed evaluation of daylighting performance are presented. The detailed evaluation parameters include the exterior vertical illuminance and annual daylight exposure received by a window. This chapter also gives an account of the accuracy of the calculation method of exterior vertical illuminance based on tests by computer simulation and measurement under real skies. The performance-based approach, which is accepted by the Hong Kong government as an alternative measure for regulatory control of daylighting in buildings, is studied in chapter 8. A conclusion of the research is drawn in chapter 9 which also discusses the limitations of the research and needs for further research study.

CHAPTER 2
GENERAL INFORMATION OF HONG KONG

2.1 Introduction

Hong Kong, with a population of about 7 million in a land area of just over 1,000 km^2, is one of the most densely populated cities in the world. As the population and number of domestic households are expected to increase continuously, a large number of densely-packed building estates of tall residential blocks are built to meet the ever increasing demand. In this study, calculation methods of the selected evaluation parameters were developed for daylighting design and assessment. Although some of the parameters were evaluated using the meteorological data in Hong Kong, the calculation methods should be applicable to other cities using the local weather data. This chapter presents the general information of Hong Kong. The weather as well as the demographics and building environment are briefly described. In Hong Kong, the daylight provision is safeguarded by the Building (Planning) Regulations under the Hong Kong Law Chapter 123 – Building Ordinance (HKSAR, 1997). The clauses governing the daylighting environment of a building will be introduced. Besides, the performance-based approach, which is recently accepted by the Buildings Department as an alternative measure for regulatory control of daylighting in buildings, will also be introduced.

2.2 Weather in Hong Kong

Hong Kong (22.3° N, 114.2° E), a Special Administrative Region of China, locates at the south-east coast of the Continent of Asia opposite to the South China Sea. Hong Kong's climate is sub-tropical, tending towards temperate for nearly half the year. Winter is around December to March. These months are characterized by the winter monsoon blowing from north or north-east. As the dry cold air from the continent meets the warm wet air over the ocean, frequent cloud outbreaks occur over Hong Kong especially during the later part of winter. In springtime, there are occasional spells of high humidity in March and April. Fog and drizzle are common on high ground which is exposed to the southeast. March is the month that overcast sky (cloud cover equals 8 oktas) is most common. The average daily bright sunshine duration is less than three hours in this month. Summer is long, hot and humid. It may last from May to September. Active south or south-west monsoon in the early part of summer brings occasional heavy showers and thunderstorms. Long periods of sunny days with high insolation are common especially during the later part of summer. The daily global solar radiation peaks in July at about 17 MJ/m^2. Besides, tropical cyclones originating over the west Pacific Ocean may strike the territory bringing strong winds and heavy rain lasting for a few consecutive days. The autumn in Hong Kong is short and may last from October to November. During these months, there are breezes and plenty of sunshine in comfortable temperatures. There are about six hours of daily bright sunshine on average. Clear sky (0 oktas) is observed most frequently in December. According to the meteorological data collected from 1970 to 2000, the monthly average air temperature, daily global solar radiation, daily bright sunshine hours and the frequency of occurrence of various cloud cover are shown in Figure 2.1 to Figure 2.4.

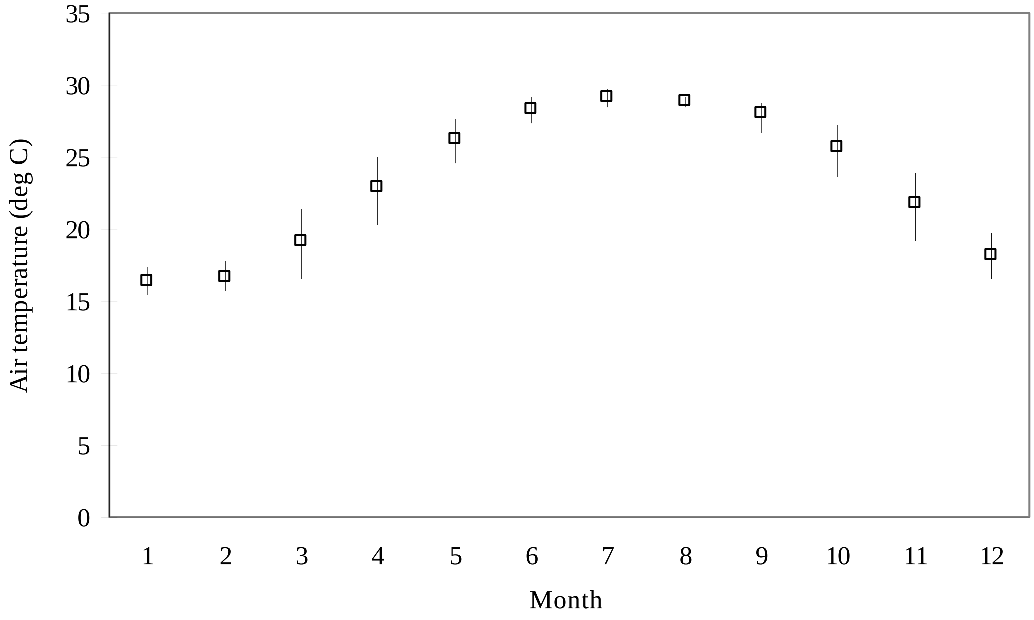


Figure 2.1 Monthly averaged air temperature (averaged over 1970-2000)

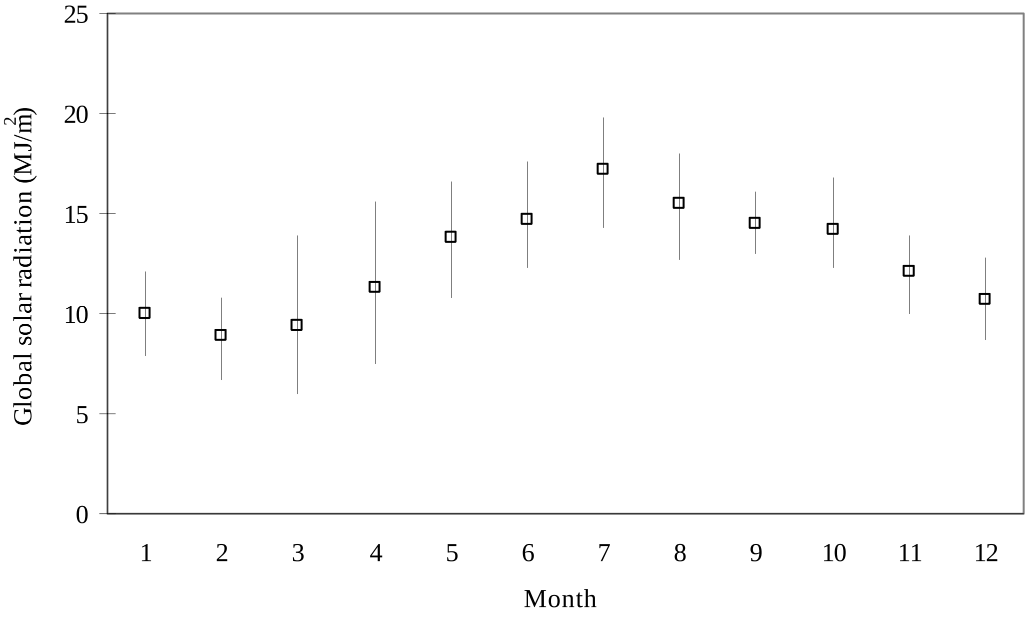


Figure 2.2 Monthly averaged daily global solar radiation (averaged over 1979-2000)

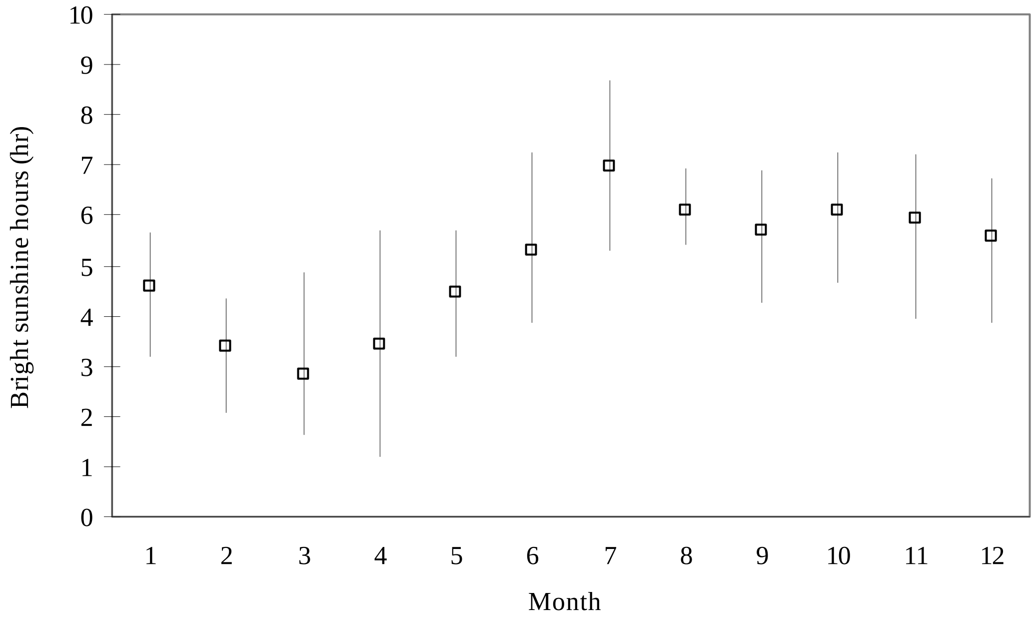


Figure 2.3 Monthly averaged daily bright sunshine hours (averaged over 1970-2000)

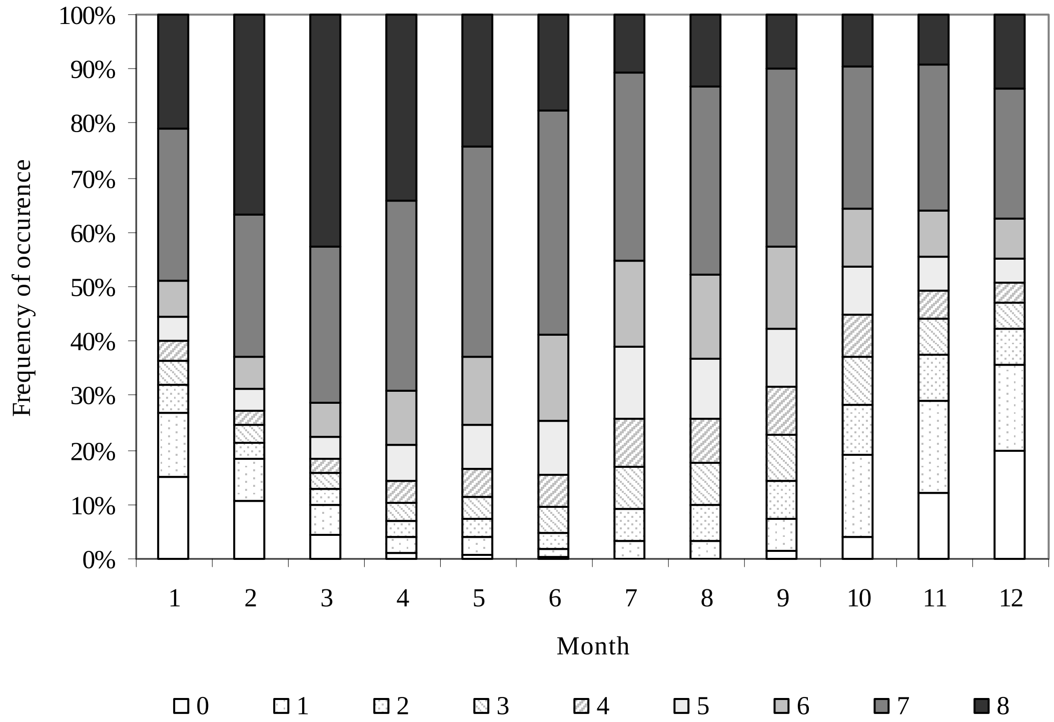


Figure 2.4 Cloud cover in oktas (averaged over 1970-2000)

The global solar radiation is measured by the Hong Kong Observatory since 1978. The hourly global solar radiation values are measured at King's Park by a thermoelectric pyranometer (sealed thermo-pile dome solarimeter) together with an integrating counter. A bimetallic actinograph is used as a back-up. The daily global solar radiation has the highest value in July and lowest value in February. It may be partly explained by the long day length in July and short day length in February. Radiation on vertical surfaces is not measured by the Hong Kong Observatory. Besides, there is no data for the diffuse radiation or the instantaneous irradiance value. Apart from the Hong Kong Observatory, a measuring station was set up at the City Polytechnic University of Hong Kong (Lam & Li, 1996a, 1996b) to measure the hourly horizontal global and diffuse radiation since 1991. Vertical global solar radiation and daylight illuminance on the four major compass orientations are also measured since 1996 (Li & Lam, 2000a, 2000b, 2002). Another measuring station was also set up at the Chinese University of Hong Kong in 2002. Vertical solar radiation values are recorded in addition to the horizontal radiation.

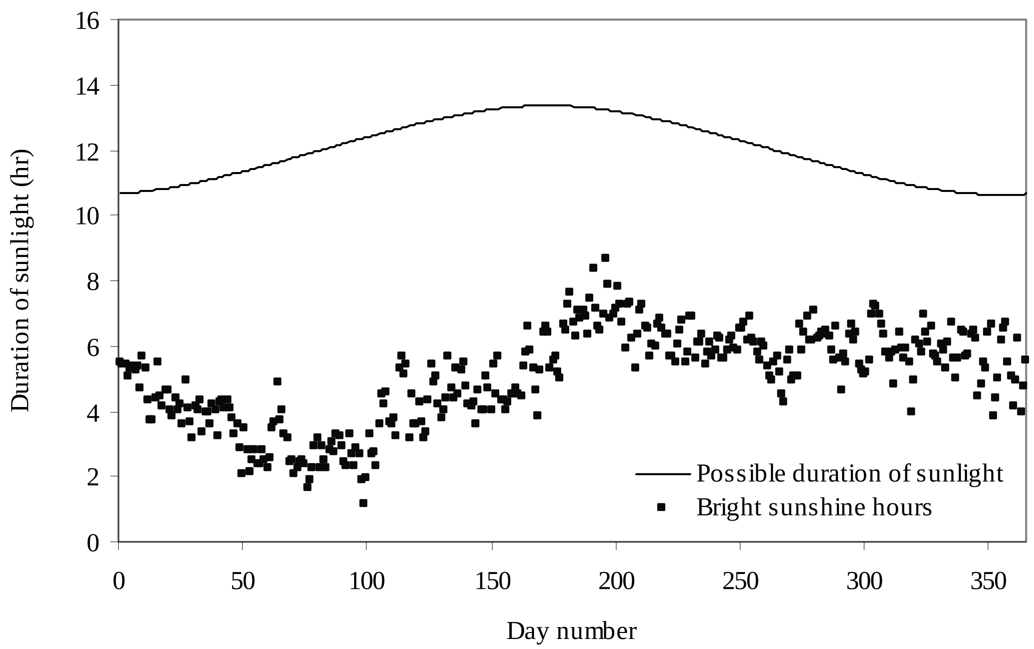


Figure 2.5 Averaged daily bright sunshine hours (averaged over 1970-2000) and possible duration of sunlight

The bright sunshine hours are measured and recorded at King's Park by a Campbell-Stokes recorder. The bright sunshine hour reading is expressed in fraction of an hour over a 60-minute apparent solar time interval centred at the hour. Based on the Hong Kong Observatory data from 1970 to 2000, the average value of annual bright sunshine hours for a horizontal plane is about 1842 hours. The bright sunshine hours have the smallest value in March because of the short day length and the heavy cloud and humid weather conditions during this period. Figure 2.5 compares the average possible duration of sunlight between sunrise and sunset and the average daily bright sunshine hours in Hong Kong from 1970 to 2000. It is observed that November has the highest ratio of bright sunshine hours to possible duration of sunlight. Therefore, the bright sunshine should be most likely to occur in November. The type of cloud and the amount of cloud cover is observed visually and recorded by skillful observer hourly. The cloud cover data is usually used to categorize the type of sky. Skies without cloud (0 oktas) and totally covered by cloud (8 oktas) are normally treated as clear and overcast skies respectively, while the rest of the sky conditions (1-7 oktas) are considered to be partly cloudy. Based on the meteorological data collected by the Hong Kong Observatory from 1970 to 2000, about 20% of the daytime is overcast (8 oktas), 6% is clear (0 oktas) and the rest of 74% is partly cloudy (1-7 oktas).

2.3 Demographics and building environment in Hong Kong

Hong Kong’s 1,102 km^2 of land contains 6.8 million people. It is one of the world’s most densely populated cities. Most of the population is being housed in 214 km^2 of urban development (HKSAR, n.d.). The population of Hong Kong increased from 5.8 million in mid-1992 to 6.8 million in mid-2002 (CASD, 2003). Although the natural birth rate is declining faster than the death rate in recent years, there is in-flow of population from mainland China resulting in the overall growth rate. The population is expected to increase continuously and reach 8.38 million in 30 years' time according to the population projections released by the Census and Statistics Department (CASD, 2004). Besides, the number of domestic households increases faster than the population. It put more pressure on the demand of residential flats, thus a large number of densely-packed building estates are built to meet the ever increasing demand. With limited land area, there is a tendency for developers to build tall residential buildings. The inhabitant density of many building estates could be as high as 300,000 inhabitants per km^2.

In order to maximize the space from the finite resources of land, most building developments are high-rise building blocks. The height of residential building is becoming higher and higher in order to maximize the sellable area. The number of storeys for some of the residential blocks may even go to 60. A compact cruciform building plan of eight units per floor is normally adopted to allow habitable rooms with windows facing outward and having maximum clearance from one another. It results in that the building planners usually have little or even no consideration of orientation for better daylight performance. The building blocks are so closely packed that the block-to-block distance could be as close as 10 m. It results in severe sky obstructions and limitation of the admittance of natural light for flats on the lower floors.

2.4 Building regulations in Hong Kong

The planning, design and construction of buildings in Hong Kong are regulated under the Hong Kong Law Chapter 123 – Building Ordinance. Part IV of Subsidiary F1 – Building (Planning) Regulations concerns about the Lighting and Ventilation provisions for a building. This part aims to safeguard the occupants in office or residential buildings with effectual means of lighting and ventilation. The building regulations include two prescriptive requirements on natural lighting. The first requirement is that all habitable rooms shall be provided with glazing area equal to at least 10% of the floor area. Windows with area of at least 6.25% of the room floor area shall be openable. The top of the opening shall be at least 2 m or 1.9 m above the floor for detached and semi-detached buildings respectively. The second requirement relates to the minimum separation between building blocks based on an uncovered and unobstructed rectangular horizontal plane (RHP) in front of the window. The required dimensions of the RHP for habitable rooms are a minimum length defined by a maximum vertical obstruction angle of 71.5° and a minimum width of 2.3 m. The distance limited by this angle is equivalent to one-third of the building height. The window sill height shall be at a level 1 m above the room floor level. Therefore, the window sill height shall be considered as 1 m above the floor level when calculating the vertical obstruction angle, whether or not the sill is at such level. The regulation also limits the distance from anywhere in a room used for habitation to the window to be not more than 9 m. Also, the floor to ceiling height of an office or habitation in any building shall be not less than 2.5 m.

The clauses mentioned above, which are still currently in use, were first introduced in 1956, but they have their origins dated back to as early as 1894 (Ng, 2003b). In the past decades, the building environment in Hong Kong has been changed from low-rise terrace type to dense urban area with high-rise buildings. The regulation governing the daylighting provision is now out of date. Besides, the recent trend of smaller households and the growth of population have resulted in a steady increase in the number of households and hence a requirement of more residential units. With limited land area, there is a tendency for developers to build even taller residential buildings. In order to satisfy the existing prescriptive requirements, developers have to set aside a wider separation between glazed facades for taller buildings. In 1999, the Building Department of Hong Kong commissioned a study to look into the regulations concerning lighting and ventilation in buildings with an intention of allowing more design flexibility than that permitted by the prescriptive method. The lighting part was undertaken by a team of researchers at the Chinese University of Hong Kong led by Ng (Buildings Department, 2004). After the completion of the consultancy study, the Buildings Department issued a Practice Note (Buildings Department, 2003) on the performance-based approach in lighting and ventilation requirements. The Practice Note allows an alternative approach in assessing the daylighting performance of a building. This performance-based approach is, at the time of writing up of this thesis, on a 2-year trail period commenced December 2003. The performance-based approach will be briefly introduced in the following section.

2.5 Performance-based approach of building regulations in Hong Kong

The performance-based approach suggested by the Buildings Department is introduced in the Practice Note PNAP278 (Buildings Department, 2003). It is applicable to domestic buildings and uses the vertical daylight factor (*VDF*) at the centre of the window pane as an alternative measure for regulatory control of daylighting in buildings. According to PNAP278, *VDF* is defined as "the ratio in percentage of the total amount of illuminance falling onto a vertical surface of a building to the instantaneous horizontal illuminance from a complete hemisphere of sky excluding direct sunlight". It takes into account light coming from the sky directly and from reflected light of surrounding buildings and ground both above and below the horizon. The sky luminance distribution is normally assumed to be the CIE standard overcast sky. According to the consultancy study undertaken by Ng (Buildings Department, 2004), a daylight performance survey, which was conducted in residential buildings in Hong Kong in 2003, suggests that the occupancy satisfaction rate stays at a certain level once the *VDF* is above 8% for habitable rooms and 4% for kitchens. These two *VDF* criteria are adopted as the performance-based approach for daylight environment assessment in buildings in Hong Kong (Buildings Department, 2003). The *VDF* requirements of the performance-based approach are tabulated in Table 2.1.

Table 2.1 *VDF* requirements of the performance-based approach in Hong Kong

Room of domestic building	VDF at centre of window pane
Habitable room	8%
Kitchen	4%

The design of buildings can be based partly on the unobstructed RHP requirements and partly on the performance standards. It is stated that demonstration of compliance to the performance standards can be by any suitably verified and scientifically validated methods. However, the calculation of *VDF* is not a simple task and may require computer simulation using detailed data of the geometry and surface properties of the building itself and surrounding buildings. In many cases, detailed data are not available and designers may want to compare several design options with just rough sketches. Therefore, a simplified assessment method called the unobstructed vision area (UVA) method is recommended as a reliable way to demonstrate compliance to the *VDF* requirements for daylighting in buildings.

The UVA method assumes that the value of *VDF* at the lowermost window is directly proportional to the two-dimensional *UVA* in front of the window. The UVA method allows easy adoption of performance-based approach for site planners and architects who are unfamiliar with daylighting calculations. The *UVA* is defined as the horizontal open area in a “cone” that the window “sees” when the “cone” is overlaid onto the site plan. The so-called “cone” is actually a sector (of a circle), or a fan-shaped area, on the plan. This sector is symmetrical, perpendicular to the window, 100° wide and length is equal to the height of the façade (measured from the window upper edge) in which the window is provided. The sector for measurement of *UVA* was originally based at the centre of the window pane as shown in Figure 2.6. It was subsequently modified after receiving opinions from professional representatives so that PNAP278 allows measuring the UVA sector as projected up to both edges of the window glazing pane and the maximum length of the UVA fan-shaped area should be measured from the external wall surface containing the window glazing pane, instead of from the sector base. The revised method of *UVA* measurement is shown in Figure 2.7. In PNAP278, the *UVA* requirement is given for compliance to the performance standards. It is given for habitable room (8% *VDF*) and domestic kitchen (4% *VDF*) with glazing area equal to 10%, 15% and 20% of usable floor area. The required minimum *UVA* for habitable room of glazing area equal to 10% of usable floor area is extracted in Table 2.2. For the detailed *UVA* requirement specified by PNAP278, please refer to Appendix A1. In chapter 8, a review of the UVA method will be presented and its correlation with *VDF* will be validated.

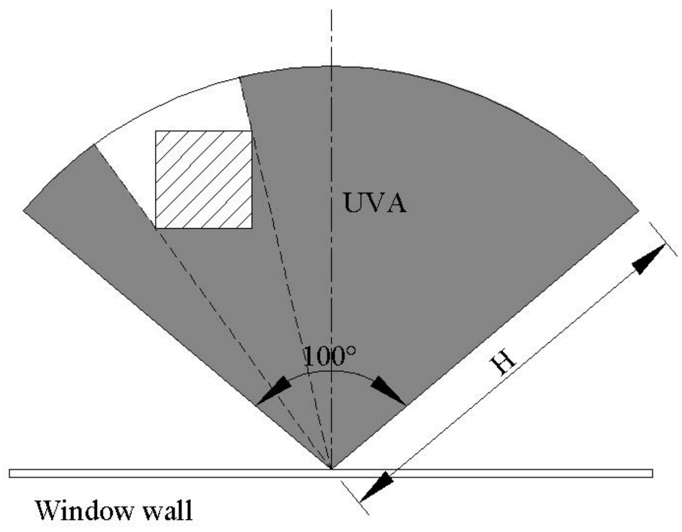


Figure 2.6 Measurement of *UVA* in the original study

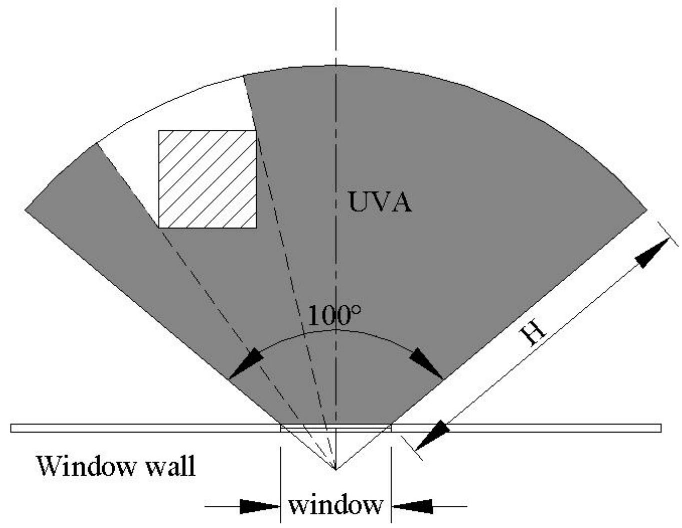


Figure 2.7 Measurement of *UVA* in PNAP278

Table 2.2 Minimum *UVA* for satisfying *VDF* requirement of 8%

Height of building (m)	Minimum UVA (m^2) for habitable room with glazing area equal to 10% of usable floor area
10	50
20	100
30	250
40	400
50	600
60	900
70	1200
80	1600
90	2000
100	2400
110	2900
120	3500
130	4100
140	4800
150	5400
160	6200
170	7000
180	7800
190	8700
200	9600

CHAPTER 3
REVIEW OF DAYLIGHTING DESIGN AND ASSESSMENT METHODS

3.1 Introduction

This chapter starts by introducing the nature of daylight and the reasons to utilize daylight in buildings. The problems associated with daylight are also briefly discussed. As daylight availability at the external surface of the window is considered to be the critical factor affecting the daylighting performance of an interior, the factors affecting the daylight availability at a window are reviewed. This chapter focuses on previous researches on the daylighting design and assessment methods. The principles, assumptions and limitations of each method are discussed. Suitable parameters are selected to be used for general and detailed evaluation of daylighting performance of a densely packed building development. The daylighting design criteria suggested by international standards, recommendations and voluntary assessment schemes are also reviewed.

3.2 Nature of daylight

Sun can be thought of the origin of all lives on earth. Sun gives out heat and light which fertilizes all the living organisms, including human. It is approximately 150 billion metres away from the earth. The radiation from the sun is transmitted in form of electromagnetic waves, including ultraviolet wave, visible light and infrared wave. Visible light from the sun is generally the main source of natural light on earth, although meteorological phenomenons like fire and lightning, insects like fireflies and materials like phosphorus can also emit light, they are rarely treated as light sources. During the travel of solar radiation to the earth’s surface, some of the energy is lost due to selective scattering, diffuse reflection, and absorption in the atmosphere. Therefore, the amount of radiation reaching the earth's surface varies with geographic locations and local weather conditions. The light reaching the ground in this way is called daylight which consists of the sunlight and skylight components. The direction of sunlight is expressed in terms of two angles: solar altitude (ϕ_s) and solar azimuth (γ_s). Solar altitude is the vertical angle of the sun above the horizon and solar azimuth is the horizontal angle of the sun from due south in the northern hemisphere. The sky we see from the ground is luminous as it scatters light coming from the sun. Sky is in fact small suspended particles, such as dust and water vapour, which act to diffuse and scatter the sunlight as it passes through the atmosphere. This scattering, together with clouds, produces sky luminance. The diffuse light coming from the sky hemisphere (not including the sun) is called skylight. In this study, daylight is treated as the natural light from the whole sky hemisphere, including the sunlight and skylight (either direct, reflected or interreflected). The total horizontal illuminance on the earth's surface may exceed 100 klx on clear days; on cloudy days the illuminance may drop to less than 10 klx. The wavelength of daylight ranges from 380 nm to 760 nm. Although the spectral distribution of daylight changes continuously with sun position and sky conditions, daylight is generally a full-spectrum light source which contains a higher portion of the short wavelength spectrum (around 450 nm). See Figure 3.1 for the spectral radiant power distributions of daylight (GE Consumer & Industrial Lighting, n.d.). The apparent colour of daylight varies continually. The colour temperature of daylight generally lies between 4,000 K and 10,000 K, but may be lower near sunrise and sunset. Overcast skies are generally associated with lower colour temperature (4,500 K - 7,000 K), and clear skies with high colour temperatures (about 10,000 K).

Sunlight has a colour temperature in the 4,000 K - 5,500 K range, depending on solar altitude.

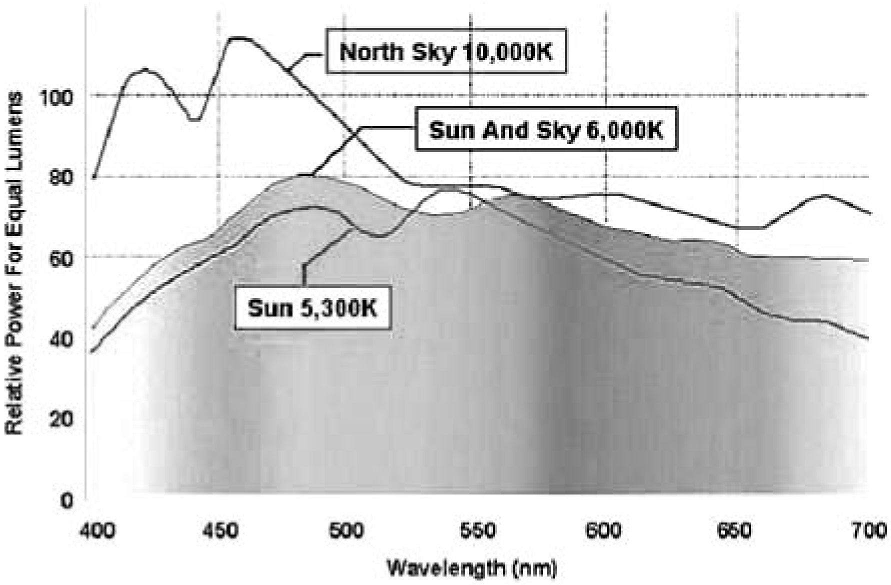


Figure 3.1 Spectral radiant power distributions of daylight

3.3 Reasons to utilize daylight in buildings

With today's advanced technology, we can rely on electricity and artificial light. Then what are the reasons for a building to utilize daylight for which electrical light could substitute? The answer is that daylight has some properties that artificial light (up to this moment) cannot replace. People are all born to live under natural daylight. Daylight is considered to be the best source of light for its excellent colour rendering, colour temperature and quality. It is the light source that closely matches human visual response. Human's eyes adapt to the high daylight illuminance level provided by daylight which may exceed 100 klx under clear sky. However, the normal illuminance level provided by electrical lighting in typical office is only around 500 lx to 1,000 lx. Apart from the illuminance level, the dynamic nature of daylight is also an advantage. It changes in intensity from time to time and season to season.

This variability can bring certain richness to many building designs and add interest to a space. In the psychological point of view, daylight gives a sense of cheeriness, warmth and brightness that can have a significant positive impact on people. Daylight inside a building must enter through an aperture, like a window which offers the occupants a view out. Its presence is considered beneficial because it allows the occupants to keep in touch with the exterior environment. It also offers opportunity for refreshment and relaxation by a change of scene and focus. In fact this psychological or emotional benefits arising from contact with outside was ranked the highest among the advantages ascribed to daylight by architects and engineers (BRE, 1988).

The potential for energy conservation is another attractive reason of utilizing daylight. In the past thirty years, energy efficiency has been an important consideration in good building design. The initial motivation for reducing energy consumption was financial. It was a response to the dramatic increases in fuel prices in the 1970s. Later, environmental problems like global warming, ozone depletion, acid rain, pollution and such strengthened the demand for energy conservation. The rate at which the non-renewable resources are depleted and carbon dioxide is released into the atmosphere is directly influenced by the way buildings are designed and operated. In energy conscious building design, admitting renewable natural light into a space can reduce the need to supply electric light, which is usually generated in expense of a non-renewable resource. According to the IESNA Recommended Practice of Daylighting (IESNA, 1999), the lighting energy reduction potential of a daylighting system is related to daytime occupancy patterns, installed lighting power density, hours of daylighting application, annual relationship between daily hours of daylight availability to daily hours of space use, occupant use of adjustable shades and the effectiveness of the electric lighting control system. Literature (BRE, 1988; Rutten, 1994; Schrum & Floyd, 1995; Winkelmann & Lokmanhekim, 1985) suggested that the electricity saving by monitoring daylight-linked photoelectric dimming systems in spaces ranged from 30% to 63% relative to the spaces in which electric lighting was used during daylight hours. Another research (Choi et al., 1984) also showed that efficient utilization of daylighting could dramatically reduce the total electricity load and peak demand.

Apart from the potential of energy saving, daylight is also beneficial in the hygienic aspect. People are now more aware of the hygienic environment of their home, especially after the outbreak of the Severe Acute Respiratory Syndrome (SARS) in 2003 summer. A healthy interior environment is considered to be crucial to the building design. As early as in 1942, medical evidences (Garrod, 1944) showed that diffuse daylight and sunlight were powerful lethal agents to bacteria and that direct sunlight was about ten times as potent. Buchbinder (1942a) concluded that the concentration of the organisms which caused air borne respiratory infection could be reduced by natural daylight and sunlight. During the period of world wars, sunlight was especially important for buildings like hospitals. It was considered to be second in importance to fresh air in providing a healthy environment for the sick. Architects were encouraged to produce buildings which were well sunlit in order to promote health and hygiene. This was reflected in school design where sunlight came to be perceived as a valuable amenity essential for children’s health. The World Health Organization also promoted sunlight as an aid to hygiene in buildings in its publication in 1990 (Page, 1990). It claimed that direct sunlight indoors exerted a bactericidal effect, promotes cleanliness through improved perception of dirt and dust.

In the biological aspect, daylight plays an important role in maintaining a healthy environment. Light can regulate daily and seasonal rhythms, hormones, and reproduction of animals. Some of these effects of light had been shown to occur in humans also (Bernecker, 1994). Light entering the eyes stimulates both the sensory capacity of vision, as well as the non-visual part of the brain where the human circadian system operates. This system is considered to be a fundamental part of the biological clock which regulates the body to the natural 24-hour day-night cycle. This internal clock controls daily rhythms of sleep, temperature, hormone secretion, and other physiological parameters, including cognitive function. Researches showed that light had an impact on the human circadian system. Human body reacts to the light exposure in the daytime by secreting a kind of hormone which synchronises the body clock to a 24-hour light-dark cycle. In a space without window or skylight, the lighting level of artificial light is not strong enough to activate the system to regulate the biological clock. It may adversely affect the health, mood and behavior. Studies were reported that the effect of inadequate of lighting exposure was related to health problem like sleep disorder, insomnia and seasonal affective disorder. Evidence also showed that the disruption of circadian rhythm due of light exposure could be a potential risk factor to Alzheimer’s disease and various types of cancer. In this point of view, daylight provides number of benefits over the electrical lighting. Besides, natural light is beneficial on calcium absorption, metabolism, and hormone secretion to mention a few.

To conclude, daylight is an important factor in site layout and architectural design. It affects the functional arrangement of spaces, occupant comfort (physical, biological and psychological), structure, and energy use in buildings. It seems that human should function better, emotionally and physically, under natural light in which the human bodies were designed to operate. Perhaps daylight is just a kind of natural need of human beings.

3.4 Problems associated with daylight in buildings

Windows are designed to admit natural light to the interior for its psychological benefits, excellent quality, reduction in energy consumption and passive solar heat gain in winter. Although there are many advantages of utilizing daylight, complaints have long been reported about the daylighting system of a building, like the daylight glare from window and excessive solar heat gain. It could be due to the reason that sunlighting control is not designed very well. Direct sunlight is not always welcome because of the excessive brightness and the associated heat. Sunlight falling on critical task area can produce glare, radiation and thermal effect to the room space. In fact, the problems arising from solar gain or direct insolation was ranked the highest in the disadvantages ascribed to daylight by architects and engineers (BRE, 1988). The discomfort caused by glare from daylight includes the sensations of distraction, annoyance, dazzle, and even pain. It can initiate immediate discomfort to the occupants. As computers are becoming more and more popular, almost all offices and homes are equipped with computers. Bright light, especially sunlight, reflected from the video display unit will cause reflective glare to the user. Although it seems that daylight is more liable to cause glare compared to electrical lighting due to its high intensity, experiments (Aubrée & Chauvel, 1972, 1976; Chauvel et al., 1982; Markus, 1967) found that there seemed to be a greater tolerance of mild degrees of glare from windows than from comparable light electric sources. It could be due to different human reactions to electric sources and windows providing a view (Lam, 1977). There are several measures to deal with the glare from windows.

Overhangs, canopies and awnings can reduce glare by cutting down sky view, but daylight penetration into the interior is reduced at the same time. Adjustable translucent curtain or blind as well as louvered blind or fin can be fitted externally or internally to the window, so that they can be lowered on the days of high sky luminance. The use of high internal surface luminance can also reduce the glare effect from windows.

Daylight, especially sunlight, brings in not only visible light, but also the undesirable heat. In summer, sunlight is usually not welcomed because of the associated heat. In high density cities, most buildings are high-rise blocks built close to each other. In winter, large obstructions block the low-angle sun to the window so that the benefits of winter solar heat gain are lost. In summer the undesirable sunlight can reach it, thus causing overheating of the space. External blinds and sunbreaks can be used to prevent the summer sunlight from overheating up the interior space. The other passive measures include reducing window area and using tinted solar control glazing. Tinted glazing, however, should generally reduce the daylight level more than the solar gain entering the space (except for the specialized low-emissivity glazing) (Evans, 1981). It also changes the colour of the daylight entering the space. External shading is recommended to be installed whenever it is needed. Solar control devices (e.g. light shelves) can be used to block the direct radiation and to eliminate excessive solar gain, while it provides high diffuse light transmission to the interior. Examples of solar control devices can be referred to the BRE environmental design guide (BRE, 1999b) which has detailed explanation and suggestion in balancing the conflicting requirements of solar gain and daylight.

3.5 Factors affecting the daylight availability at a window

The daylight availability at a window is dependent on the external obstructing environment and the sky (including the sun) brightness. External obstruction reduces the access to both skylight and sunlight. In urbanized regions like Hong Kong, high-rise buildings are so densely-packed that skylines as seen from the windows are usually very complicated and irregular. In this section, the parameters quantifying the external environment are reviewed for the standards, published research reports, design codes and design guides. Another factor determining the daylight availability at a window is the sky brightness. It can be quantified by the sunlight intensity and the sky luminance distribution relative to the window orientation. Standard equations of sky luminance distribution are recommended by the CIE (2003) for different sky types which can be generally categorized into clear, partly cloudy and overcast skies. For sub-tropical regions like Hong Kong, partly cloudy sky is the most common sky type.

3.5.1 External obstructing environment

In many standards and design guides (BRE, 1986a, 1991; BSI, 1992; CIBSE, 1999), obstructions are quantified by the limiting obstruction angle (θ) which is the angle subtended by the opposite obstructing building to the horizontal at the external surface of the window. It is measured in the section perpendicular to the window wall. The obstruction angle approach is widely adopted to quantify the obstructing environment (BRE, 1986a, 1991; BSI, 1992; CIBSE, 1999). It has been used in the average daylight factor calculation and vertical sky component estimation for decades (Longmore, 1975; Lynes, 1979; Crisp & Littlefair, 1984). (The average daylight factor and vertical sky component will be explained later in this chapter.)

The obstruction angle is similar to another parameter called space-to-height ratio (d/h). These two parameters are shown in Figure 3.2. The space-to-height ratio is the ratio of the building-to-building distance (d) to the height of obstruction above the reference point (h). Various methods are developed to assess the extent of sky obstruction due to the external building and objects. The recommended values of these two parameters are usually based on their correlation with the equivalent results of the daylight assessment parameters. For the limiting obstruction angle, some of the design guides (BRE, 1991; BSI, 1992; CIBSE, 1999) specify the maximum obstruction angle to be 25°, such that the minimum vertical sky component is equal to 27%. The critical values of obstruction angle were determined by Littlefair (2001) for latitudes ranging from 35° to 60°. The values of the obstruction angle were determined by ensuring that the same vertical illuminance is received directly from the sky at different locations. For latitudes up to 20° and from 20° to 30°, Chung (2004) calculated the critical obstruction angles to be 55° and 48° respectively. It must be emphasized that the obstruction angles are for continuous long parallel obstruction. In urban layout designs, buildings are not usually arranged in continuous parallel rows, but they are normally arranged separately in discrete forms. Daylight can come from gaps at the sides of the building depending on the building density. Then the critical obstruction angles caused by the opposite building should be higher than those recommended by Littlefair (2001) and Chung (2004). Therefore, daylight assessment criteria based on a single value of limiting obstruction angle or space-to-height ratio are considered to be not suitable for dense urban building environment.

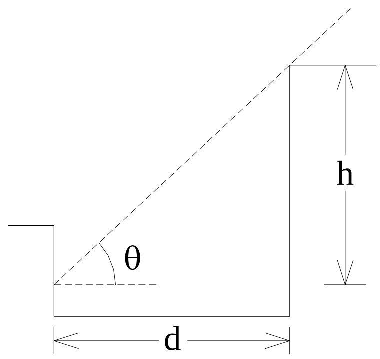


Figure 3.2 Designation of obstruction angle θ

Apart from the obstruction angle and space-to-height ratio, Jones (1983) had developed a method of dealing with the light from simple exterior obstruction which was infinitely long in the direction parallel to the window and of any configuration in the direction normal to the window. This method assumed that the exterior obstruction was an area source consisting of an infinitely long lambertian surface. This method was adopted in the IESNA Recommended Practice for the Lumen Method of Daylight Calculations (IESNA, 1989). Similar to the obstruction angle approach, Jones' method also limits the external obstruction to be of infinite length. For the three methods quantifying the external environment – obstruction angle, space-to-height ratio and Jones' method, the obstructing buildings are all assumed to be infinitely long with constant height and parallel to the window wall under concern. In urban building environment, obstructions are usually tall and densely packed. Skylines seen from window are complex and uneven. It is difficult to quantify the external environment using one single value of obstruction angle. Therefore, Tregenza (1989b) proposed a method quantifying the large external obstructions. The obstruction was defined by four angles: upper and lower extent angles, as well as the right and left extent angles. This method was used to calculate the average daylight factor on the working plane for a room with a window facing large obstruction. It is a useful method to quantify large external obstruction which is not infinitely long, but the configuration of the obstruction is limited by the assumption that it is of fixed angular height. This limitation will be discussed in chapter 5.

Matusiak (2002) had suggested the solid angle projection method to quantify the external environment. It was based on the orthographical projection of the sky on the base of the imaginary unit hemisphere. The external obstruction was expressed as the area ratio of the obstruction's projection to the base area of the unit hemisphere which is equal to π. It was shown that the orthographical projection of an infinitely long street has the shape of an ellipse. It was also mathematically proved by the author as shown in Appendix B1 to Appendix B3. The orthographical projections of lines of various orientations were elaborated by the author. The projections of horizontal or vertical lines parallel to the wall, at which the point under concern locates, have the shape of part of an ellipse, while the projections of lines perpendicular to the wall have the shape of radial lines centred at the centre of the base of unit hemisphere. Any exterior object can be projected to the base area of the unit hemisphere at the window and its orthographically projected area can be calculated mathematically. The calculation of orthographically projected area is shown in Appendix B4. The orthographically projected area approach is considered to be useful to quantify the external obstruction in a high-rise building environment.

3.5.2 Sky luminance distribution

It is mentioned previously that the sky brightness can be quantified by the sunlight intensity and the sky luminance distribution relative to the window orientation. Standard equations of sky luminance distribution are recommended for different sky types. Among the three major sky types: clear, partly cloudy and overcast skies, the relative luminance distribution of an overcast sky was proposed the earliest by researchers. Early in the year 1908, daylight measurements (Hopkinson, 1954; Kähler, 1908) had already demonstrated that the luminance distribution of fully overcast sky conformed closely to a pattern in which the sky was brightest at the zenith and luminance decreased systematically until at the horizon. In 1942, Moon and Spencer surveyed and arranged previous research works, and proposed the following formula for the sky luminance (L_γ) at a given altitude angle (γ):

$$L_\gamma = \frac{L_Z}{3}\left(1 + 2\sin\gamma\right) \tag{3.1}$$

where L_Z is the sky zenith luminance. This expression was adopted by the CIE in 1955 as a standard distribution of relative sky luminance in accord with the luminance distribution of the overcast sky. According to the CIE Technical Report CIE 110-1994 (CIE, 1994), the CIE standard overcast sky is defined as a 'completely overcast' sky for which the ratio of its luminance in the direction at angle γ above the horizon to its luminance at the zenith is standardized as specified in Equation (3.1). The luminance at any point of the same elevation is the same, irrespective of the altitude of the sun. The horizontal illuminance under an unobstructed CIE standard overcast sky (E_d) is given by the expression below:

$$E_d = \frac{7}{9}\pi L_Z \tag{3.2}$$

The sky luminance distribution equation proposed by Moon and Spencer (1942) is not completely general. In 1955, this was demonstrated theoretically by Fritz and experimentally by Petherbridge that the luminance distribution of the sky was influenced by the reflecting properties of the ground. The general formula of overcast sky should be given in the form:

$$L_\gamma = \frac{L_Z}{1+b}(1 + b\sin\gamma) \tag{3.3}$$

where b is a constant dependent on the reflectance of the ground. It has the value of 2.0 for ground of normal reflectance (about 0.1) and 1.0 for snow-covered ground (reflectance about 0.8). Steven and Unsworth (1980) had also shown that this equation could represent a general one-dimensional anisotropic model, radiance or luminance distribution.

Although the overcast sky type was standardized by the CIE, it has been pointed out in the literature (Muneer, 1995) that fully overcast sky type is not unique. There are at least two types of overcast sky, namely thin and heavy overcast sky. The former sky type is covered with bright and thin clouds. Its sky luminance pattern may include a circumsolar component, so that the sky luminance distribution is orientation dependent. Igawa and Nakamura (2001) reported that the CIE standard overcast sky is similar to the latter sky type which is considerably dark sky covered with thick clouds. Muneer (1998) also suggested that the CIE overcast sky model is applicable only to heavy overcast sky when the complete sky canopy is covered with uniform dark clouds. Although there were researches (Muneer, 1998; Nong et al., 1993) pointing out that the CIE overcast sky model may lead to significant underestimation of the available daylight within building interiors, another group of researchers (Enarun & Littlefair, 1995) had reported that this sky model performs the best among all worldwide models adopted in southern England under a fully overcast sky. Researchers (Li et al., 2004) in Hong Kong also claimed that the CIE standard overcast sky model produces a better agreement with the fully overcast sky measurement data obtained in Hong Kong than a uniform sky pattern. Nevertheless, the world-wide use of CIE standard overcast sky for window design and studies of different daylighting systems is universally accepted.

Overcast sky characterizes the sky condition which is fully covered by clouds, while the clear sky function models the sky totally free of cloud. The original luminance distribution model of the CIE standard clear sky was first proposed by Kittler in 1967 and was adopted as CIE standard clear sky in 1973 (CIE, 1973). The CIE clear sky functions are based on the exponentially determined relative gradation and scattering indicatrix functions expressed by its mathematical function with two sets of parameters specifying the relatively clean (countryside) and more polluted (urban) atmospheric conditions. The relative gradation function expresses the drop or rise in sky luminance from the sky zenith towards its horizon, while the relative scattering indicatrix function expresses the diffusion of sunbeams within the atmosphere dependent on the angular direction. It had been demonstrated in experimental measurement (Igawa, 2001) that the CIE standard clear sky shows very close luminance distribution to completely clear up sky. The relative sky luminance at an arbitrary position in the CIE standard clear sky is given by the following expressions:

$$\frac{L_a}{L_Z} = \frac{f(\chi)\varphi(Z)}{f(Z_s)\varphi(0)} \tag{3.4}$$

$$\varphi(Z) = 1 + a \times \exp\left[\frac{b}{\cos(Z)}\right] \tag{3.5}$$

$$f(\chi) = 1 + c \times \left[\exp(d \times \chi) - \exp\left(d \times \frac{\pi}{2} \right) \right] + e \times \cos^2 \chi \tag{3.6}$$

where $f(\chi)$ and $\varphi(Z)$ are the scattering indicatrix function and luminance gradation function respectively. The parameter χ is the shortest angular distance between the sky element and the sun. The parameters Z and Z_s are the angular distances from the zenith to the sky element and sun element respectively. The values of a, b, c, d and e are equal to -1.0, -0.32, 16, -3.0 and 0.30 respectively for the CIE standard clear sky (polluted atmosphere). The sun and aureole close to it are excluded from this luminance distribution.

Both the CIE standard overcast and clear skies are extreme states of skies which are either fully covered with cloud or totally clear up respectively. The sky conditions lie between these two extremes are called intermediate skies or partly cloudy skies. In Hong Kong, the frequency of occurrence of the overcast and clear skies is relatively smaller than the partly cloudy sky. According to the meteorological data collected by the Hong Kong Observatory from 1970 to 2000, the overcast sky condition account for about 20% of the daytime in a year while clear sky account for about 6% only. Most of the real skies lie between the CIE standard overcast and clear skies. The CIE Technical Report CIE 110-1994 (CIE, 1994) defined the partly cloudy sky as a sky (skies) for which “the luminance of any given sky element will be defined for a given sun position under an intermediate weather condition (or conditions) which occurs between the CIE standard clear and overcast skies.” The luminance distribution of partly cloudy sky depends on the solar altitudes in the same way as does the CIE standard clear sky. The sun and aureole close to it are also excluded from this luminance distribution.

Igawa and Nakamura proposed the “All Sky Model” and the “All Sky Zenith Luminance” in 2001. The sky model represents all the sky luminance distributions for clear sky to overcast sky continuously. It is expressed as functions of solar altitude and normalized global illuminance that is derived from global illuminance. In 1997, Kittler and his colleagues proposed 15 standard skies trying to model all the sky conditions. This set of skies was adopted as the CIE standard general skies in 2003 (CIE, 2003). The formulae assume the prevailing skies to be homogeneous. The general sky functions define the relative luminance of a sky element at any point of the sky as a function of the zenith luminance. Similar to the CIE standard clear sky function, the CIE standard general skies are also based on the standardized relative scattering indicatrix. The CIE general skies adopt six standard indicatrix and six gradation functions. Not all six by six functions are used because some combinations are very seldom while others are frequent. The combinations result in 15 types of CIE standard general skies. The standard incorporates both the CIE standard clear sky and the CIE standard overcast sky, which are treated as particular cases of the general skies. Kittler and his colleagues (Kittler et al., 1997) reported that a subset of four sky types of luminance distribution was adequate to describe the sky conditions appearing at each station. Researchers in Hong Kong (Li et al., 2003) had studied three years of local sky luminance data. They reported that a subset of five luminance distributions would be sufficient to describe the sky patterns without any significant deterioration in the accuracy of prediction. The five best-fit standard skies are sky type 1, 3, 6, 11 and 13.

3.6 Review of daylighting design and assessment methods

In this section, various methods for daylighting design and assessment are investigated. They include the sunpath, possible and probable sunlight duration, no-sky line, room depth criterion, daylight factor, lumen method, vertical sky component, vertical daylight factor, daylight coefficients and exterior vertical illuminance.

3.6.1 Sunpath

Daylight performance of an interior is usually assessed separately in terms of the availability of sunlight and availability of skylight. The availability of sunlight is normally quantified by the access to the sunpath as well as the possible and probable sunlight duration. Access to the sunpath can be studied graphically using the Stereographic Sunpath Diagram (e.g. BSI, 1992) and the Sunpath Indicator (BRE, 1991). These two indicators are similar in nature. Obstructions can be plotted on the diagram or indicator to find the time when the sun is not blocked by them. The solar altitude and azimuth can be easily read from the Stereographic Sunpath Diagram, while the Sunpath Indicator can be overlaid directly on the site layout plan of correct scale to observe the sunpath. They are useful for sunlighting design of a building development. The sunlight penetration to a window on a particular day can be observed by the sunpath diagram, but the sunpath diagram gives no numerical value of sunlight hours. Besides, when the building density gets higher, analysis using sunpath diagrams will become more difficult.

3.6.2 Possible and probable sunlight duration

Apart from the sunpath, the access to sunlight can also be quantified by the possible and probable sunlight duration. According to the British Standard (BSI, 1992), possible sunlight hours is defined to be the total number of hours during the year in which the centre of the sun is above the unobstructed horizon, and probable sunlight duration is the long-term average of the total number of hours during the year in which direct sunlight reaches the unobstructed ground. They are sometimes used to quantify the sunlight availability at a window. Then the possible sunlight hours is the total time that the sun would shine at a window with a cloudless atmosphere, while probable sunlight duration is the mean total time when cloud is taken into account. The probable sunlight duration received at a window can also be expressed as a percentage of the annual probable sunlight duration received by an unobstructed ground. In this thesis, this percentage is named as the sunlight duration factor. The values of probable sunlight duration can be found graphically by the Stereographic Sunlight Probability Diagram (e.g. BSI, 1992) and the Sunlight Availability Indicator (BRE, 1991).

A number of researches had studied the relations between daylight satisfaction and sunlight availability. A survey (Bitter & van Ierland, 1965) conducted in 1965 reported that two hours of possible sunlight on 19 February indicates that there would be enough sunlight falling on a window over the year. Another survey (Gilgen & Barrier, 1976) reported similar results that a minimum of 60-90 minutes and an optimum of 2 hours of possible sunlight duration should be achieved on 8 February. Klingenberg and Seidl (1982) recommended at least 4 possible sunlight hours at the window on 20 March. This recommendation has been included in the German standard on daylight provision (DIN 5034 Part 1). Littlefair (2001) as well as Day and Creed (1996) also reported that for southerly locations, where summer sun is less welcome, a possible sunlight criterion of specific possible sunlight hours on a particular winter date should be imposed. The above recommendations concerns about the possible sunlight duration in a particular day. However, sunlight availability assessment method using possible sunlight hours in only one day seems to be not comprehensive. It is possible that a building may have many hours of possible sunlight on a day but just none in the others. Besides, possible sunlight duration does not take the sky conditions and weather data into account. Therefore, one-day-criterion of possible sunlight duration is not a good enough assessment parameter. Ne'eman and his colleagues (1976a) suggested that the probable sunlight duration instead of possible sunlight should be used to quantify the sunlight availability. They claimed that it is the duration of sunlight in an interior, rather than its intensity and the size of the sunny patch, which correlates best with the occupants' satisfaction. They recommended a sunlighting requirement of 400 hr to 500 hr of probable sunlight duration per year and that the sunlight should be spread over at least 6 months of the year. They also suggested that good and flexible sunlighting control should be exercised. Ne'eman and his colleagues (1976a) suggested a sunlighting criteria using the annual probable sunlight duration, while Day and Creed (1996) suggested that the winter sunlight duration might be a better indicator and reference of the subjective response by the occupants. For general building design, sunlight should be admitted to a space whenever it is desirable and practical. At the same time local climatic requirements and the type of activity should guide the proper design of protection against sunshine. In this way excessive heat and glare can be avoided when the sun is unwanted while a full benefit of the sun, when it is welcomed, can be obtained.

In the widely adopted British Standard BS8206 (BSI, 1992), it is recommended that 'interiors in which the occupants have a reasonable expectation of direct sunlight should receive at least 25% of probable sunlight duration and at least 5% of probable sunlight duration should be received during the winter months, between 23 September and 21 March.' In other words, the annual sunlight duration factor should be at least 25% and the winter sunlight duration factor should be at least 5%. The standard also states that the degree of satisfaction is related to the expectation of sunlight. This standard as well as Day and Creed (1996) recommend winter probable sunlight duration as one of the sunlighting design criteria. However, by specifying a certain value of winter probable sunlight duration, like 5%, one consequently excludes some orientations from compliance with the requirement. For example in Hong Kong, all winter sunlight comes from the southern direction that a window wall facing north can never receive any winter sunlight (See Table 3.1). Then, a window wall facing north will never comply with the standard requirements.

Table 3.1 Sunlight duration factors received at vertical walls in Hong Kong

	Probable sunlight hours		
Orientation	Summer	Winter	Annual
S	27%	48%	75%
SW	30%	37%	67%
SE	29%	35%	64%
W	29%	28%	57%
E	28%	26%	54%
NW	23%	13%	36%
NE	22%	11%	33%
N	25%	0%	25%

Some researchers (Bitter, 1966; Horch & Kruger, 1961) claimed that the judgments of sunlight-adequacy should be related to the efficiency of heating systems. They claimed that it could be related to the fact that penetration of sunlight to the interior in cold climate is more preferable when the heating system is not efficient. In the context of the region where winter is relatively warm, like that in Hong Kong, the relation between the efficiency of air conditioning system and the overheating disturbance due to sunlight penetration has not been studied.

3.6.3 No-sky line

The degree of penetration of sunlight can be studied using the no-sky line. It is the outline on a given surface of the area from which no sky can be seen (BSI, 1992). It is therefore the locus of points beyond which no direct view of the sky can be seen. The no-sky line is also used to check the uniformity of daylight in an interior. If a significant area of the working plane lies beyond the no-sky line, the distribution of daylight in the room is expected to look poor and supplementary electric lighting will be required. The no-sky line can be measured directly in the room under concern or its position can be found from site layout plan. There are design guides (CIBSE, 1999) suggesting the calculation procedure for finding the position of no-sky line. In Hong Kong where the skylines are usually very complicated, it would be difficult to draw the no-sky line of an interior without the aid of lighting simulation software.

3.6.4 Room depth criterion

The room depth criterion is used to check the daylight distributing performance of a window in a side-lit room. It is independent of the external environment and sky condition. It is simply a method to test the function of a window to distribute daylight to the back of the room. It was developed by Lynes (1979). The criterion is based on the concept that the rectangular interior is divided into two halves by an imaginary partition, perfectly transparent and parallel to the window wall. The principle of this criterion is to limit the ratio of the average daylight factor in the half of the room which includes the side window to the average daylight factor in the other half of the room to under three. If the ratio is under three, the back half of the room would not be expected to look dim compared to the front half of the room, provided that the window is not severely obstructed. The principle assumes that the vertical illuminance which strikes the side of the imaginary partition facing the window is directly proportional to the average daylight factor in the front half of the room. The room depth criterion states that the daylight uniformity should be satisfactory if the following inequality is satisfied.

$$\frac{L}{W} + \frac{L}{H_W} < \frac{2}{1-\rho_{back}} \tag{3.7}$$

where L is the depth of the room, W is the width of the room, H_W is the window head height above the floor and ρ_{back} is the area-weighted average reflectance in the back half of a room. This inequality is also used to calculate the maximum depth of a side-lit room where daylight distribution is expected to be uniform. When the external view of the window is severely obstructed so that the back of the room will 'see' no sky, the room depth criterion is not suggested to be used. Lynes (1979) claimed that if an appreciable fraction of the back half of the room falls behind the no-sky line, the diversity of the daylighting will be excessive even if the room depth criterion is satisfied. Therefore, the room depth criterion and no-sky line are suggested to be used together to check the daylight uniformity. The no-sky line of the room should be first found. If the sky is visible from a large portion of the room, then the room depth criterion can be used to check the daylight distribution. In the context of densely-packed building environment, the external view of a window is usually heavily obstructed and the skylines are irregular and complicated. The no-sky line method and room depth criterion are therefore difficult to be adopted.

3.6.5 Daylight factor

In most of the daylighting assessment methods, sunlight is often excluded from the calculation because of its continuously varying properties. One of the most widely-adopted daylight assessment methods is daylight factor. It is the recommended procedure of the CIE (CIE, 1970) and is used in more than 100 countries around the world to determine the performance characteristics of daylighting systems (Robbins, 1986). Sunlight is excluded in the assessment and only skylight (diffuse illumination) is taken into consideration. Daylight factor is defined as a ratio, expressed as a percentage, of illuminance at a point on a given plane due to light received directly or indirectly from a sky of known or assumed luminance distribution (CIE standard overcast sky), to the illuminance on a horizontal plane due to an unobstructed hemisphere of the sky (BSI, 1992). Hopkinson et al. (1966a) reported the advantages of daylight factor by giving the following sentences: “It expresses the efficiency of a room and its windows as a natural lighting system. Humans perceive relative rather than absolute luminances. The daylight factor provides a better indicator of the luminous environment experienced by humans than absolute illuminances because it expresses the amount of light in a space relative to the light that would be seen outdoors in sidelit spaces.” The value of daylight factor for a space is a constant provided that the sky luminance distribution stays the same as the CIE standard overcast sky. This special characteristic of daylight factor has led to its wide use for daylighting performance assessment. Another critical reason for daylight factor to be widely used is that its calculation is quite simple. Daylight factor at a point in a room is comprised of three components: sky component, externally reflected component and internally reflected component. Sky component is the light received directly from the sky; externally reflected component is the light received after reflection from the ground, buildings or other external surfaces; internally reflected component is the light received after being reflected from surfaces inside the room.

Before the development of average daylight factor, the daylight factors in a room were usually calculated by point-by-point method (Hopkinson et al., 1966b). The sky component for a point in a room can be calculated using the BRS Daylight Table (BRE, 1986a; BSI, 1992), BRS Daylight Factor Protractor (BRE, 1986a; BSI, 1992) and Waldram Diagram (BRE, 1986a). The BRS Daylight Table and BRS Daylight Factor Protractor enables the sky component to be determined if the external obstruction can be quantified by an obstruction angle. Grid methods are applied to the Waldram Diagram which outputs the sky component by plotting the area of visible sky on the grid. Externally reflected component is usually calculated by the equivalent sky component method which assumes the luminance of the obstructions to be one-tenth of the average luminance of the sky. The calculation methods of internally reflected component are based on the theory of the integrating sphere (Hopkinson et al., 1966b). The most critical assumption made in this theory is that the interior surfaces of the room are matt fully-diffusing reflecting surfaces and behave as if the room is a sphere with these idealized surfaces. The internally reflected component can be calculated based on the total flux incident on the window or it can be calculated by another method which is based on the BRS split-flux principle (Hopkinson et al., 1954). This principle divides the flux entering the room through the window into two parts. The first one is the flux that enters the room directly from the sky or from obstructions above the horizon. The other one is the flux that enters the room directly from the ground or from obstructions below the horizon.

At the preliminary design stage, the building design parameters vary from time to time. Calculation of point-by-point daylight factors may be time-consuming and provides no critical information for daylighting design. For general assessment of a daylighting environment, average daylight factor can be used. It relates specifically to the average daylight factor on the working plane or all interior surfaces. It is useful for fast and easy assessment of the interior daylight availability. The BRS split-flux principle mentioned above for the calculation of internally reflected component was elaborated by Longmore (1975) to develop the formula for the average daylight factor on the working plane. In 1989, this formula was modified by Tregenza (1989b) in order to extend the formula to include large vertical obstructions. The modified formula assumes that the effective mean illuminance from the sky on the window of the room under concern is the same as on the obstructing buildings, and that their surfaces are uniformly diffusing. As mentioned previously in section 3.5, the configuration of the obstruction is limited by the assumption that it is of fixed angular height. This limitation will be studied in chapter 5.

Apart from the average daylight factor on the working plane, the average daylight factor over all interior surfaces can also be calculated. Average daylight factor over all interior surfaces in the form of lumen calculation for side-lit room was developed by Lynes in 1979. It is the mean daylight factor averaged over all the interior surfaces – ceiling, floor, walls and windows of a side-lit room. It is not related to specific reference plane. This expression depends upon the assumption that if the ground and outdoor obstructions have about 10% of the mean sky luminance then the daylight factor on outside face of window would be equal to the percentage value of half the angle subtended by the visible sky. Crisp and Littlefair (1984) had compared the results of the average daylight factors calculated from Longmore's formula and Lynes's formula. A series of rooms was chosen for comparison. The correlation between the two sets of results was found to be very good with a slope of approximately 0.7 (ratio of average daylight factor calculated by Lynes' equation to that by Longmore's equation). This is reasonable since the Lynes formula averages over all the surfaces inside the room, including ceiling and window wall which receive only interreflected light. Crisp and Littlefair (1984) had modified Lynes's formula to give a better estimation of average daylight factor over the working plane. This was done by considering the ratio of the average illuminance for all room surfaces to that for the working plane. The ratio was reported to be about $\frac{1+\rho}{2}$ where ρ is the area-weighted average reflectance of all surfaces in the room. The average daylight factor over all interior surfaces is widely adopted in many international standards (BRE, 1986a, 1986b; BSI, 1992). As stated in the British Standard BS8206 (BSI, 1992) and the CIBSE Code of Interior Lighting 1994 (CIBSE, 1994), if electric lighting is not normally to be used during the daytime, the average daylight factor (over the working plane) should be not less than 5%. If electric lighting is to be used throughout daytime, the average daylight factor should be not less than 2%. Even if predominantly daylit appearance is not required in dwellings, it is recommended that the average daylight factor should be at least 1% in bedrooms, 1.5% in living rooms and 2% in kitchens.

Daylight factor approach has long been a popular daylight assessment parameter because of its simplicity. It is a common practice to use this classical daylight factor for daylight assessment even at present days. However, over the past 30 years, researchers have identified several limitations of the daylight factor. Littlefair (1984) and Tregenza (1980) had found that calculated daylight factor could be a poor predictor of the horizontal illuminance across all the weather conditions. They both reported that the ratio of internal to external illuminance varied greatly under real skies as found from simultaneous measurements of daylight. As the CIE standard overcast sky does not account for the effects of orientation, it is expected to have significant errors by real sky measurement. By carrying out a long-term measurement of horizontal external illuminance, vertical external illuminance, and internal illuminance in model room, Littlefair (1984) found that there are large differences which occur with orientation for the frequency distribution of external vertical illuminance. In 1992 Love concluded the limitations of daylight factor which include "considerable variability over time when determined from measured values, inapplicability when direct sunlight is present indoors or outdoors, failure to correlate with human assessment of the general brightness of spaces, and practical difficulties in its determination by the field measurement of illuminances". As the CIE overcast sky luminance distribution has relatively dark horizon, it may tend to underestimate the illuminance at a point inside a side-lit room, which will receive most of its direct light from near the horizon. In order to improve the daylight factor method for different orientations, the use of orientation factors is proposed (BRE, 1983; CIBSE, 1999). The daylight factor is multiplied by an orientation factor before being used with the distribution of horizontal diffuse external illuminances, in order to allow for different amounts of daylight received by rooms of different orientations. As daylight factor is founded on a measure of illumination under a single idealized overcast sky, it fails to account for realistic daylight conditions and it offers only limited insight into true daylighting performance (Nabil & Mardaljevic, 2005).

It was also reported by Lynes et al. (1966) that daylight factor was not a very good indicator in terms of human sensation. Daylight factor (except for the average daylight factor over all the interior surfaces) assesses the daylight availability by the illuminance ratio on a horizontal plane. However, the human sense of brightness in a room usually comes from the illuminance of the walls. Measurements on a horizontal plane may give a misleading impression of the effectiveness of daylight in a side-lit room, since light entering the windows would illuminate vertical surfaces preferentially. In 1994, Love and his colleagues questioned the use of daylight factor as an index of brightness sensation in a room by the following sentence: "variations in the daylight factor across a space for a given set of conditions overstate the variability of illumination in terms of human perception". They suggested that the vertical illuminance to the horizontal illuminance at a given point in a space would be a useful performance indicator.

Although daylight factor is criticized by some researchers for its limitations on horizontal illuminance estimation and human sensation correlation, it is accepted worldwide as a useful assessment indicator of interior daylight performance. Besides, daylight factor is so commonly adopted that its usage and definition are well known to the architects and designers. Therefore, it is worth to study its calculation method in order to promote satisfactory environment by daylighting performance assessment using daylight factor. In chapter 5, calculations of daylight factor of an interior will be studied.

3.6.6 Lumen method

Daylight factor can be used to estimate the daylight illuminance of a space if overcast sky is assumed. Apart from the daylight factor method, the lumen method, which uses the coefficient of utilization for lighting calculation, can also be used to calculate the interior daylight illuminance. The lumen method had been further developed to extend to the daylight estimation. It was developed by Biesele et al. in 1953 and modified by Griffith et al. in 1955. It is adopted in the IESNA recommended practice (IESNA, 1989) to calculate the interior daylight illuminance. It is based on the principle that the illuminance reaching a point in a room is a function of the amount of light present at the plane of the window or skylight. The interior illuminance is calculated through the use of coefficient of utilization tables. The lumen method is an analysis procedure used to predict interior daylight illuminance under predetermined conditions of time of day, day of year, site location latitude and longitude, and sky condition (clear, partly cloudy or overcast). The daylight calculations for toplighting and sidelighting are separated. For the lumen method for toplighting, the calculation procedure is similar to the zonal-cavity method for interior electric lighting design. It is assumed that the skylights are positioned uniformly across the ceiling area and that the skylights are spaced in such a way as to distribute the daylight evenly across the working plane. Nevertheless, the skylights are assumed to be installed under an unobstructed sky. Both of the diffuse sky and direct sun are taken into consideration. Then the average horizontal illuminance in a space can be calculated from the exterior horizontal illuminance, transmittance and light loss factor of skylights, coefficient of utilization of the room, number of skylights and area of each skylight.

As for the lumen method for sidelighting, direct sunlight is not allowed to enter the room cavity. It is assumed that the designer will control the direct sunlight through the use of overhangs, blinds and shades. The exterior vertical illuminance on the window wall is distributed to the working plane according to the coefficient of utilization of an interior. The vertical illuminance on the exterior of the window of various obstructions is determined by Jones's method (Jones, 1983) which has been briefly introduced in sub-section 3.5.1. Jones' method is also called the lune method in the IESNA recommended practice (IESNA, 1989). The lune method assumes that the exterior obstruction is an area source consisting of an infinitely long lambertian surface of any orientation and shape. For obstructions that partially block the sky, the method makes use of the equivalent sky exitances. It divides the sky into lunes and the equivalent exitance for each lune is calculated. Then the vertical illuminance on a wall due to the lune of unobstructed sky is calculated. By using this method repeatedly, the illuminances and exitances of all exterior surfaces can be determined, and finally the reflected illuminance due to the external obstruction can also be calculated. The internally-reflected component is not considered separately but included into the coefficients of utilization in the IESNA lumen method of daylight calculation. The possibility of modifying the coefficient of utilization in order to include the direct sunlight incident on the window is discussed by Saraiji and Mistrick (1993).

3.6.7 Vertical sky component

Although the ratio of vertical to horizontal illuminance at a given point in a space is suggested to be a useful daylighting performance indicator (Love et al., 1994), no such ratio is well developed and promoted for interior assessment up to present. However, outdoor vertical to horizontal illuminance ratios had been developed for assessment of the exterior daylight availability of a window. One example of this outdoor ratio is the vertical sky component. It quantifies the amount of skylight falling on a vertical wall or window. It is the ratio, expressed as percentage, of direct sky illuminance falling on the vertical wall at a reference point to the simultaneous horizontal illuminance under an unobstructed CIE standard overcast sky (BRE, 1991). Its maximum value is about 39.6% for a completely unobstructed vertical wall. In the UK, the BRE report (BRE, 1991) suggests the critical vertical sky component to be 27% which is based on the recommended limiting obstruction angles of 25° by Evans (1980) for continuous obstructions. The vertical sky component approach can be adopted for other latitudes by ensuring that the same vertical illuminances come directly from the sky at different locations. The equivalent vertical sky components for latitudes ranging from 35° to 60° had been calculated by Littlefair in 2001. For latitudes up to 20° and from 20° to 30°, Chung (2004) calculates the equivalent vertical sky components to be 9% and 13% respectively. The value of vertical sky component can be estimated graphically by the special form of Waldram Diagram (BRE, 1991), the BRS Sky Component Protractors (BSI, 1992) or the Skylight Indicator (BRE, 1991). As the vertical sky component considers only the direct skylight falling on a vertical wall, it may not be suitable for windows in an urbanized environment in which the reflected illuminance from obstruction and ground can be significant.

3.6.8 Vertical daylight factor

Vertical daylight factor (*VDF*) is another vertical to horizontal illuminance ratio for daylight availability assessment at the exterior surface of a window. The original daylight factor quantifies the skylight availability from the CIE standard overcast sky on a horizontal plane (except for the calculation of average daylight factor of all surfaces in the room), while *VDF* quantifies that on the vertical window plane. It is equal to the ratio, expressed as percentage, of vertical illuminance on the window to the horizontal illuminance from the unobstructed sky. *VDF* is defined as "the ratio of the total amount of illuminance falling onto a vertical surface of a building over the instantaneous horizontal illuminance from a complete hemisphere of sky excluding direct sunlight." It takes into account light coming from the sky directly and reflected light of surrounding buildings and the ground both above and below the horizon. Significant correlation between *VDF* and interior daylight illuminance was concluded by researchers. Long term measurement by Littlefair (1984) showed that there was a good correlation between the internal horizontal illuminance and the external vertical illuminance with a multiplying factor. He concluded the experiment by the following sentence: "this method of calculating the internal illuminance ratio from the corresponding (external) vertical illuminance appears to give a better fit to the experimental measurements" than the daylight factor method. Tregenza (1980) also concluded a similar result in an experiment that "less variation was found when the internal illuminance was expressed as a fraction of the external illuminance on the vertical plane of the window than as a fraction of the horizontal illuminance". Although *VDF* is not a widely used assessment parameter, it is especially useful for daylighting performance assessment in the dense urban environment where the interior daylight level highly depends on the daylight availability at the window.

An example of the use of *VDF* is that the Buildings Department of Hong Kong has recently accepted a set of performance-based approach using *VDF* on window surface as an alternative measure for regulatory control of daylighting in buildings (Buildings Department, 2003). The performance-based approach has been briefly introduced in chapter 2. A daylight performance survey (Ng, 2003b) was conducted in residential buildings of Hong Kong. The survey results suggest that the occupant satisfaction rate stays at a certain level once the daylight performance is above a particular value. For living rooms satisfaction rate stays at around 80% when *VDF* is 10% or above. There is little to be gained by providing a *VDF* value say 15% or 30%. However, once the *VDF* fails below around 8%, satisfaction rate drops very rapidly. It may be explained by the fact that human sensation of brightness has an inherent sensitivity. One may notice the increase of brightness when the lighting level is above a 'just noticeable difference' which gives rise to the threshold of sensation (Hopkinson, 1963). Therefore, a threshold of *VDF* may exist when people are asked to assess the daylighting performance of their homes. The *VDF* criteria of 8% for habitable rooms and 4% for kitchens are adopted as the performance-based approach for daylight environment assessment in a building in Hong Kong (Buildings Department, 2003). By adopting the limiting obstruction angle approach of 25° by Evans (1980), the critical values of *VDF* are calculated to be 18% and 21% for latitudes up to 20° and from 20° to 30° respectively, if the ground reflected (including the obstruction reflected component below the horizon) and inter-reflected components are assumed to be 3% (Chung, 2004). It is noted that the criteria suggested by the Buildings Department are much lower than the recommended values calculated by the limiting obstruction angle approach. It shows that Hong Kong people may get used to the low daylight performance of existing building design and therefore the expectation of natural light is relatively low.

3.6.9 Daylight coefficients

Daylight factor or *VDF* relies on the assumption that the sky luminance distribution resembles that of a CIE standard overcast sky. For other sky types, the use of a constant internal-to-external illuminance ratio could give only coarse estimates of the interior illuminance. It had been pointed out (Littlefair, 1984; Tregenza, 1980) that if the instantaneous interior illuminance is of interest, then using daylight factor for the estimation of interior illuminance under real skies may result in large error. In 1983, Tregenza developed the daylight coefficient method. The daylight coefficient function indicates the sensitivity of illuminance in a room to variation in the luminance of the sky (Tregenza, 1999). The concept depends on the idea of dividing up the sky into a large number of very small elements, and considering each element on its own. The amount of daylight that falls into a room depends on two factors: the luminance of the sky as well as the form and materials of the surrounding surfaces. The daylight coefficients method changes the way of estimating daylight by considering these two independent factors separately. The daylight coefficient is used to deal with the latter factor which remains constant for all sky conditions. It takes into account the fact that the illuminance within the room is not equally sensitive to the changes in the brightness of different parts of the sky. It relies on the concept of dividing the sky into tiny zones and analyzing separately their contributions to the internal illuminance. Then, the total internal illuminance is found by summing up the illuminance contributions from all the sky zones. Daylight coefficients can also be measured with scale models (Tregenza, 1989a). The daylight coefficient depends on the geometry of the room and the external obstructions, the reflectances of many surfaces, and the transmittance of the windows. It is, however, independent of sky luminance distribution. Therefore, it is possible to calculate the internal illuminance of an interior under a large number of different sky luminance distributions without the need to repeat the light reflection and interreflection processes. The advantages and disadvantages of the daylight coefficient approach were discussed by Littlefair (1992). He reported that the daylight coefficient technique is most worthwhile when a very large number of sky luminance distribution need to be evaluated, but it is not the most efficient way when the sky luminance distribution does not change. He also proposed to split the daylight coefficient into its direct and room-reflected component parts in order to decrease the computing effort.

3.6.10 Exterior vertical illuminance

The exterior vertical illuminance at window is the total daylight illuminance, due to direct and reflected sunlight and skylight. Its calculation is not restricted to a particular sky type. It indicates the instantaneous daylight (sunlight and skylight) availability of a window. For coarse estimation, exterior vertical illuminance at a window can be found by multiplying *VDF* to the instantaneous exterior horizontal illuminance under unobstructed sky. It gives a fair estimation of the exterior illuminance under overcast sky. However, it may result in large error for sky types other than overcast sky, especially when the sky luminance distribution has strong directional effect (Littlefair, 1984; Tregenza, 1980). Besides, the *VDF* calculates only the diffuse skylight component. Direct sunlight is excluded from the calculation. In clear days, the solar normal illuminance may be well over 100,000 lx, while the direct illuminance at vertical surface due to the unobstructed diffuse sky is usually under 20,000 lx. Even the illuminance on vertical surface due to direct sunlight being reflected once from the obstruction may be as high as 10,000 lx. Many researchers (Alshaibani, 2002; Matus, 1990; Plant et al., 1966; Tsangrassoulis et al., 1999; Wa-Gichia, 1998) claimed that the reflected light from the façade is a useful light source, especially to the surfaces without direct sunlight. Wa-Gichia (1998) concluded that the factors affecting the effectiveness of an opposing façade as a daylight reflective device are the sunlight intensity and the geometric relationship of the window with the opposing façade. Tsangrassoulis et al. (1999) and Alshaibani (2002) had tried to draw a conclusion for the above factors by using a parameter called Obstruction Illuminance Multiplier (OIM), which is defined as the ratio of illuminance received on a vertical surface due to light received from the sky, ground, and the obstruction to the illuminance on the same surface without the presence of obstruction. They both arrived at similar conclusion that for a window facing north with a south-facing obstruction, the reflected surface can increase the daylight illuminance on a glazing. Tsangrassoulis et al. (1999) claimed that the OIM value generally increases with the angular height of the obstruction. It means that the daylight illuminance at the north-facing window would increase when there is a higher opposing obstruction. However, as the obstruction blocks part of the sky, the above conclusion would be justified only if the reflectance of the obstruction surface and the sunlight intensity are high enough that the obstruction luminance would be higher than that of the obstructed sky.

The calculation of exterior vertical illuminance at a window under partly cloudy or clear skies can be facilitated using an approach proposed by Tregenza (1995). He claimed that the direct sunlight is so strong that its direct component and direct reflected (reflected one time from the obstruction) component would dominate the total illuminance at the point of calculation. The choice of sky luminance distributions can be unimportant and therefore a uniform sky is assumed for the calculation. Besides, careful assumptions are made for the portions of the building and ground that are sunlit at the time of calculation. The total illuminances at the sunlit and shaded portions can be calculated using configuration factor. By repeating the calculations using configuration factor, the reflected illuminances due to the sunlit and shaded portions can be found and therefore the total illuminance at the point of calculation can also be evaluated. The calculations were demonstrated for a building layout in form of a street that the buildings are horizontal and parallel to each other. For complicated configurations of obstruction layout, the daylight coefficient approach (Tregenza, 1999) can be adopted. This method also allows sky types other than uniform sky. Then the exterior vertical illuminance at a window under any sky type of known luminance distribution can be calculated. A year profile of daylight availability can be evaluated for a window to study the annual daylighting performance of a window. It provides useful information for energy saving estimation using the top-up daylighting control.

3.7 Selection of general and detailed evaluation parameters

One of the objectives of the study is to select suitable general evaluation parameters and detailed evaluation parameters to be used for daylighting performance assessment of a densely packed building development. The general evaluation parameters can be used at the preliminary design stage. They aim to assess the overall daylighting environment of an interior. The detailed evaluation parameters can be used at detailed design stage. They aim to provide useful information for daylight availability and energy performance analysis.

Average daylight factor, which is one of the most widely-adopted parameters, has been introduced previously. It is commonly used to assess the general daylighting performance of an interior. Although it fails to predict the horizontal illuminance across all sky conditions, it is accepted worldwide as a useful assessment indicator. Its usage and definition are well known to the architects and designers. Therefore, average daylight factor is selected as one of the general evaluation parameters. In the context of a dense urban environment, daylight availability at a window is considered to be the most critical factor affecting the interior illuminance, solar heat gain, occupants' satisfaction and the daylighting performance of a room. Therefore the daylight availability at a window is a useful parameter for general evaluation of daylighting performance. The daylight availability at a window can be generally divided into sunlight and skylight availability. The availability of sunlight is normally quantified by the access to the sunpath as well as the possible and probable sunlight duration. Sunpath diagrams are useful for the assessment of sunlight availability. However, when the building density gets higher, analysis using sunpath diagrams will become more difficult. Possible sunlight duration does not take the sky conditions and weather data into account. Probable sunlight duration, which takes the average cloud conditions into account, is considered to be more suitable to quantify the sunlight availability of a window. Therefore, probable sunlight duration or sunlight duration factor, which is defined as the ratio (in percentage) of probable sunlight duration received at the reference point to the annual probable sunlight duration received by an unobstructed ground, is selected to be another general evaluation parameter. As for the skylight availability, it can be quantified using the vertical sky component, vertical daylight factor and exterior vertical illuminance at a window. The vertical sky component considers only the direct skylight falling on a vertical wall. It may not be suitable for windows in an urbanized environment that the reflected illuminance from obstruction and ground can be significant. The vertical daylight factor quantifies the skylight availability from the CIE standard overcast sky at a vertical point. It takes into account light coming from the sky directly and reflected light of surrounding buildings and the ground both above and below the horizon. Although the CIE standard overcast sky is not the prevailing sky condition in many places, vertical daylight factor is considered to be useful for general evaluation of the skylight availability at a window. The vertical daylight factor method is also adopted as a performance-based approach for regulatory control of daylighting in buildings of Hong Kong (Buildings Department, 2003). Therefore, it is also selected to be used for general evaluation of daylighting performance of a window in a dense urban environment.

The exterior vertical illuminance at a window quantifies the daylight availability of a window. It is the total illuminance, due to direct and reflected sunlight as well as direct and reflected skylight. A single value of exterior vertical illuminance under a particular sky may not be meaningful to the assessment of the daylighting performance of a window in a year term. However, once the calculation method is developed, a year profile of average illuminance can be estimated using the long-term meteorological data. The cumulative availability of exterior vertial illuminance at the external surface of a window can also be evaluated. Then the number of hours in a year for which a predefined minimum illuminance level is achieved can be calculated. It indicates how often in a year the target illuminance is achieved by daylight alone. Similarly, the number of hours for which a predefined illuminance level is exceeded can also be calculated. Research studies (Roache, 2002) indicate that a too high daylight level, which is likely to produce visual and thermal discomfort, may trigger the operation of some kinds of blinds or shades on the window. Then it would decrease the amount of daylight admitted to the interior. Illuminances that fall between the bounds of the minimum and maximum daylight levels are said to be useful daylight illuminance whose concept is developed by Nabil and Mardaljevic (2005). Daylight in the range of useful daylight illuminance is beneficial to the interior visual environment without causing visual and thermal discomfort. The annual duration of useful daylight can be calculated from the year profile of the average illuminance at the window. It provides useful information for energy saving estimation using the top-up daylighting control. In this thesis, the exterior vertical illuminance is selected for detailed evaluation of daylighting performance of a window. The exterior vertical illuminance indicates the daylight availability of a window at particular time. When the annual total daylight availability is of interest, a new parameter called the annual daylight exposure is proposed. Its meaning is similar to the "vertical illuminance" under an "annual cumulative sky", which sums up the sunlight and skylight from all parts of the sky hemisphere in a year. The annual daylight exposure received at a window is proposed to be another parameter for detailed evaluation of daylighting performance.

In conclusion, the average daylight factor, vertical daylight factor and probable sunlight duration are selected to be used for general evaluation of daylighting performance of a space in a dense urban environment. The vertical daylight factor is used to quantify the skylight availability and probable sunlight duration is used to quantify the sunlight availability at a window. As for the detailed evaluation of daylighting performance, the exterior vertical illuminance and annual daylight exposure are proposed to be used.

3.8 Summary of daylighting design criteria recommended by international standards and design guides

In this section, standards and recommendations regarding daylighting design and assessment are summarized. Building laws and regulations ensure the health and safety of people in and around buildings by imposing functional requirements for building design and construction. As building regulations are always opposed against the economical arguments, they aim to maintain only the minimally acceptable living standard. In the contrast, standards and recommendations usually aim to provide a better-than-minimum performance. There are many international standards and guidelines concerning the interior daylighting performance assessment. They include the British Standards, CIBSE lighting guide, CIE report, IESNA lighting report and so forth. The assessment parameters include the room depth criterion, no-sky line, probable sunlight duration, vertical sky component, average daylight factor and so forth. Although most of the parameters are widely adopted, some of them are difficult to be adopted in a high-rise building environment. Apart from the international standards concerning the interior daylight environment, there are some voluntary assessment schemes which aim to assess the overall performance of a building. They include the LEED Green building rating system in the US (LEED, 2002), BRE’s Environmental Assessment Method (BREEAM) (BRE, 2004) in the UK and the Hong Kong Building Environmental Assessment Method (HK-BEAM). The LEED is a voluntary, consensus-based standard for developing high-performance and sustainable buildings in the US. The BREEAM has been used to assess the environmental performance of both new and existing buildings in the UK. It covers a wide range of environmental issues, including daylight performance in the Health and Wellbeing Section. Credits are awarded according to the building performance in a particular area. The HK-BEAM scheme was established by the Department of Building Services Engineering of the Hong Kong Polytechnic University in 1996. The concepts of the assessment methods were largely based on the BREEAM. The latest versions of HK-BEAM are 4/04 "New Buildings" (HK-BEAM Society, 2004b) and 5/04 "Existing Buildings" (HK-BEAM Society, 2004a). The daylighting criteria are based essentially on recommendations and guidelines used in the UK such as those found in BREEAM, CIBSE and BRE publications. Although guidelines are given on the daylighting environmental assessment, many buildings disregarded the assessment for daylight design due to difficulties found in applying the parameters in local high-rise buildings.

Table 3.2 summarized the recommendations and guidelines by the CIBSE Daylighting and Window Design Lighting Guide LG10 (CIBSE, 1999), British Standards BS 8206 (BSI, 1992), the BRE Report BR 209 (BRE, 1991), IESNA Recommended Practice of Daylighting RP-5-99 (IESNA, 1999), LEED Green Building Rating System (LEED, 2002), BREEAM (BRE, 2004) and HK-BEAM (HK-BEAM Society, 2004a, 2004b). The room depth criterion and the no-sky line criterion are recommended in the CIBSE lighting guide LG10 and the British Standards BS8206. These two criteria should be used together. If a significant portion of the room falls behind the no-sky line, the room depth criterion is not suggested to be used. In the context of high-rise building environment, buildings are so densely packed that it is common to have most part of an interior falling behind the no-sky line. Therefore, the room depth criterion is not suitable to be adopted in a high-rise building environment. A southern window orientation is recommended by the CIBSE lighting guide LG10 for buildings in the northern hemisphere. A southern direction benefits the windows by enabling the potential of long winter sunlight exposure and effective shading against the undesirable summer sunlight. Windows should be oriented due south whenever it is possible and exposure to sunlight should be reduced on east and west facades. It is also a Chinese traditional culture that the courtyard house faces south whenever it is possible (Liang, 1984). A window facing south-east direction was also recommended as early in 1933 by RIBA. However, the quality of view is another important consideration of window orientation. It is common for the architects and site layout planners to design a window of a better view with the sacrifice of daylighting performance.

The probable sunlight duration are recommended as the sunlight availability indicating parameters in the CIBSE lighting guide and British Standards. It is specified in the British Standards that it is the duration of sunlight in an interior which correlates best with the occupants' satisfaction. However, this parameter is not selected to be adopted in the voluntary assessment schemes BREEAM and HK-BEAM. It could be due to the difficulty of calculating this parameter in dense urban environment. No guidelines are given in the British Standards on the calculation of probable sunlight duration received by a window. Although the sunlight availability indicator (BRE, 1991) is developed to calculate the probable sunlight duration, its adoption in a densely packed building environment is relatively difficult. A new method for the calculation of probable sunlight duration will be proposed in chapter 5 in order to promote better sunlighting design. Limiting the obstruction angle of opposite building can safeguard the daylight availability of an interior. The CIBSE lighting guide, British Standards, Building Research Establishment Report and the

IESNA Recommended Practice of Daylight also specify the maximum degree of external obstruction to be 25° if a good daylight environment is going to be achieved. The equivalent value of vertical sky component is equal to 27%. For the latitudes of Hong Kong (22° N), Chung (2004) calculates the equivalent obstruction angles and vertical sky component to be 48° and 13% respectively. It is mentioned previously that a single value of obstruction angle may not be suitable for densely packed building environment where skylines are usually complicated and irregular. Besides, the vertical sky component considers only the direct skylight component. This parameter may not be suitable in the high-rise building environment where the interior daylight availability is highly dependent on the reflected components from obstruction and ground. The daylight assessment criteria using average daylight factor is adopted in the CIBSE lighting guide, British Standard, LEED, BREEAM and HK-BEAM. The general criterion of average daylight factor is at least 5% for rooms where electric lighting is not normally to be used and at least 2% for rooms where electric lighting is to be used throughout daytime. Most of the calculation methods of daylight factor depend on the assumption that the obstruction is infinitely long and parallel to the window wall. However, this type of site layout is not common in the context of urbanized high-rise building environment. Therefore, the calculation procedures of average daylight factor should be modified for easy adoption in a high-rise building environment. The calculations of average daylight factor will be discussed in chapter 5.

Table 3.2 Summary of international recommendations

		CIBSE LG10	BS 8206	BR 209
Daylight uniformity	Room depth	Supplementary electric lighting is needed if the room depth criterion is not met in rooms with windows in one wall only.		
Daylight uniformity	No-sky line	Supplemetary electric lighting is needed if a significant part of the working plane lies behind the no-sky line.		
Sunlight availability	Building orientation	In northern hemisphere, for a space to have good access to sunlight for amenity purposes, its window wall should face within 90° of due south. For a building to make the most of passive solar heating, its main window wall should face within 30° of due south.		
Sunlight availability	Probable sunlight hours	Interiors in which the occupants have a reasonable expectation of direct sunlight should receive at least 25% of probable sunlight hours. At least 5% of probable sunlight hours should be received during the winter months, between 23 September and 21 March.		
Skylight availability	Obstruction angle	If none of the obstructing buildings subtends an angle to the horizontal (at the 2m reference height) greater than 25°, then there will still be the potential for good daylighting in the interior.	Examination of the duration and extent of site shadowing is recommended at planning stage. It is suggested to refer to BR209 for guidance on this issue.	If none of the obstructing buildings subtends an angle to the horizontal (at the 2m reference height) greater than 25°, then there will still be the potential for good daylighting in the interior.
Skylight availability	Vertical sky component, VSC	The value of VSC, at the window position 2m above ground, should be at least 27%.		The value of VSC, at the window position 2m above ground, should be at least 27%.
Skylight availability	Average daylight factor on working plane, DF_{wp}	If the room depth criterion is not met, the DF_{wp} should be at least 5%. In domestic interiors, a DF_{wp} of 2% is acceptable, though some tasks may require electric light.	If electric lighting is not normally to be used during daytime, the DF_{wp} should be at least 5%. If electric lighting is to be used throughout daytime, the DF_{wp} should be at least 2%. In dwellings, the minimum DF_{wp} is 1% in bedrooms, 1.5% in living rooms and 2% in kitchens.	

Table 3.2 (continued)

		RP-5-99	LEED	BREBEAM	HK-BEAM
Daylight uniformity	Room depth	The distance of useful daylight penetration is usually not more than twice the window head height.			
	No-sky line			One credit is awarded where sky is visible at a height of 0.85m from the floor for 80% of the room area for living room, dinning room and office, and from every work-surface and table in the kitchen.	
Sunlight availability	Building orientation	Guidelines are given to reduce sunlight exposure to sunlight on east and west facades.			
Skylight availability	Obstruction angle	If the view of the sky in the upper half of the window, at 3m inside the window wall, is more than 50% obstructed by surroundings, the daylight contribution to illuminance will likely be minor.			
	Average daylight factor on working plane, DF_{wp}		One credit is awarded where a minimum DF_{wp} of 2% is achieved in 75% of all space occupied for critical visual tasks.	One credit is awarded where the DF_{wp} of the kitchen is higher than 2%. One credit is awarded where the DF_{wp} of the living room, dinning room and office are higher than 1.5%.	One credit is awarded where the DF_{wp} in all normally occupied spaces is at least 0.5%. Two credits are awarded where the DF_{wp} in all normally occupied spaces is at least 1%. Three credits are awarded where the DF_{wp} in all normally occupied spaces is at least 2%.

3.9 Conclusion

In this study, daylight availability at a window is considered to be the most critical factor affecting the interior daylighting performance in a dense urban environment. The factors affecting the daylight availability at a window was studied. They include the external obstructing environment and the sky luminance distribution. The parameters and methods used for daylighting design and assessment were reviewed. They included the sunpath, possible and probable sunlight duration, no-sky line, room depth criterion, daylight factor, lumen method, vertical sky component, vertical daylight factor, daylight coefficients and exterior vertical illuminance at window. The average daylight factor, vertical daylight factor and probable sunlight duration are selected to be used for general evaluation of daylighting performance of a space in a dense urban environment. As for the detailed evaluation of daylighting performance, the exterior vertical illuminance, which can be further evaluated to calculate the annual duration of useful daylight, and annual daylight exposure received at a window are proposed to be used.

CHAPTER 4
RESEARCH METHODOLOGY

4.1 Introduction

In chapter 3, average daylight factor, vertical daylight factor and probable sunlight duration were selected to be used for general daylighting performance evaluation of a building in a dense urban environment. The review of the calculation methods suggested that the external obstructing environment was usually assumed to be infinitely long with constant height and parallel to the window wall. This assumption is considered to be not applicable for a densely packed building environment. Therefore, a new method of defining the exterior obstruction, which is called the external view division method, was developed for the calculation of average and vertical daylight factors. It will be presented in the next section. As for the calculation of probable sunlight duration, no available calculation method was concluded in chapter 3. Therefore, a new calculation method was developed. It depends on dividing the sky hemisphere into many sky patches, so that a sky map of annual cumulative probable sunlight duration can be constructed. The sky hemisphere division method will be introduced in this chapter. A questionnaire survey was conducted for the development of daylighting design criteria for residential buildings in dense urban environment. The sample selection, questionnaire development and data analysis are explained in this chapter.

As for the detailed evaluation of daylighting performance, exterior vertical illuminance and annual daylight exposure were selected to estimate the daylight availability at a particular time and in the whole year. The calculations of both parameters rely on similar division methods of the sky hemisphere and external view.

Besides, the calculations are based on the unit hemisphere method which will be explained in this chapter. In order to test the accuracy of the calculation method of exterior vertical illuminance, a computer simulation and a measurement under real skies were performed. The methodologies are discussed in this chapter.

4.2 External view division method for the calculation of average and vertical daylight factors

In the context of a densely packed building environment, quantifying the external obstructing environment is probably the most difficult and critical task for the calculation of average and vertical daylight factors. The quantifying method should be simple, accurate and expedient. A coarse representation of obstruction configuration may sacrifice the accuracy of the calculation method. On the other hand, a too complicated method may be time consuming but not much more precise. In a densely packed urban environment, buildings are usually in shape of tall rectangular blocks. A building environment is most commonly described and illustrated using a layout plan. It provides the required geometrical information of all the buildings in an area. It would be convenient if the external environment can be defined using the information in the layout plan. For a window of 180° wide, the external view of a window can be represented by a semi-circle in plan. In the external view division method, this 180° external view is divided azimuthally into many segments, so that the visible sky from the window can be defined by a set of altitude angles. If this semi-circle is divided into 36 equal segments, then the angular width of each segment would be equal to 180° ÷ 36 = 5°. The accuracy of the calculation result would definitely increase with the number of segments. However it will complicate the evaluation procedures, but not significantly improve the accuracy.

A division into 36 segments is considered to be adequate yet simple to produce an accurate result. The vertical plane for finding the lower and upper limits of the visible sky is at the mid-angle of every segment. In this way, the azimuth angles ϕ defining the 36 segments, which are the azimuth angles of the vertical planes for finding the limits of visible sky, are found. They are shown in Figure 4.1. The azimuth angle ϕ is measured from the normal to the window wall. It is negative when the azimuth angle is measured in anti-clockwise direction and positive when it is measured in clockwise direction.

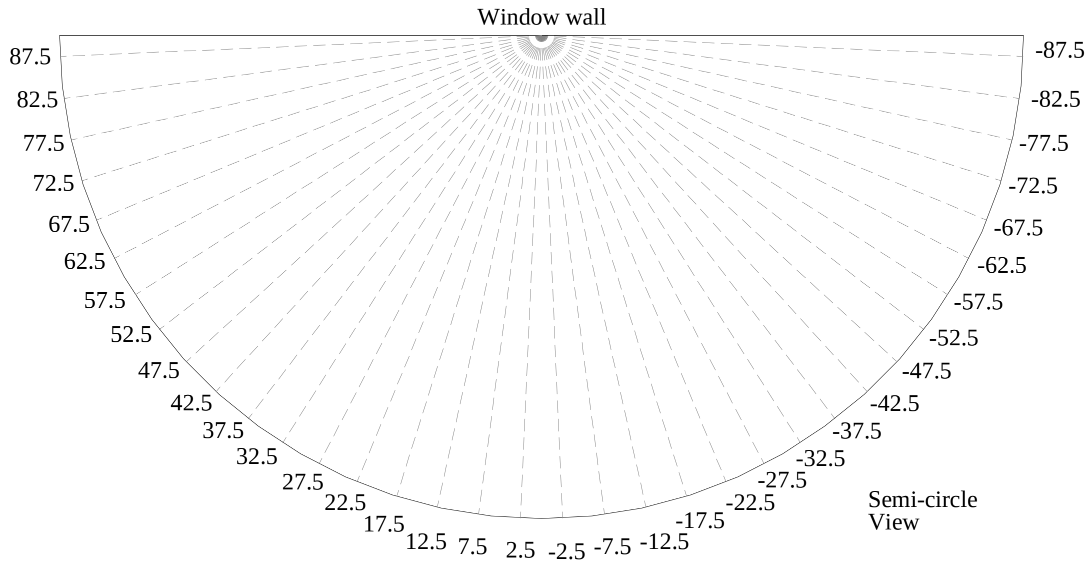


Figure 4.1 Azimuth angles ϕ for defining the external obstruction

The lower and upper limits of the visible sky in every segment are represented by altitude angles $\theta_L^{sky(\phi)}$ and $\theta_H^{sky(\phi)}$ respectively. The angle $\theta_L^{sky(\phi)}$ is the altitude angle subtended from the centre of the window to the top of the obstructions at azimuth angles ϕ. As for the angle $\theta_H^{sky(\phi)}$, it is the altitude angle subtended from the centre of the window to the edge of the external shading. It can be calculated from the external shading configurations using simple trigonometric equations. Both of them are measured from the normal to the window. They are always positive. Their definitions are shown graphically in Figure 4.2. By using the external view division method, the external environment of a window is defined by 36 pairs of altitude angles $\theta_L^{sky(\phi)}$ and $\theta_H^{sky(\phi)}$. Then the values of average and vertical daylight factors can be calculated using the method developed by the author. The method will be presented in chapter 5.

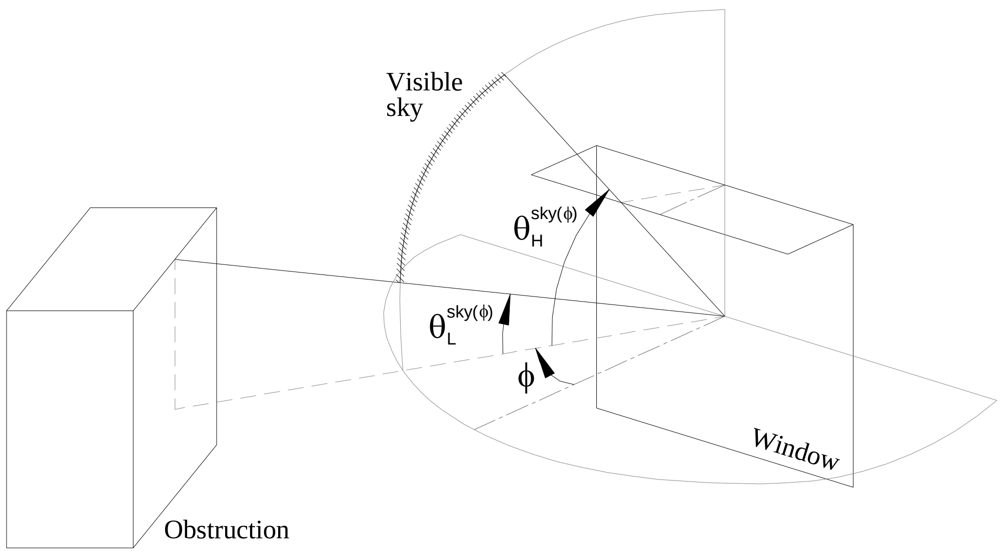


Figure 4.2 Altitude angles $\theta_L^{sky(\phi)}$ and $\theta_H^{sky(\phi)}$ for defining external obstruction

4.3 Sky hemisphere division method for the calculation of probable sunlight duration

In the calculation of sunlight duration factor, a sky map of annual cumulative probable sunlight duration was constructed. The sky hemisphere was divided into patches, so that the contribution of probable sunlight from every sky patch could be evaluated. The sky map was used to calculate the probable sunlight duration received at a window. In this section, the sky hemisphere division method is discussed. The most common sky division method is the International Daylight Measurement

Programme (IDMP) luminance scanning grid which is widely adopted for sky luminance measurement and cloud cover assessment. It involves 145 zones of identical shape and area across the sky vault (Tregenza, 1987). This sky division method aims to distribute the zones evenly across the sky and contain a high proportion of its total area. In this way, every luminance measurement will give about equal weighting to the whole sky luminance distribution. Besides, human observers of cloud cover are normally instructed to give equal weight to equal areas of the sky (WMO, 1975). An equal area sky grid is therefore appropriate for sky luminance measurement and cloud cover assessment. Although the IDMP luminance scanning grid is the standard sky division method, it is not suitable to be adopted for the development of the sky map of annual cumulative probable sunlight duration. As the sky map is used for finding the probable sunlight duration received at a window, the sky division method should facilitate easy and clear procedures of defining the portion of visible sky as seen from a window in a dense urban environment. For this reason, a new sky hemisphere division method was developed.

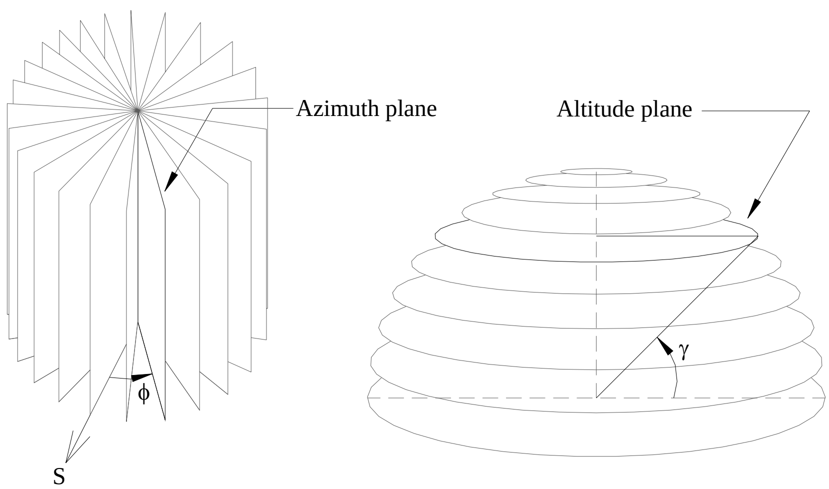


Figure 4.3 Explanation of azimuth planes and altitude planes

With reference to the external view division method explained in previous section, the external view of a window is divided azimuthally into 36 segments and the visible sky as seen from the window is defined by 36 pairs of altitude angles. It is a convenient method to define the external environment of a window in a densely packed urban environment. Therefore, this external view division method is elaborated for use in dividing the sky hemisphere. The sky hemisphere is first divided azimuthally into subdivision. After that the subdivisions are divided altitudinally into sky rings. In other words, the sky is divided into patches by azimuth planes and altitude planes as shown in Figure 4.3. The angular width of the azimuthal subdivisions and the angular height of the altitudinal sky rings are both set to be equal to 5°. The angular width and height of all the sky patches are arranged to be equal so that the procedures of defining the external environment would be simpler and clearer. Therefore, 72 (360 ÷ 5 = 72) azimuthal subdivisions and 18 (90 ÷ 5 = 18) altitudinal sky rings are divided from the sky hemisphere. By the above described sky division method, the sky hemisphere is divided into 1,296 (18 × 72 = 1,296) sky patches. The final sky patch divisions of the sky hemisphere are illustrated in Figure 4.4. This sky hemisphere division method was adopted for the development of the sky map of annual cumulative probable sunlight duration which will be introduced in chapter 5.

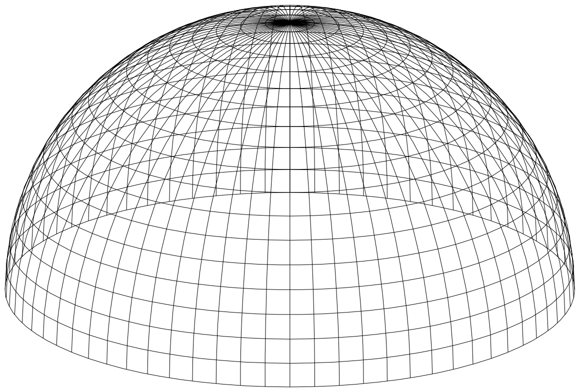


Figure 4.4 The sky patch divisions of the sky hemisphere

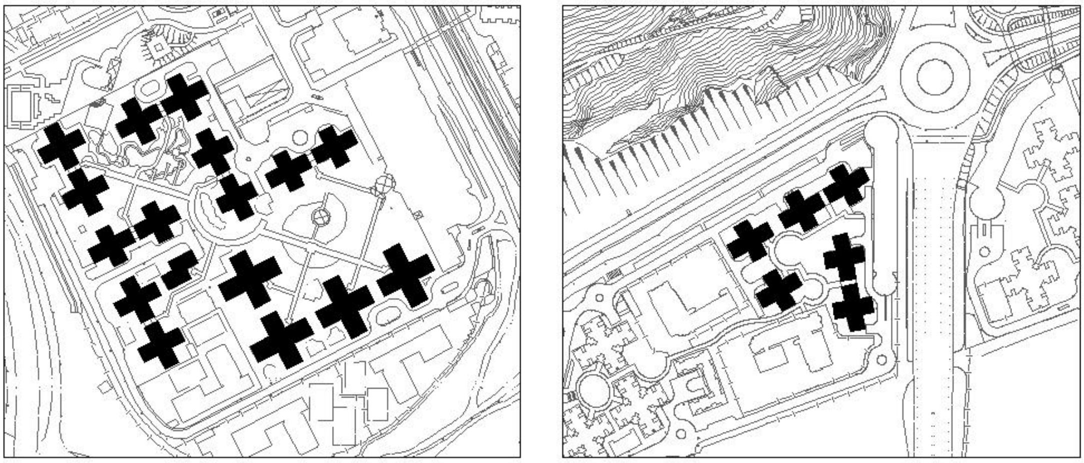
4.4 Questionnaire survey for the development of daylighting design criteria

A questionnaire survey was conducted in order to study the occupants' attitude towards the general daylight performance of their households and to develop a set of daylighting design criteria. The survey was generally divided into two stages. At the first stage, the subjective sensation of the respondents to the general daylight environment of their workspace or living space was collected from the questionnaire survey. The subjective sensation did not correspond to a particular time. The respondents were asked to express their feelings of the overall daylighting performance of their households. The influence of each sensation to the overall performance was studied under a correlation analysis. At the second stage, the daylight environment was evaluated quantitatively by assessment parameters. In section 3.7, the parameters selected for general evaluation are average daylight factor, vertical daylight factor (VDF) and probable sunlight duration. The calculation of average daylight factor involves information of all the interior finishes of the room, which were difficult to be collected in the questionnaire survey. If an average reflectance of all interior surfaces is assumed, aveage daylight factor would be just proportional to VDF. It would be meaningless to use two similar parameters for the investigation. Therefore, average daylight factor was not used for the quantitative assessment. In order to study the effect of summer and winter sunlight on the occupants' satisfaction, probable sunlight duration was calculated for the summer and winter time. When the summer and winter probable sunlight duration are expressed as the percentages of the probable sunlight duration received by an unobstructed ground in the whole year, they are called the summer sunlight duration factor ($SSDF$) and winter sunlight duration factor ($WSDF$). The sum of these two factors would be the annual sunlight duration factor ($ASDF$). As a result, the assessment parameters for the second stage of the questionnaire survey were chosen to be $SSDF$, $WSDF$, $ASDF$ and VDF. Their values were evaluated in order to investigate their relations with the subjective qualitative assessment by the respondents. A correlation analysis was carried out to study the relation between the four quantitative assessment parameters and the questionnaire observations. A set of daylighting design criteria was developed by studying the critical values of the assessment parameters which result in different ratings of user satisfaction. Please refer to chapter 6 for the development of daylighting design criteria. The objectives of the questionnaire survey were to identify the influence of various sensations to the overall satisfaction of a daylight environment, to investigate the correlations of human's subjective sensation with the reference parameters and finally to develop a set of daylighting design criteria based on $SSDF$, $WSDF$, $ASDF$ and VDF.

A postal questionnaire was adopted instead of survey interview. A survey interview is used usually where many open-ended questions have to be asked. It has several advantages over postal questionnaire. It may improve response rates and reach less well-educated respondents more easily (Houtkoop, 2000). Besides, the interviewers are able to make on-the-spot assessments of the daylight environment of the households. However, it is definitely more expensive in terms of both the data collecting and data analyzing processes. As open-ended questions are usually asked in interviews, there will be a costly coding operation allied to the study using survey interviewers. Inconsistency may be resulted from inherent interpretation of the same question by different interviewers. Due to the limitations of budget and man force, this survey was administered by postal questionnaire whose main advantage is low cost of data collection.

4.4.1 Sample selection

At the first stage of the questionnaire survey, the subjective sensation to the general daylight environment of a residential flat was studied. At the second stage, the daylight performance was quantitatively assessed using four reference parameters: *SSDF*, *WSDF*, *ASDF* and *VDF*. The building estates were selected such that the occupants should have worked or lived in the flats for more than one year. In Hong Kong, Tin Shui Wai and Tseung Kwan O are two of the newly developed districts which are mainly for residential purpose. Tin Shui Wai is located in the north of the New Territories, while Tseung Kwan O is located in east Kowloon. More than 13,000 flats were completed in Tin Shui Wai in late 1999 and early 2000. Two housing estates: Tin Shing Court in Tin Shui Wai and Choi Ming Court in Tseung Kwan O were identified as survey sites. Both estates situate at the outer areas of the two districts such that some windows of the estates face no significant building obstruction. For the lower flats facing the garden of the estate, their windows are expected to be severely obstructed by the other blocks. As a result, almost full ranges of calculated probable sunlight duration and *VDF* were resulted for the flats in these two residential estates. It enables a wide range of correlation analysis between the subjective human sensation and quantitative assessment of daylight environment at the second stage of the survey.



Tin Shing Court   Choi Ming Court

Figure 4.5 Site layout plans for Tin Shing Court and Choi Ming Court

Tin Shing Court was completed in three phases from 1997 to 1999. It has totally 17 blocks (12 Concord modules, 4 Harmony modules and 1 special type) and 6,580 flats. The Concord and Harmony blocks are 40-storey high, while the block of special type is 30-storey high. The Concord blocks in Tin Shing Court were surveyed. Choi Ming Court was completed in 2001. It has totally 6 Concord blocks and 1,920 flats. All blocks are 40-storey high. Figure 4.5 shows the site layout plans of the two building estates. The Concord blocks in Choi Ming Court were surveyed. Almost all of the building blocks, except one block of special type in Tin Shing Court, adopt the compact cruciform building plan of eight units per floor. The building layouts are symmetrical with eight residential flats on each floor facing four different directions. Figure 4.6 shows the typical floor layout plan of a Concord building block. An enlarged layout plan for one of the flats is shown in Figure 4.7. The length and width of the living room are about 5.7 m and 2.6 m respectively, while the floor to ceiling height is 2.5 m. An overhanging canopy, whose depth is 0.375 m, is installed for every window. The window in the living room is shaded from the two sides by a sidefin of 0.375 m deep. The height of a 40-storey block is about 120 m, while the height is about 100 m for the 30-storey block. The block-to-block distance ranges from 5 m to 38 m. For some windows at the lowest floor, the obstruction angles subtended by the opposite building can be up to 70º above horizon.

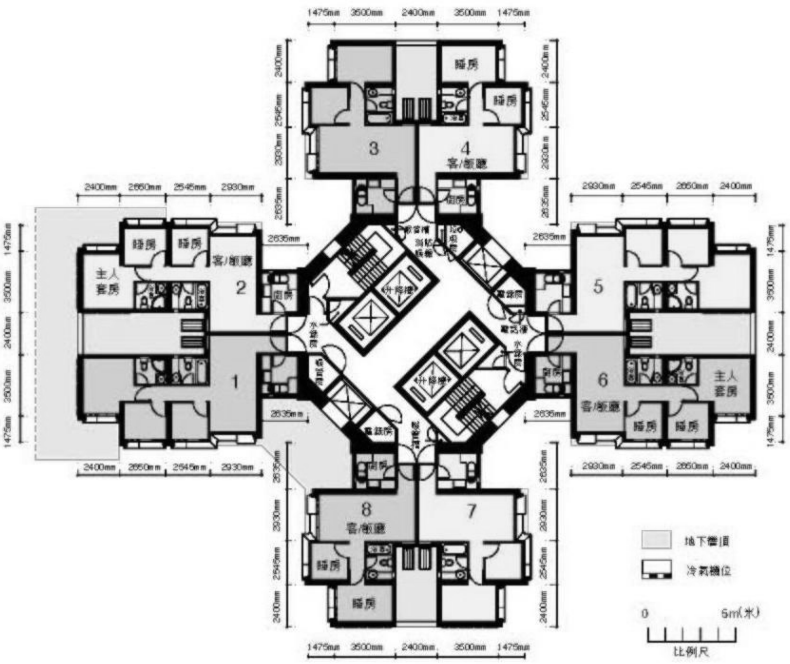


Figure 4.6 Floor layout plan for a Concord building block

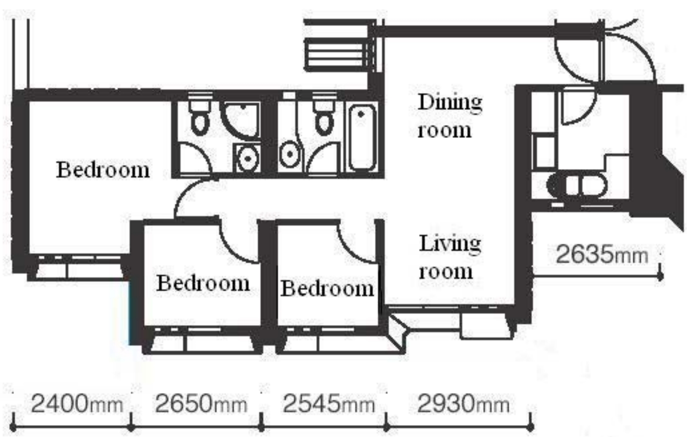


Figure 4.7 Layout plan for one of the flats in a Concord building block

4.4.2 Questionnaire development

In order to identify the influence of various sensations to the satisfaction of a daylight environment, a structural model for the overall performance of a daylighting system was hypothesized. It is shown in Figure 4.8. The overall daylighting performance of a space was assumed to be related to a combination of the brightness sensation, comfort sensation, sensation to the amount of daylight, solar heat and daylight glare. At the first stage, the influence of each sensation to the overall performance was studied under a correlation analysis. At the second stage, another correlation analysis was carried out to study the relation between the five sensations and the four quantitative assessment parameters: *SSDF*, *WSDF*, *ASDF* and *VDF*. A quantitative assessment parameter which is significantly correlated to each human sensation is aimed to be found out.

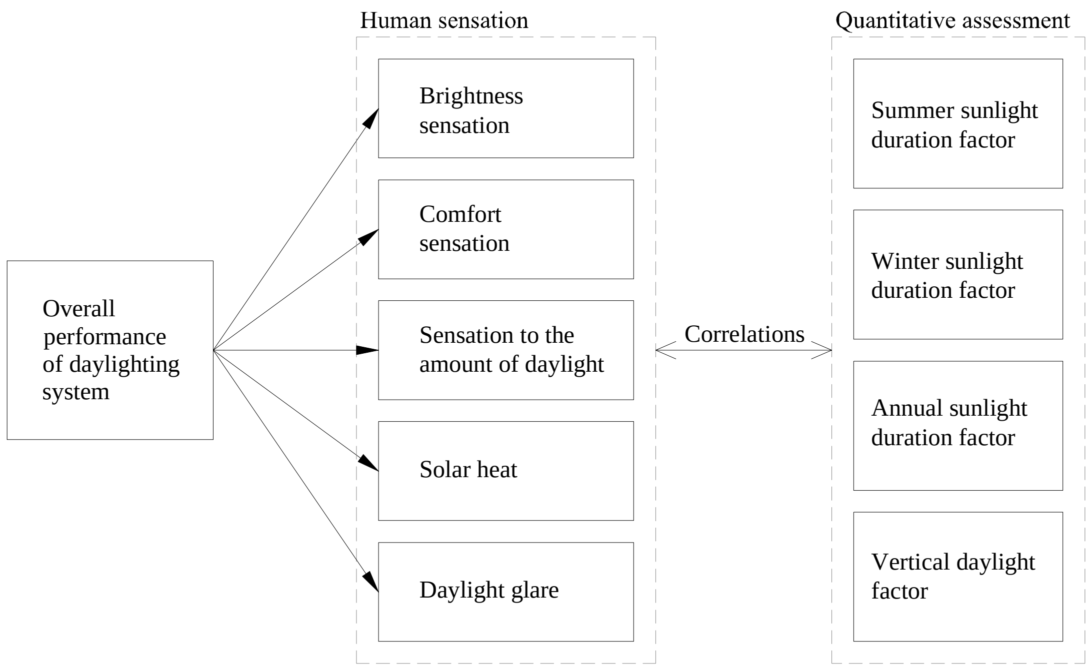


Figure 4.8 The structural model for the overall performance of a daylighting system

The questionnaire contains 15 closed questions and 1 open-ended question. Respondents were restricted to select from the provided answers in the 15 closed questions. As for the open questions, respondents were allowed to answer in their own words and give any answer. The first 14 questions asked for subjective sensations and preferences for a number of aspects of the natural visual environment. Question 1 to Question 11 concerned about the daylight environment in the respondents' living rooms. Question 1 and Question 2 sought information concerning respondents' habits of using blinds or curtains. Question 3 asked for the electrical lighting condition when the occupants read a newspaper in the daytime. Question 4 and Question 5 sought information about the sensations towards daylight glare and solar heat respectively. The comfort sensation to the daylight environment was studied by Question 6, while the brightness sensation was studied by Question 7. Question 8 asked for the respondents' opinion towards the amount of daylight in their living rooms. Besides, the respondents were asked in Question 9 whether or not the daylight environment of their living rooms have to be improved. In Question 10, they were asked whether they were satisfied with the daylight environment of their living rooms. A mark (from 0 to 10) for the overall evaluation of the daylight performance was to be given in Question 11. Question 12 and Question 13 sought information about the respondents' preferences of daylight among different rooms and different times of the day. An open-ended question was provided in Question 14 to allow the respondents to express their opinions. The gender and age range of the respondents were asked in the last two questions. Table 4.1 presents the abbreviations and corresponding questions in the questionnaire.

Table 4.1 Abbreviations and questions in the questionnaire

	Abbreviations	Questions
Availability of daylight	Habit of using curtains	Q1 The blinds/curtains of the window in your living room are usually drawn?
	Reason to draw curtains	Q2 What is the reason for you to draw the blinds/curtains in your living room?
Task performance	Need for electrical lighting while reading in daytime	Q3 How often do you switch on the electrical lighting while reading (e.g. newspaper) in your living room in the daytime?
Subjective sensation	Frequency of glare problem	Q4 How often do you feel uncomfortable because of the strong light or glare entering your living room?
	Frequency of heat problem	Q5 How often do you feel uncomfortable because of the heat from sunlight entering your living room?
	Comfort sensation	Q6 How comfortable is the daylight environment in your living room without electrical lighting in the daytime?
	Brightness sensation	Q7 How bright is the daylight environment in your living room without electrical lighting in the daytime?
	Amount of daylight	Q8 How adequate is the daylight in your living room without electrical lighting in the daytime?
Overall sensation to daylight environment	Need to improve daylight environment	Q9 Do you think that the daylight environment of your living room have to be improved?
	Satisfaction to daylight environment	Q10 Do you agree that the daylight environment of your living room is satisfactory?
	Overall evaluation	Q11 If 10 is the highest mark, what mark will you give to the daylight environment of your living room?
Preferenceto sunlight	Time preferences to sunlight	Q12 What is the best time to have sunlight for living room, dinning room, bedroom, bathroom and kitchen?
	Importance of sunlight	Q13 Which room do you think that sunlight is most important to?
	Other opinions	Q14 Do you have other opinions of the daylight environment of your living room?
General information of respondents	Gender	Q15 Gender
	Age	Q16 Age group

The detailed contents of the questionnaire are shown in Appendix C1 and Appendix C2 for reference. The format and wordings of the questions were tested for accurate communication before conducting the questionnaire survey. The time required for completing all the questions was investigated so that it was less than five minutes and it was marked in the covering letter. The method of sampling and how the respondent came to be chosen was also explained in the covering letter. The envelope of the Hong Kong Polytechnic University was used to give a professional appearance rather than like a junk mail. A return envelope with stamp was attached to every questionnaire. As explained by Oppendheim (1992), the most important determinant both of response rate and of the quality of the responses is the subject's motivation. He claimed that rewards intrinsic to the subject of the survey can also improve results. Therefore, it was explained in the covering letter that the objective of this questionnaire survey was to find out an acceptable criteria of daylighting performance for site layout planning. Besides, it was mentioned that every questionnaire was important to the improvement of the daylight environment in the future building development. In order to increase the response rates, a small gift was also given to the respondent who returned the questionnaire before the due date. The questionnaires were delivered to and collected from the residential flats during June and July in 2002. Totally 2,000 copies of the questionnaires were distributed to the two housing estates. A total of 652 completed copies from two estates returned, 321 copies were returned from Tin Shing Court and the rest was returned from Choi Ming Court. The response rate was about 33%.

4.4.3 Quantitative assessment

At the second stage of the survey, the daylight performance of the space was quantitatively assessed using four reference parameters: *SSDF*, *WSDF*, *ASDF* and *VDF*. Due to the limitation of time, budget and man force, it was difficult to carry out an on-site measurement for every household. The probable sunlight duration can be measured using equipment like the Campbell-Stokes recorder. However, it is impractical to measure summer, winter and annual sunlight hours for every household on-site. If the value of *VDF* is measured on-site, the sky condition at the time of measurement should conform to the CIE standard overcast sky. Any inconsistency of sky conditions among different measurement times may affect the accuracy of the *VDF* values. It could be difficult and time-consuming to measure *VDF* for more than 600 households under the same sky condition which conforms to the CIE standard overcast sky. Therefore, *SSDF*, *WSDF*, *ASDF* and *VDF* were calculated by newly developed calculation methods which will be explained in chapter 5. The calculation method of *VDF* is based on several assumptions suggested by Tregenza (1989b). The obstruction and ground were assumed to be perfectly diffusing reflecting surfaces. The illuminance on the obstructing building was assumed to be the same as the illuminance on the window itself. The light flux falling on the cavity between the building and ground was assumed to be uniformly distributed and the fraction of reflected flux not lost out of the cavity was assumed to be 0.5. The ground illuminance was assumed to be uniform with the value equal to half of the horizontal illuminance under unobstructed sky. As for the calculation of *SSDF*, *WSDF* and *ASDF*, a sky map of annual cumulative probable sunlight duration was constructed for Hong Kong. The bright sunshine hour recorded by the Hong Kong Observatory was used as the base data in the sky map.

4.4.4 Data analysis

Respondents' subjective sensation to the general daylight environment of their living room was collected at the first stage of the questionnaire survey. For each housing estate, the frequency of answer to each closed question was counted and the percentage was calculated. Then the subjective sensation results were studied using a correlation analysis. A correlation matrix was constructed to analyze the relations between different subjective sensations and overall evaluation of the daylight environment. The non-parametric (Spearman's) rank order correlation coefficients were evaluated for every set of results. At the second stage, the daylight environment was evaluated quantitatively by assessment parameters: *SSDF*, *WSDF*, *ASDF* and *VDF*. Their values were calculated for the window in the living room of every respondent in the two estates. The range of each assessment parameters was reported. The mean, standard deviation, minimum and maximum values were also reported. Besides, the distribution of every quantitative assessment parameter was evaluated. The effect of orientation and external obstruction to the calculated values of *SSDF*, *WSDF* and *ASDF* was studied for the two housing estates. The effect of self-obstruction by the external wall of the adjacent flat was also studied. Moreover, a correlation analysis was carried out to study the statistical relations between the respondents' subjective sensation and the quantitative assessment of daylight environment using *SSDF*, *WSDF*, *ASDF* and *VDF*. The non-parametric (Spearman's) rank order correlation coefficients were evaluated for every set of results. In order to study the effect of obstruction and relative location of the external wall of the adjacent flat to the correlation analysis result, the flat samples were divided into groups according to the orientations of windows in the living room and the relative location of the external wall of the adjacent flats. The mean values as well as the minimum and maximum values of *SSDF*, *WSDF*, *ASDF* and *VDF* were calculated for each group of flat samples. Then, another correlation analysis was carried out for each group of data. Data of Q9 and Q10 were analyzed for the development of daylighting design criteria. In Q9, the respondents were asked whether the daylight environments in their living rooms need to be improved. In Q10, they were asked whether they agreed that the daylight environments were satisfactory. Daylighting design criteria were set up according to different percentages of "need no improvement" based on Q9 and different percentages of satisfaction based on Q10. The quantitative assessment results were first divided into groups based on the *ASDF* values. The mean value of *ASDF* for each group of data was calculated. Then the percentages of satisfaction and "need no improvement" were computed for each group of data. The percentages were plotted against the mean value of *ASDF*. Polynomial regression line to the second order was plotted and daylight design criteria were evaluated according to different percentages of satisfaction and "need no improvement". Daylighting design criteria based on *VDF* were set up by the same procedures.

4.5 Sky hemisphere and external view division methods for the calculation of exterior vertical illuminance and annual daylight exposure

The calculation methods of exterior vertical illuminance and annual daylight exposure are based on the daylight coefficients approach which was developed by Tregenza and Waters (1983). It depends on the idea of dividing up the sky into a large number of very small elements, and analyzing separately their contributions to the internal illuminance. In sections 4.2 and 4.3, external view and sky hemisphere division methods were introduced. In the calculation of exterior vertical illuminance and annual daylight exposure, these two division methods were combined and elaborated to facilitate the calculations of vertical skylight coefficients, which are defined as the daylight coefficients at the external surface of a window in this thesis. Based on the sky hemisphere division method, the sky hemisphere is divided into many sky patches. The symbol $sky(\phi,\gamma)$ represents a sky patch whose centre subtends an azimuth angle ϕ from the south direction and an altitude angle γ above the horizon. The angle ϕ is measured from the south. It is negative when the centre of the sky patch is to the east of south and positive when it is to the west of south. The angle γ is measured from the horizon to the centre of the sky patch. It is always positive. For a 5° division, ϕ ranges from -177.5° to 177.5°, while γ ranges from 2.5° to 87.5°. Then the sky hemisphere is divided into 1,296 sky patches which are defined by the angles ϕ and γ. The external view from the window centre is divided azimuthally and altitudinally into many small patches by treating it as a vertical hemisphere. Similar to the division of the sky hemisphere, it is divided into patches by azimuth planes and altitude planes. If the angular width and height of every patch is 5°, the vertical hemispherical view is also divided into $36 \times 36 = 1296$ patches. Figure 4.9 shows the vertical hemispherical view outside the window and its division into 1296 patches. Then any object visible to the window can be described by a set of patches. Any point visible to the window can be defined by an azimuth angle δ and an altitude angle λ. The azimuth angle is measured from the normal to the window. It is negative when the angle is measured in anti-clockwise direction and positive when it is measured in clockwise direction. The altitude angle is measured from the horizontal. It is positive when it is above the horizontal and negative when it is below the horizontal. Both δ and λ range from -87.5° to 87.5.

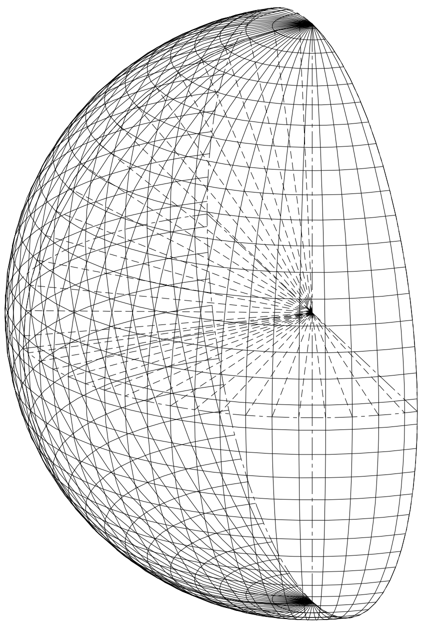


Figure 4.9 Division of external view into 1,296 patches

If the view from the window is completely free from obstructions, the patches above horizon represent the sky and those below horizon represent the ground. Then there will be 648 patches representing the sky and 648 patches representing the ground. In an urban environment, some portion of sky or ground is blocked by external building. The patches belong to this portion of obstructed sky or ground will then represent obstruction. For any object visible to the reference point, a particular set of patches will be projected onto it. If the centre point of a patch (defined by the middle of altitude and azimuth ranges of the patch) is projected onto this object, then the whole patch is considered to be belonged to that object. Otherwise, the whole patch would belong to other object on which the centre of the patch projects. The obstruction and ground can then be described by a set of patches. The area of obstruction projected by a patch is called obstruction patch, while that on the ground is called ground patch. The patches are named by the locations of their centre point which is described by their azimuth angle δ and altitude angle λ.

4.6 Unit hemisphere method for the calculation of exterior vertical illuminance and annual daylight exposure

The calculation methods of exterior vertical illuminance and annual daylight exposure were based on the unit hemisphere method (Simons & Bean, 2001). According to the principle of this method, the illuminance at a point due to a uniformly diffusing source is given by integrating, over the whole projected area, the product of source luminance and the orthographically projected area of the source on the base of the unit hemisphere at the reference point. This method was used in combination to the sky hemisphere and external view division methods in order to calculate the values of exterior vertical illuminance and annual daylight exposure received at a window. Therefore, the discussion and explanation of the unit hemisphere method in this section is based on an external view of a window which has been divided into sky, obstruction and ground patches. By assuming a patch to be perfectly diffusing with uniform luminance, the direct illuminance contribution due to this patch can be computed by multiplying its luminance value and its orthographically projected area at the point of calculation. Then the orthographically projected area of a particular patch should indicate the sensitivity of illuminance at the reference point to the luminance of that patch. The sensitivity should increase with the orthographically projected area of that patch. High sensitivity means that the illuminance at the reference point would be affected significantly by the luminance value of that patch.

In order to calculate the illuminance contribution due to a patch (sky patch, obstruction patch or ground patch), the orthographically projected area of a patch is evaluated first. The location of a patch relative to the reference point is represented by the azimuth and altitude angles (δ and λ) of its centre point. If the luminance of the patch is uniform with a value of $L_{patch(\delta,\lambda)}$, then the illuminance due to this patch on a vertical plane can be found directly from the following equation:

$$\begin{aligned} & L_{patch(\delta,\lambda)} \int_{\delta_2}^{\delta_1} \int_{\lambda_2}^{\lambda_1} \cos^2 \lambda \cos \delta d\lambda d\delta \\ & = L_{patch(\delta,\lambda)} (\sin \delta_1 - \sin \delta_2) \left(\frac{\lambda_1 - \lambda_2}{2} \times \frac{\pi}{180} + \frac{\sin 2\lambda_1 - \sin 2\lambda_2}{4} \right) \end{aligned} \tag{4.1}$$

In this integral equation, δ_1 and δ_2 are the upper and lower boundaries of the azimuth angle of the patch, while λ_1 and λ_2 are the upper and lower boundaries of the altitude angle of the patch. As δ and λ are the azimuth and altitude angles of the centre of the patch whose angular width and height are equal to 5°, their upper and lower boundaries could be found by the following equations:

$$\delta_1 = \delta + 2.5^\circ \tag{4.2}$$

$$\delta_2 = \delta - 2.5^\circ \tag{4.3}$$

$$\lambda_2 = \lambda + 2.5^\circ \tag{4.4}$$

$$\lambda_2 = \lambda - 2.5^\circ \tag{4.5}$$

According to the unit hemisphere method, the illuminance due to this patch is equal to the product of its luminance $L_{patch(\delta,\lambda)}$ and its orthographically projected area at the base of the unit hemisphere at the reference point. Therefore, the orthographically projected area of the patch (δ, λ) at the reference point on a vertical surface is expressed as:

$$OPAV_{ref}^{patch(\delta,\lambda)} = [\sin(\delta + 2.5) - \sin(\delta - 2.5)]\left[\frac{\pi}{72} + \frac{\sin 2(\lambda + 2.5) - \sin 2(\lambda - 2.5)}{4}\right] \tag{4.6}$$

This expression is applicable to the evaluation of orthographically projected area of the patch on a vertical surface. If the orthographically projected area at a horizontal plane (e.g. the ground) $OPAH_{gd}^{patch(\delta,\lambda)}$ is going to be found, another expression should be used. The calculation procedures are summarized in Appendix B5 and Appendix B6. The orthographically projected area of $patch(\delta, \lambda)$ on a horizontal plane is calculated to be:

$$OPAH_{ref}^{patch(\delta,\lambda)} = \frac{\pi}{72}\left[\sin^2(\lambda+2.5) - \sin^2(\lambda-2.5)\right] \quad (4.7)$$

Figure 4.10 shows the orthographical projections of all patches on the base of a unit-hemisphere at a vertical point. They should include all projections of the sky, obstruction and ground patches. By using the unit hemisphere method, the illuminance contribution due to a patch can be found by multiplying its orthographically projected area and its luminance value.

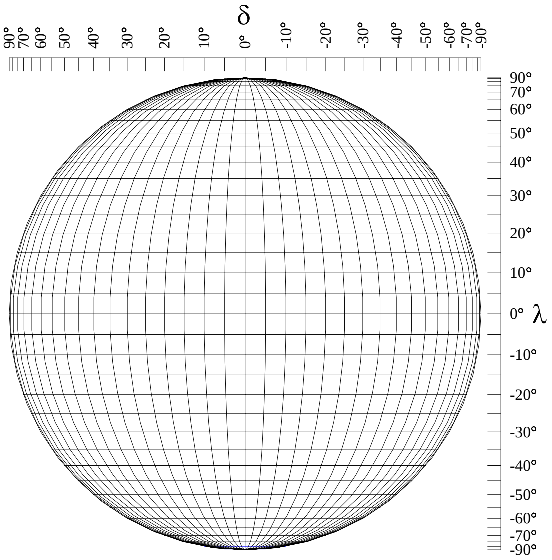


Figure 4.10 Orthographically projections of all patches

4.7 Computer simulation for testing the accuracy of the calculation method of exterior vertical illuminance

As the computer technology is becoming more advanced, computer-based simulation offer flexibility, convenience and time-saving for daylighting evaluation. It provides a convenient means of parametrically evaluating designs in comparison to other design alternatives. For calculation of daylight illuminances, lighting software with daylighting capability is available (Baty, 1996, 1997). Daylight performance in a room can be easily simulated using lighting simulation software. One of the common methods of calculating arrays of interior illuminances is daylight coefficients approach (Tregenza & Waters, 1983, 1984) which is introduced previously. Many powerful computer simulation systems adopt the daylight coefficients concept to perform detailed daylight analysis and rendering. Mardaljevic (1995) used daylight coefficients within the powerful simulation software - RADIANCE. RADIANCE is a collection of programs for the graphical simulation and analysis of lighting. It is a backward raytracer which is based on a mixed stochastic and deterministic raytracing approach (Ward & Rubinstein, 1988; Ward & Shakespeare, 1998). The method starts at a measurement point and traces rays of light backwards to the sources. Input files of RADIANCE specify the scene geometry, materials, luminaires, time, date and sky conditions (for daylight calculations). The calculated values include spectral radiance, irradiance and glare indices. It is capable of accurately predicting illuminance levels and daylight factors in the most complex of rooms (Attenborough & Goodwin, 1996). It can model any light source including diffuse daylight and sunlight. The primary advantage of RADIANCE, which is a UNIX software, over simpler lighting calculation and rendering tools is that there are no limitations on the geometry or the materials that may be simulated.

In order to test the accuracy of the calculation method of vertical illuminance, a simulation study by RADIANCE to compute the vertical illuminance was carried out for several building layouts. Vertical illuminances were simulated under the CIE standard overcast sky. The geometrical information of the building layouts was first converted to scene geometry for creating a RADIANCE model. The properties of the building surfaces were specified in a material file. The CIE standard overcast sky was generated in the "gensky" file. Then the model and the sky were compiled into an “octree” file by the scene compiler “oconv”. The “octree” file is required by RADIANCE for rendering. Simulation was performed using the basic computation enginee “rtrace”. The parameters for indirect calculation *ab*, *ad*, *as*, *aa* and *ar* were set to be 4, 2048, 64, 0.05 and 60 respectively. The parameter *ab* sets the number of ambient bounces to the specified integer. A setting 0 will turn off the interreflection calculation. The parameters *ad* and *as* set the numbers of ambient divisions and supersamples respectively. The number of ambient divisions is how many initial samples will be set out over the divided hemisphere and the number of ambient supersamples is the number of extra rays that will be used to sample areas in the divided hemisphere that appear to have high variance. The parameters *aa* sets the ambient accuracy to the specified fraction. This is the maximum error (only in indirect calculation) permitted in the indirect irradiance interpolation. The parameter *ar* sets the ambient resolution to the given integer. This setting is similar to a universal grid resolution in a more conventional radiosity calculation. The vertical illuminances at various points of the building layouts were simulated using RADIANCE and they were compared with the vertical illuminance results computed by the calculation method developed by the author.

4.8 Measurement for testing the accuracy of the calculation method of exterior vertical illuminance

The most straightforward way to evaluate the daylight performance in a room is to construct a scale model of the room of interest and observe the interior environment under real skies or artificial skies. Lighting parameters, like illuminance and luminance, can be determined for the sky conditions under which measurements are made. The values measured in the scale model may represent the actual readings measured in the room of interest, because the physical properties of light are such that daylight penetrates into and interreflects within the scale model room almost identical to how it would in a full-scale building. The technical report published by the Building Environmental Performance Analysis Club (BEPAC) (1990) recommends that external obstructions should be modeled accurately, both in size and reflectance. It suggests that the minimum size of model to be 1:40. Literature (Cannon-Brookes, 1997; Kim et al., 1985; Love & Navvab, 1991; McDowell et al., 1994; Reed & Nowak, 1955) reported that models of scale smaller than 1:20 tended to overestimate illuminance levels in real interiors. Experiment by Cannon-Brookes (1997) suggested that the degree of the divergence depended on the accuracy of the physical representation and whether maintenance factors were used. Apart from the inaccuracies due to the construction of the scale model, Hayman (2003) summaried the error of daylight measurement to be daylight equipment errors, which include the frequency response, linearity, response time, repeatability, noise level and compatibility of photoconductive devices, and set up errors, which include the calibration, installation and adjustment of equipment. Therefore, scale models are commonly used only to support mathematical calculations in predicting the performance of daylighting systems. They can also provide insight into the sunlight penetration and distribution in the room.

Scale model measurement can also be carried out under the artificial skies. The common artificial skies are the mirrored box sky, the dome sky and the scanning sky simulator. The mirrored box sky (Crisp & Littlefair, 1984; Hopkinson et al., 1966b) consists of a luminous ceiling with mirrored walls. A good approximation of the CIE overcast sky luminance distribution can be achieved quite easily. However, it is difficult to produce other types of skies. The side-lit model may also suffer from multiple reflections of the model in the mirrors. As for the dome sky, it needs to be at least 5 times the width of the model. It is usually made of white opaque hemisphere illuminated by lighting sources in a circular groove. It is possible to reproduce the uniform sky, the CIE standard overcast sky or the CIE standard clear sky. Another type of sky dome (Navvab, 1996; Schiler, 1989) is completed with a vault made of multitude of incandescent lamps. All types of sky can be reproduced by this kind of sky dome. An artificial sun can also be installed. Another type of artificial skies is the scanning sky simulator (Michel & Scatezzini, 2002; Michel et al., 1995). It comprises a luminous vault made of luminous discs, a rotating model support and a control and monitoring unit. The hemisphere of sky is divided into six symmetric parts, so that only one-sixth of the sky is physically reproduced. The effect of the overall hemisphere is simulated by six successive rotations of 60° each of the scale model under the simulator.

In order to test the accuracy of the calculation method of vertical illuminance under real skies, a measurement was conducted using a simple model. The experiment focused on verifying the ability of the calculation method to compute the total daylight illuminance at a vertical surface facing large obstruction under real skies. The site location, measurement parameters, measurement equipment and data analysis will be discussed one by one.

4.8.1 Site location and model for measurement

In order to minimize the calculation errors due to surrounding obstruction, a measurement site free from obstruction was selected. The site location is a primary school called Sai Kung Central Lee Siu Yam Memorial School. It is located in Sai Kung which is one of the rural areas in Hong Kong. The site is generally free from effective obstruction. Please refer to Appendix D1 for the surrounding views of the site as well as the photos and site map of the primary school.

A simple model was constructed for the measurement. The model was setup on the roof of the primary school. It consisted of two vertical planes of 0.5 m high and 0.5 m wide facing each other. One should act as the obstruction plane of another. The two vertical planes were perpendicular to a horizontal ground plane between them. The ground plane was of 0.5 m wide and 0.5 m long. Figure 4.11 shows the setup of the model. The reflectance of the vertical planes was measured to be 0.71 while that of the ground plane was measured to be 0.14. The rest of the ground was assumed to have a reflectance value of 0.2. The model was oriented so that the two vertical planes were aligned with the North-south line. The base of the model was adjusted every time to level the ground plane of the model. Photos of the experimental set up are shown in Appendix D2.

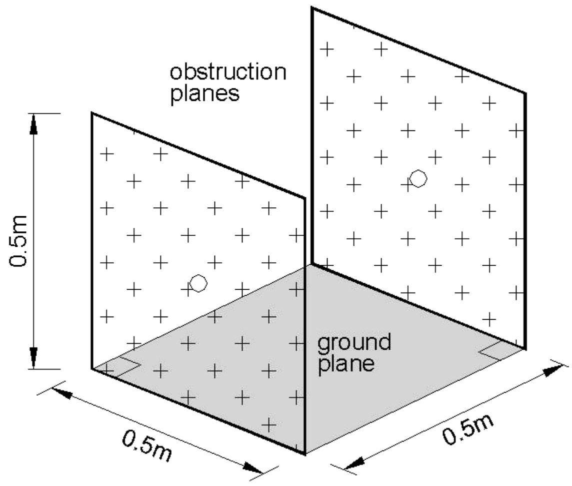


Figure 4.11 Model for measurement

4.8.2 Measurement parameters

The total daylight illuminances at the centre points of the two vertical planes were measured. The global and diffuse horizontal illuminances as well as the sky zenith luminance were also measured simultaneously. The measurement parameters include:

1. Global horizontal illuminance
2. Diffuse horizontal illuminance
3. Sky zenith luminance
4. Vertical illuminance at centre of vertical plane facing east
5. Vertical illuminance at centre of vertical plane facing west

Measurements were conducted on seven days: 10 June, 11 June, 25 June, 17 August and 15 September in 2004 as well as 21 January and 25 February in 2005. The skies on 25 June, 15 September and 21 January were partly cloudy. The sky on 25 February was generally overcast. The sky conditions of the rest of the days were generally clear. The vertical surfaces of the experimental model were aligned with the North-south line, so that the two vertical planes faced east and west respectively.

4.8.3 Measurement equipment

The global and diffuse horizontal illuminances as well as the vertical illuminances of the vertical planes were recorded simultaneously using the Konica Minolta illuminance meter T-10M which enables multi-point measurement. Four illuminance receptor heads and adaptors were connected to the main body of the illuminance meter. (The main body of the meter can be connected up to 30 receptor heads in a serial manner at the same time.) The adaptor of each illuminance receptor head was connected by 10Base-T network cable (category 5 straight cable) of less than 20 m long. Sky zenith luminance can be measured by a luminance meter. However, simultaneous measurement of luminance and illuminance is difficult to be recorded by different pieces of equipment. Therefore, a measurement technique, which was suggested by Parparir and his colleagues (2002) as well as Simons and Bean (2001), was adopted for the simultaneous measurement of sky zenith luminance. An illuminance receptor head of the illuminance meter T-10M was installed in a tailor-made baffled tube which was lined with black flock. The acceptance angle of the tube is about 2.5°. Before carrying out the measurement, the measured illuminance was first calibrated against the sky zenith luminance measured by a luminance meter under real skies. The calibrations were conducted in three days at the site location. The sky conditions of the three days were all clear. The calibration result is shown in Appendix D3. Then the measured illuminance data could be transformed to sky zenith luminance values. In this way, the global and diffuse illuminance, sky zenith luminance and vertical illuminances of the model were measured simultaneously.

The measuring range of the illuminance meter T-10M is from 0.01 lx to 299,900 lx. The receptor head is silicon photocell whose relative spectral response is within 8% (f1') of the CIE spectral luminous efficiency $V(\lambda)$. The cosine correction characteristics are within ±1% at 10°, within ±2% at 30°, within ±6% at 50°, within ±7% at 60° and within ±25% at 80°. The diameter of the receptor head is 16.5 mm. The operating temperature ranges from -10 °C to 40 °C. Diffuse horizontal illuminance was measured using the KIPP & ZONEN shadow ring CM 121. The shadow ring was mounted to the point of measurement with the angle between ring axis and horizontal equals the latitude of Hong Kong (22.3 °N) so that the axis of the shadow ring was parallel with the polar-axis. The ring width is 55 mm and the ring width/ring radius ratio is 0.185. The measured values were corrected using the LeBaron formula (LeBaron, Michalsky & Perez, 1990).

4.8.4 Data analysis

The total vertical daylight illuminances at the centres of the two vertical planes were measured under real skies and computed by a new calculation method developed by the author. The new method will be explained in chapter 7. It relies on the sky hemisphere and external view division method which has been explained in section 4.6. The new calculation method can be used to calculate the vertical daylight illuminance under any sky types of know sky luminance distributions. Therefore, the sky luminance distribution for every set of measurement has to be found out in order to calculate the vertical daylight illuminances at the two vertical planes. The sky type at the time of measurement was classified according to the CIE standard of general sky (CIE, 2003). Kittler et al. (1997) reported that a subset of 4 sky types of luminance distribution was adequate to describe the sky conditions appearing at a location. Li and his colleagues (2003) had studied three years of sky luminance data in Hong Kong. They reported that a subset of five luminance distributions would be sufficient to describe the sky patterns without any significant deterioration in the accuracy of prediction. They standardized the clear skies in Hong Kong to be sky types 11 and 13. The partly cloudy skies belonged to sky type 6 and overcast skies were standardized to be types 1 and 3. In order to simplify the data analysis process, the sky type classification for the measurement data was confined to these five sky types. As the sky conditions were quite stable for all the days of measurement, only one sky type was assumed for each measurement day.

As mentioned before, the sky conditions of the measurement days include clear (10 June, 11 June and 17 August), partly cloudy (25 June, 15 September and 21 January) and overcast (25 February). As only one CIE general sky type (sky type 6) was concluded for the partly cloudy sky, the sky conditions of 25 June, 15 September and 21 January were classified as sky type 6. For the clear and overcast skies, the ratio of sky zenith luminance to the corrected diffuse horizontal illuminance (L_Z / E_d) was adopted for the sky type classification. Kittler and Darula (2002) claimed that the ratio L_Z / E_d plotting against the solar altitude was found to be suitable to state the sky type, so that a standard L_Z / E_d curve could be defined for every CIE standard general sky type. Therefore for each measurement day, the value of L_Z / E_d was calculated for every set of measurement. They were plotted against the solar altitude and their departures from the standard L_Z / E_d curves were calculated. Then the root mean square error (RMSE) was computed and the sky type of a measurement day was classified according to the least value of RMSE. The ratio L_Z / E_d was plotted against the solar altitude for all the measurement data under clear, partly cloudy and overcast skies. The graphs are shown in Appendix D4. The classification of sky type for the seven measurement days is summarized in Table 4.2. Then the equation of sky luminance distribution was found for every measurement day according to the CIE standard of general sky (CIE, 2003) and the vertical daylight illuminances at the centres of the two vertical planes could be computed by the new calculation method. Measurement results were compared with the calculation results. Scatter plots were produced for different sky types. The mean bias error (MBE) and root mean square error (RMSE) were calculated.

Table 4.2 Sky type classification for the seven measurement days

	Measurement day	Sky condition	Sky type classification
1	10 June 2004	Clear	Sky type 13
2	11 June 2004	Clear	Sky type 13
3	25 June 2004	Partly cloudy	Sky type 6
4	17 August 2004	Clear	Sky type 11
5	15 September 2004	Partly cloudy	Sky type 6
6	21 January 2005	Partly cloudy	Sky type 6
7	25 February 2005	Overcast	Sky type 3

CHAPTER 5
DEVELOPMENT OF GENERAL EVALUATION METHODS OF DAYLIGHTING PERFORMANCE

5.1 Introduction

In this chapter, the calculation methods of average daylight factor, vertical daylight factor and probable sunlight duration are presented. Average daylight factor and vertical daylight factor were selected to be used for the general evaluation of the skylight availability at a window. Probable sunlight duration was selected to be used for the general evaluation of the sunlight availability at a window. The calculation methods of average and vertical daylight factors were first reviewed. Then they were modified so that they could be applied effectively in dense urban areas. As for the probable sunlight duration, a new calculation method was developed. The method was developed using the meteorological data of Hong Kong. However, the concepts and principles of the methods should be applicable to other dense urban environments.

5.2 Calculations of average and vertical daylight factors

In chapter 4, the parameters and methods used for daylighting design and assessment have been reviewed. Among various assessment parameters, average daylight factor is most popular and widely used. A number of design codes and guides recommend the use of average daylight factor for the assessment of interior daylighting performance (BSI, 1992; BRE, 1986a, 1986b; CIBSE, 1999). There are two types of average daylight factor. One is the average daylight factor over all interior room surfaces and the other is the average value over the working plane only. In this section, the calculations of both types of average daylight factor are discussed. The general daylighting performance of an interior can be assessed by average daylight factor, while the daylight availability of a window can be assessed by vertical daylight factor (*VDF*). An example of the use of *VDF* is that the Buildings Department of Hong Kong has recently accepted a set of performance-based approach using the *VDF* on window surface as an alternative measure for regulatory control of daylighting in buildings (Buildings Department, 2003). In this section, the calculation of *VDF* in a high density building environment will also be discussed.

5.2.1 Review of calculation methods of average and vertical daylight factors

5.2.1.1 Average daylight factors

The average daylight factor over all the interior room surfaces ($\overline{DF}_{all}$) can be calculated using the equation developed by Lynes in 1979. It is expressed as follows:

$$\overline{DF}_{all} = \frac{tA_{win}\Theta}{2A(1-\rho)} \tag{5.1}$$

It is the daylight factor averaged over all the interior surfaces – ceiling, floor, walls and windows of a side-lit room. The parameters A_{win} and A are the window area and the total area of the indoor surfaces, while t, Θ and ρ are the window transmittance, vertical angle subtended at the centre of window by the visible sky and the area weighted mean reflectance of the indoor surfaces respectively. This equation is based on the lumen calculation for side-lit rooms and the conservation law that the flux entering the room is equal to the flux absorbed. It assumes the ratio of the total amount of illuminance falling onto the window to the instantaneous unobstructed horizontal illuminance, which is equal to the value of *VDF*, is equal to $\frac{\Theta}{2}$. Then the equation of $\overline{DF}_{all}$ can also be expressed in the following way:

$$\overline{DF}_{all} = \frac{tA_{win}VDF}{A(1-\rho)} \tag{5.2}$$

If *VDF* on the outside surface of the window is found, then the values of $\overline{DF}_{all}$ can be evaluated from the interior room parameters like the window size and room reflectance. The calculation of *VDF* for a window in a densely packed site layout will be explained in the later section. Apart from the average daylight factor over all the interior surfaces, the average daylight factor on the working plane ($\overline{DF}_{wp}$) in a side-lit room can also be calculated. Crisp and Littlefair (1984) had modified Lynes' average daylight factor equation so that it is suitable to calculate the average daylight factor on the working plane in a side-lit room. This is done by considering the ratio of the average illuminance for all room surfaces to that for the working plane. The ratio is approximated to be $\frac{1+\rho}{2}$. Then the equation is modified to be:

$$\begin{aligned}\overline{DF}_{wp} &= \frac{tA_{win}\Theta}{A(1-\rho)(1+\rho)} \\ &= \frac{tA_{win}\Theta}{A(1-\rho^2)} \\ &= \frac{2tA_{win}VDF}{A(1-\rho^2)}\end{aligned} \tag{5.3}$$

This average daylight factor equation is recommended for the calculation of average daylight factor on working plane by the British Standard Institution and Building Research Establishment (BSI, 1992). The value of $\overline{DF}_{wp}$ can also be evaluated based on the split-flux principle. This principle divides the flux entering the room through the window into two parts. One part is the flux that enters the room directly from the sky or from obstructions above the horizon. And the second part is the flux which enters the room directly from the ground and obstruction below the horizon. The split-flux principle was originally developed for calculation of the inter-reflection component of daylight factor (Hopkinson et al., 1954). It was then further developed by Longmore in 1975 to evaluate $\overline{DF}_{wp}$. It calculates the internal mean daylight factor on the working plane in a side-lit room under the CIE standard overcast sky. Its expression is as follows:

$$\begin{aligned}\overline{DF}_{wp} &= tA_{win}\left[\frac{C}{A_{fw}} + \frac{C\rho_{fw} + D\rho_{cw}\rho_g}{A(1-\rho)}\right] \\ &= \left[\frac{tA_{win}C}{A_{fw}} + \frac{tA_{win}\left(C\rho_{fw} + D\rho_{cw}\rho_g\right)}{A(1-\rho)}\right]\end{aligned} \tag{5.4}$$

where C and $D \times \rho_g$ are the illuminance ratio components, expressed as percentages, on the external surface of the window due to flux incident from above and below the horizontal respectively; A_{fw} is the area of the floor and lower parts of the walls below the mid-height of the window (not including the window wall); ρ_{fw} is the average reflectance of A_{fw}; ρ_{cw} is the average reflectance of the ceiling and upper walls above the mid-height of the window (not including the window wall); and ρ_g is the average reflectance of the ground. The term $\frac{tA_{win}C}{A_{fw}}$ can be treated as the illuminance ratio falling on the working plane due to the direct skylight and externally reflected light from above the horizontal, while the term

$\frac{tA_{win}\left(C\rho_{fw} + D\rho_{cw}\rho_g\right)}{A(1-\rho)}$ is the internally reflected illuminance ratio due to the skylight and externally reflected light from above and below the horizontal. The latter is also called the BRE inter-reflection formula (BRE, 1986b).

5.2.1.2 Vertical daylight factor

VDF is defined as the ratio, expressed as percentage, of the total amount of illuminance falling onto a window over the instantaneous horizontal illuminance from a complete hemisphere of sky excluding direct sunlight (Buildings Department, 2003). With reference to Equation (5.4), as C and $D \times \rho_g$ are the illuminance ratios, expressed as percentages, due to the flux from above and below the horizontal, then their sum will be the total illuminance ratio at the external surface of the window, which is equal to the value of *VDF*. Therefore, it is elaborated by the author that *VDF* can be calculated by the equation below.

$$VDF = C + D \times \rho_g \tag{5.5}$$

The value of *VDF* can be used to quantify the daylight availability at the external surface of a window. It can also be used to assess the general daylighting environment of an interior by using it to calculate the quantity of $\overline{DF}_{all}$ and $\overline{DF}_{wp}$. Therefore, the illuminance ratios C and $D \times \rho_g$, which are the components of *VDF*, are important parameters in the daylighting availability calculation. The evaluation of these two illuminance ratios will be explained in the following sub-sections.

5.2.2 Review of calculation methods of illuminance ratios C and D×ρ_g

The illuminance ratio C comprises the light directly due to the visible sky and any light received at the window from the obstruction surfaces above the horizontal. It consists of two components: the direct skylight component (DSC) and the obstruction reflected (above horizon) component (ORC_{above}). Both of them depend upon the amount of external obstruction. The value of C is usually evaluated based on the assumption that the obstructions are infinite in extent and have their outlines horizontal and parallel to the planes of the window wall. Then C can be calculated based on one obstruction angle (θ). Values of C are suggested for different values of θ by BRE (1986a). In 1989, the calculation of the illuminance ratio C was modified by Tregenza (1989b) so that it can be applied for large external obstructions. In the modified calculation method, Tregenza uses two angles in section and two angles in plan to quantify a large external obstruction. The two angles in section include the lower limit of visible sky subtended by the line of horizontal obstruction θ_L and the upper limit of visible sky subtended by an overhanging canopy or window reveal θ_H. The two angles in plan include the azimuth angles from normal to the window to the limit of the visible sky on the right ϕ_R and left ϕ_L. The designation of the four angles is shown in Figure 5.1. The calculations of DSC and ORC_{above} are suggested by Tregenza (1989b) as follows:

$$\begin{aligned} DSC &= \frac{1}{E_d}\int_{\theta_L}^{\theta_H}\int_{\phi_L}^{\phi_R}\frac{L_Z}{3}(1+2\sin\theta)\cos^2\theta\cos\phi d\phi d\theta \\ &= \frac{L_Z f}{E_d} \\ &= \frac{9f}{7\pi} \end{aligned} \tag{5.6}$$

where

$$f=\frac{1}{3}\left(\sin\phi_R-\sin\phi_L\right)\left(\frac{\theta_H-\theta_L}{2}\times\frac{\pi}{180}+\frac{\sin 2\theta_H-\sin 2\theta_L}{4}\right.$$
$$\left.-\frac{2\cos^3\theta_H-2\cos^3\theta_L}{3}\right) \tag{5.7}$$

$$\begin{aligned}ORC_{above}&=\frac{1}{E_d}\left(\frac{L_b\pi}{2}-\int_{\theta_L}^{\theta_H}\int_{\phi_L}^{\phi_R}L_b\cos^2\theta\cos\phi d\phi d\theta\right)\\&=\frac{L_b}{E_d}\left(\frac{\pi}{2}-g\right)\\&=\frac{9L_b}{7\pi L_Z}\left(\frac{\pi}{2}-g\right)\end{aligned} \tag{5.8}$$

where

$$g=\left(\sin\phi_R-\sin\phi_L\right)\left(\frac{\theta_H-\theta_L}{2}\times\frac{\pi}{180}+\frac{\sin 2\theta_H-\sin 2\theta_L}{4}\right) \tag{5.9}$$

E_d is the diffuse horizontal illuminance due to the whole unobstructed sky. L_b is the luminance of the obstructing building. If the illuminance on the obstructing building is assumed to have the same value as the illuminance on the reference point, then L_b and ORC_{above} will be equal to:

$$L_b=\frac{L_Z f\rho_b}{\pi} \tag{5.10}$$

$$ORC_{above}=\frac{9f\rho_b}{7\pi^2}\left(\frac{\pi}{2}-g\right) \tag{5.11}$$

It is assumed that the light flux is distributed uniformly to the cavity between the building and the ground. Then the illuminance ratio C can be expressed as:

$$
\begin{aligned}
C &= \left[DSC + \frac{ORC_{above}}{1-\rho_o} \right] \times 100\% \\
&= \left[\frac{9f}{7\pi} + \frac{9f\rho_b}{7\pi^2(1-\rho_o)} \left(\frac{\pi}{2} - g \right) \right] \times 100\% \qquad (5.12) \\
&= \frac{9f}{7\pi} \left[1 + \frac{\rho_b}{\pi(1-\rho_o)} \left(\frac{\pi}{2} - g \right) \right] \times 100\%
\end{aligned}
$$

where ρ_o is the effective reflectance of the cavity. The value of ρ_o is given by:

$$\rho_o = \frac{\rho_b + \rho_g}{4} \qquad (5.13)$$

The way that the obstruction and overhang are defined by the four angles: θ_L, θ_H, ϕ_R and ϕ_L implies that the obstruction and overhang are assumed to be of fixed angular height. In other words, the portion of visible sky will be bounded by the altitude angles θ_L and θ_H at any azimuth angle location. The justification of this assumption will be studied in next section.

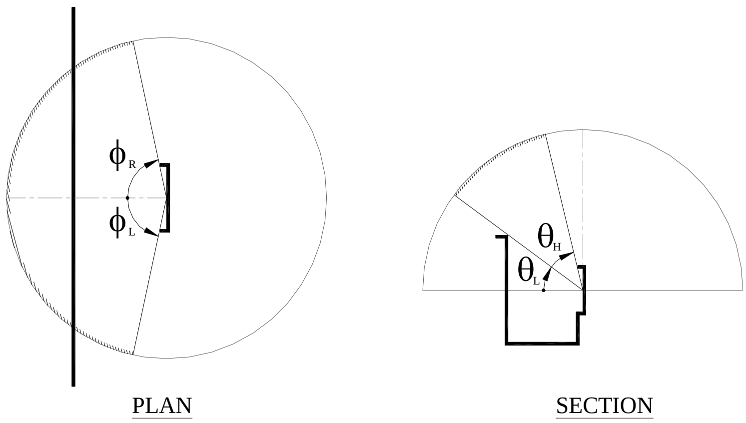


Figure 5.1 Designation of the angles: θ_L, θ_H, ϕ_R and ϕ_L

5.2.2.1 Fixed angular height assumption

As the obstruction is assumed to be of fixed angular height, it can be considered as a circular wall surrounding the window with a fixed height and distance. When this assumption is applied to an obstruction which is infinitely long and parallel to the window, the errors could be significant if only the angles: θ_L, θ_H, ϕ_R and ϕ_L are used to characterize the external environment. The portion of visible sky bounded by these four angles and the actual portion of visible sky as seen from the reference point (centre of the window) are illustrated in Figure 5.2 and Figure 5.3.

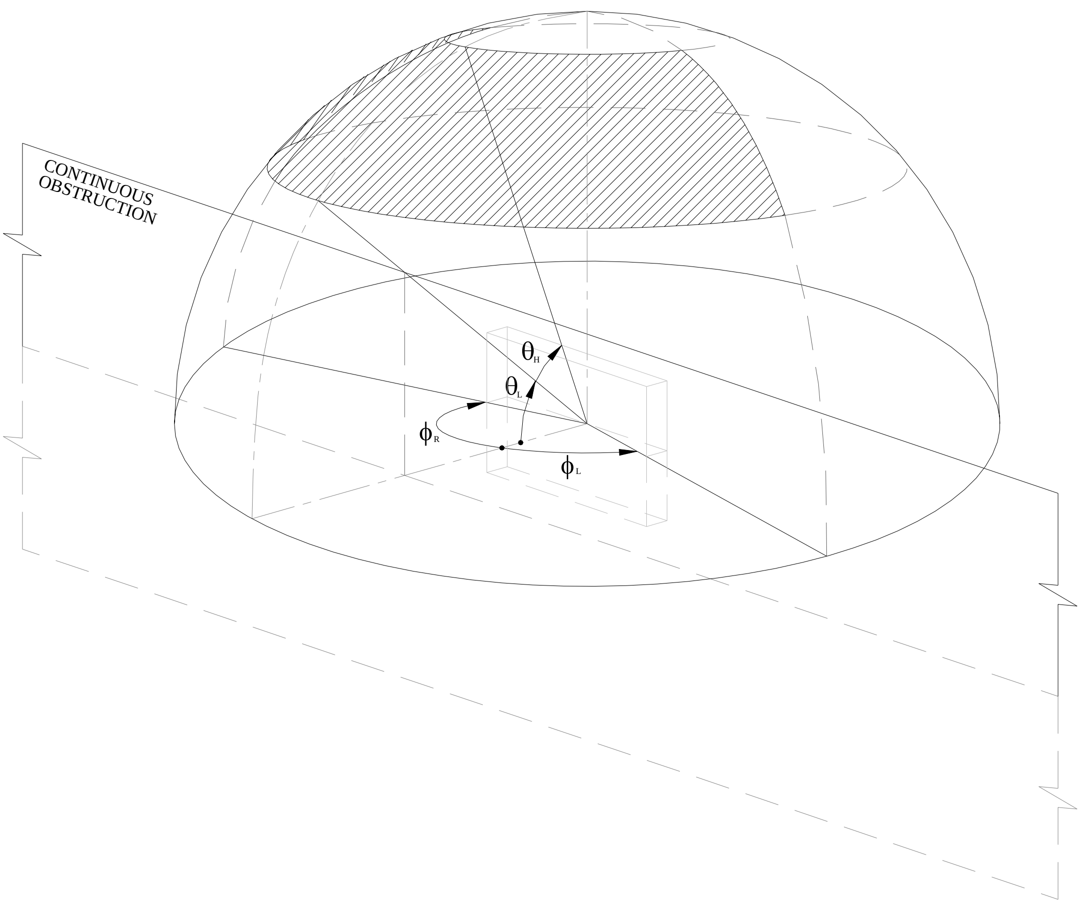


Figure 5.2 Portion of sky (shaded area) defined under the assumption of fixed angular height

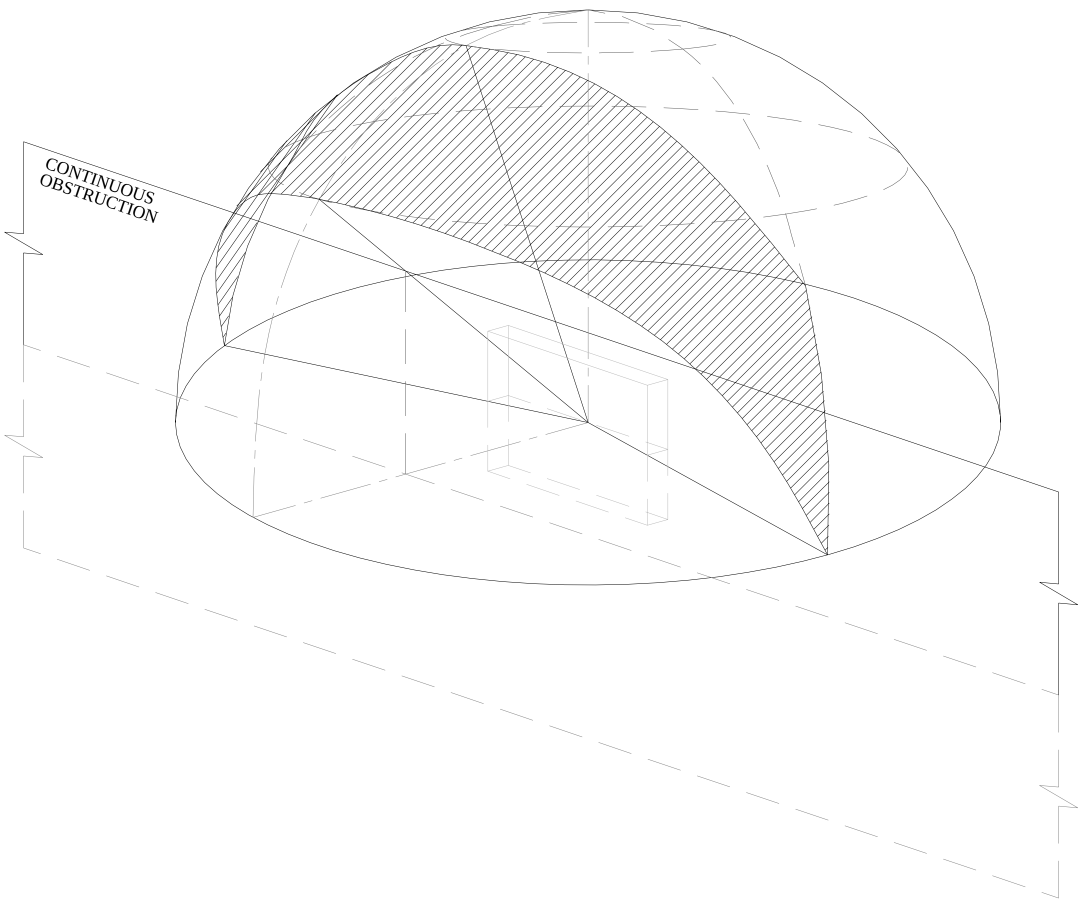


Figure 5.3 Actual portion of visible sky (shaded area) as seen from the reference point

In Figure 5.2, the shaded area represents the portion of sky defined by the four angles: θ_L , θ_H , ϕ_R and ϕ_L on the hemispherical sky vault. The shaded area in Figure 5.3 shows the part of the sky actually "seen" from the centre of the window. It is noticed that the difference between the two is quite significant. The visible sky defined by the four angles involves more portions of sky at high altitude. As the obstruction is assumed to be of fixed angular height, the altitude of the lower limit of the visible sky will be higher than the actual portion of visible sky. The difference will become more and more significant as the obstruction approaches towards the two ends. The upper limit of the visible sky is bounded by the edge of the overhanging canopy. Similarly, the altitude of the upper limit of the visible sky defined by the four angles is found to be higher than the actual portion of visible sky. For the actual visible sky as seen from the reference point to be equal to the portion of sky defined by the four angles: θ_L , θ_H , ϕ_R and ϕ_L , the geometry of the obstruction and window reveal should be like that as shown in Figure 5.4. The obstruction should be a circular wall surrounding the reference point with a constant angular height of θ_L, while the configurations of the window reveal should be like that shown in Figure 5.4. Then the actual visible sky as seen from the reference point will be exactly the same as the portion of sky bounded by the angles: θ_L, θ_H , ϕ_R and ϕ_L .

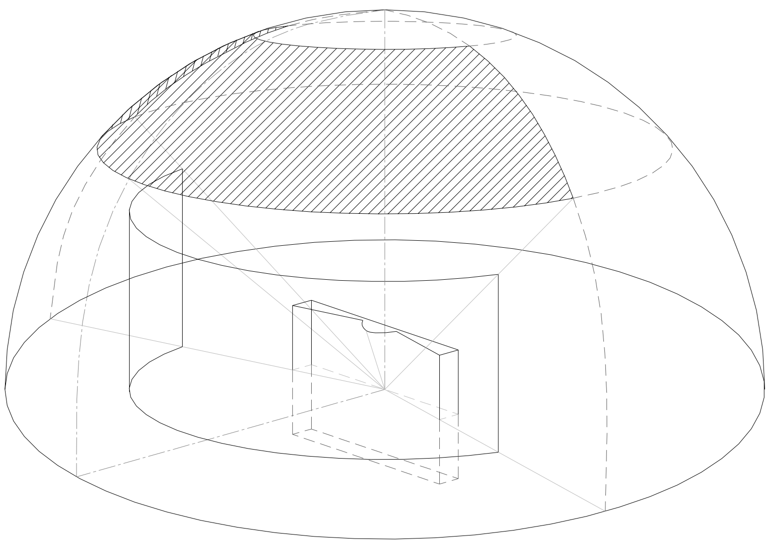


Figure 5.4 Geometry of obstruction and window reveal for the actual portion of visible sky to be equal to that shown in Figure 5.2

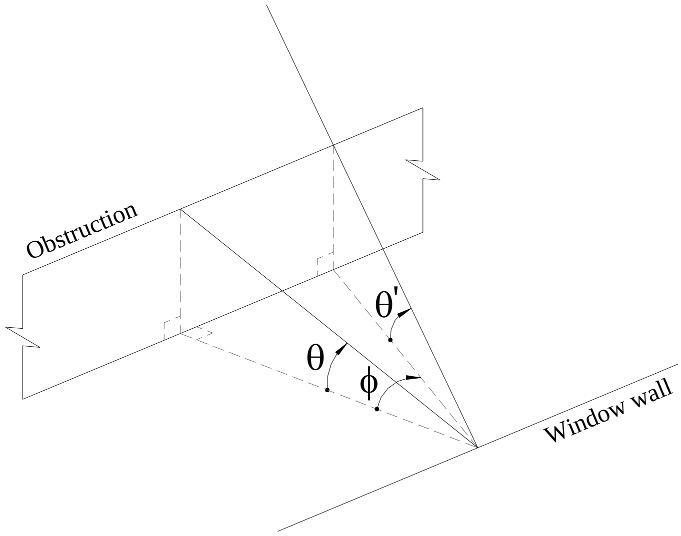


Figure 5.5 Definition of θ'

If the four angles are used to define an obstruction, which is infinitely long and parallel to the window wall, then the integration for the calculation of *DSC* and ORC_{above} is suggested to be revised. In order to bound the correct portion of visible sky, the definite integrals should be integrated to the derivative of θ', which is the altitude angle subtended by the obstruction or overhanging canopy at various azimuth angle, instead of θ. The definition of θ' is shown in Figure 5.5. The relationship between θ', θ and ϕ is shown by the following expression.

$$\tan\theta = \tan\theta'\cos\phi \tag{5.14}$$

Then the value of *DSC* due to the actual portion of visible sky as seen from the reference point can be calculated by the following function.

$$
\begin{aligned}
DSC &= \frac{1}{E_d}\int_{\phi_L}^{\phi_R}\int_{\tan^{-1}(\tan\theta_L\sec\phi)}^{\tan^{-1}(\tan\theta_H\sec\phi)} L_{\theta\phi}\cos^2\theta\cos\phi d\theta d\phi \\
&= \frac{3}{7\pi}\int_{\phi_L}^{\phi_R}\int_{\theta_L}^{\theta_H}\left[\frac{\sec^2\theta'\cos^2\phi}{\left(\tan^2\theta'\cos^2\phi+1\right)^2}+\frac{2\sin\theta'\sec^3\theta'\cos^3\phi}{\left(\tan^2\theta'\cos^2\phi+1\right)^{\frac{5}{2}}}\right]d\theta' d\phi
\end{aligned}
\tag{5.15}
$$

The above expression calculates the value of DSC due to the actual portion of visible sky at the reference point whose external obstruction is infinitely long and parallel to the window wall. The obstruction is defined by θ_L which defines its lower limit of visible sky in section across the normal to the window. The upper limit subtended by the overhanging canopy or deep window reveal is defined by θ_H, while the left and right limits of the visible sky in plan is defined by ϕ_L and ϕ_R. However, the evaluation of the above integral is very complicated and impractical to use.

5.2.2.2 Addition and subtraction of the illuminance ratio C

Tregenza (1989b) had modified the calculation of the illuminance ratio C for windows with large external obstruction. He also suggested a calculation method of the illuminance ratio C for irregular skylines. He made use of the value of $\frac{C}{2}$ which represents the value of the illuminance ratio C for half the lateral view from the window. The $\frac{C}{2}$ values were introduced by Tregenza that they could be added or subtracted to deal with irregular geometry of obstructions. The final value of the illuminance ratio C for the whole obstructing view could be evaluated by addition and subtraction processes. For complicated skylines, the addition and subtraction processes can be troublesome and confusing. It may be inefficient to be applied to the calculation of average daylight factor in a densely packed environment like that in Hong Kong. Nevertheless, when the calculation method of the illuminance ratio C is studied in detail, one will notice that the addition and subtraction process of C are in fact not mathematically reasonable. Based on Tregenza's equation, the illuminance ratio C is calculated using the following equation:

$$C = \frac{9f}{7\pi}\left[1 + \frac{\rho_b}{\pi(1-\rho_o)}\left(\frac{\pi}{2} - g\right)\right] \times 100\% \qquad (5.16)$$

As explained in the previous section, f and g are the integration solutions to the definite integrals for finding DSC and ORC_{above}. Therefore the addition and subtraction processes should be applicable to f and g according to the linearity principle of integration. The parameter C is not only the summation of DSC and ORC_{above}, it includes also the interreflection between the building facades. The direct skylight component can be added or subtracted from each other, but not for the external reflected and interreflection component. This fact may induce certain error in the calculation of the illuminance ratio C through multiple addition and subtraction processes. For simple and small obstructions, the error may be small. However, the error could be significant for large and complicated obstruction which requires numerous additions and subtractions of $\frac{C}{2}$. Therefore, the addition and subtraction processes are not recommended for the calculation of the illuminance ratio C in a densely packed building environment whose skylines are complicated and irregular.

5.2.2.3 Estimation of illuminance ratio D × ρ_g

The illuminance ratio $D \times \rho_g$ is due to the light received at the window from below the horizontal. It is composed of two components: the obstruction reflected (below horizon) component ORC_{above} and the ground reflected component GRC. These two components can be evaluated together by assuming all surfaces below the horizon to have an illuminance equal to half of that for an unobstructed ground under the same sky (Tregenza, 1989b). Then if these surfaces are assumed to be perfectly diffusing, their luminance value will become:

$$\frac{\rho_g}{\pi} \times \frac{E_d}{2} \tag{5.17}$$

As the surfaces below the horizon can be considered as a semi-infinite plane, the reflected illuminance due to these surfaces is calculated to be:

$$\frac{\rho_g}{\pi} \times \frac{E_d}{2} \times \frac{\pi}{2} = \frac{\rho_g E_d}{4} \tag{5.18}$$

Then the term $D \times \rho_g$ has a value equal to:

$$\begin{aligned} D \times \rho_g &= \frac{\rho_g E_d}{4} \times \frac{1}{E_d} \times 100\% \\ &= \frac{\rho_g}{4} \times 100\% \end{aligned} \tag{5.19}$$

5.2.3 New calculation method for dense urban environment

In high-rise building environment, skylines as seen from the windows are usually complicated and uneven. The calculation method should be simple yet accurate and applicable to irregular skylines. Most of the calculation methods assume the external obstruction to be infinitely long and have their outlines horizontal and parallel to the window wall. This assumption is not applicable to the urbanized environment of high building density. Tregenza (1989b) proposes a method to calculate the average daylight factor for window with large external obstruction. The calculation method was studied and concluded to suffer from the fixed angular assumption and multiple addition and subtraction of illuminance ratio C when it is applied to a dense urban environment. In this section, a calculation method is derived from the first principle based on several assumptions made by Tregenza (1989b). The proposed method is based on the concept of dividing the external view of the window azimuthally into many segments. The obstructing environment is defined by the obstruction angle subtended by the external building in every segment. The coefficients f and g can be evaluated based on the obstruction angles, then the illuminance ratio C, vertical daylight factor (*VDF*) and average daylight factors ($\overline{DF}_{all}$ and $\overline{DF}_{wp}$) can be evaluated. The effect of overhang and sidefins in obstructing the daylight penetration is also considered.

5.2.3.1 External view division

The external view division method had been explained in chapter 4. The external view of the window is divided azimuthally into 36 segments of 5° angular width. The vertical plane defining the lower and upper limits of the visible sky is assigned to be the centre azimuth angle ϕ of every segment. Then the azimuth angle ϕ of every segment is found and ranges from -87.5° to 87.5° in a step of 5°. It is measured from the normal to the window wall. It is negative when the azimuth angle is measured in anti-clockwise direction and positive when it is measured in clockwise direction. The lower and upper limits of the visible sky in every segment are represented by altitude angles $\theta_L^{sky(\phi)}$ and $\theta_H^{sky(\phi)}$ respectively. The angle $\theta_L^{sky(\phi)}$ is the altitude angle subtended from the centre of the window to the top of the obstructions at azimuth angles ϕ. As for the angle $\theta_H^{sky(\phi)}$, it is the altitude angle subtended from the centre of the window to the edge of the external shading. It can be calculated from the external shading configurations using simple trigonometric equations. Both of them are measured from the normal to the window. They are always positive. By using the external view division method, the external environment of a window is defined by 36 pairs of altitude angles $\theta_L^{sky(\phi)}$ and $\theta_H^{sky(\phi)}$. This method of external view division is especially useful to define the external obstruction in a dense urban environment. Figure 5.6 and Figure 5.7 show the difference between the actual visible sky as seen from the centre of the window and the sky as defined by 36 pairs of altitude angles $\theta_L^{sky(\phi)}$ and $\theta_H^{sky(\phi)}$. It is noticed that the difference is not very significant. This method eliminates the repetitious procedures of addition and subtraction of illuminance ratio C. It also removes the error due to this addition and subtraction process which is mathematically unreasonable. The evaluation method of the illuminance ratio C is improved for easy adoption in densely-packed building environment. The improvement can reduce the inconsistency of implementation method due to confusion of application of the obstruction angles.

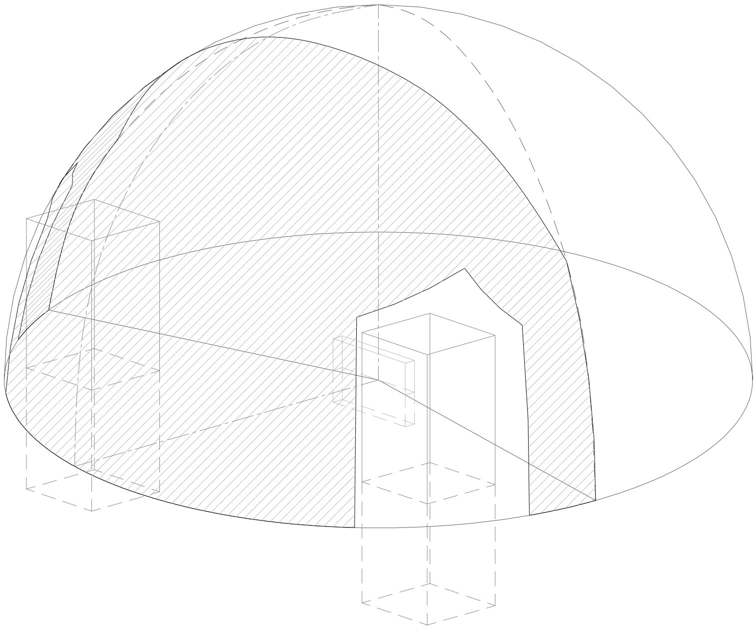


Figure 5.6 Actual portion of visible sky (shaded area) as seen from the reference point

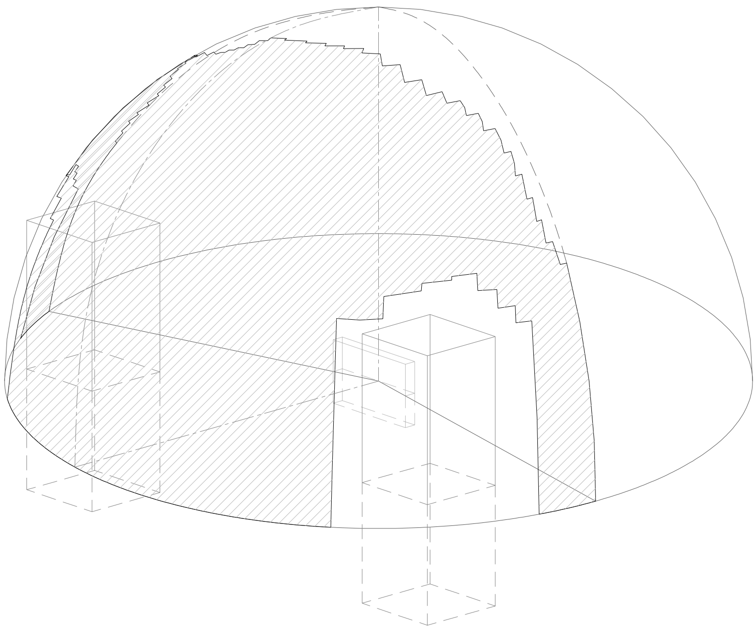


Figure 5.7 Portion of sky (shaded area) defined by 36 pairs of altitude angles: $\theta_L^{sky(\phi)}$ and $\theta_H^{sky(\phi)}$

In order to evaluate $\overline{DF}_{all}$, $\overline{DF}_{wp}$ and *VDF*, we have to calculate the illuminance ratios C and D at the centre of the window. It has been explained in the previous section that the illuminance ratio D can be estimated by Equation (5.19). As for the illuminance ratio C, it is composed of the direct skylight component (DSC) and the obstruction reflected component (above the horizontal) (ORC_{above}). After the sky hemisphere has been divided into many segments, the direct skylight component due to the portion of visible sky in one segment can be evaluated. Then the final value of DSC due to the whole portion of visible sky can be found by adding up all the components.

5.2.3.2 Direct skylight component

The direct skylight component at the reference point due to the visible sky in one segment ($DSC^{sky(\phi)}$) can be calculated by the following equation:

$$\begin{aligned} DSC^{sky(\phi)} &= \frac{1}{E_d}\int_{\theta_L^{sky(\phi)}}^{\theta_H^{sky(\phi)}}\int_{\phi-2.5}^{\phi+2.5}\frac{L_Z}{3}\left(1+2\sin\theta\right)\cos^2\theta\cos\phi d\phi d\theta \\ &= \frac{9f^{sky(\phi)}}{7\pi} \end{aligned} \tag{5.20}$$

where

$$\begin{aligned} f^{sky(\phi)} = \frac{1}{3}\left[\sin(\phi+2.5)-\sin(\phi-2.5)\right]\times\Bigg(&\frac{\theta_H^{sky(\phi)}-\theta_L^{sky(\phi)}}{2}\times\frac{\pi}{180} \\ &+\frac{\sin 2\theta_H^{sky(\phi)}-\sin 2\theta_L^{sky(\phi)}}{4}-\frac{2\cos^3\theta_H^{sky(\phi)}-2\cos^3\theta_L^{sky(\phi)}}{3}\Bigg) \end{aligned} \tag{5.21}$$

Then the direct skylight component due to the whole visible sky (DSC) is evaluated by adding up the direct skylight components from all the segments.

$$DSC = \frac{9}{7\pi} \sum_{\substack{\phi=-87.5 \\ (Step=5)}}^{87.5} f^{\,sky(\phi)} \tag{5.22}$$

5.2.3.3 Obstruction reflected component (above the horizontal)

The obstruction reflected component due to the obstruction above the horizontal in one segment $ORC_{above}^{sky(\phi)}$ can be evaluated by the following equation:

$$\begin{aligned} ORC_{above}^{sky(\phi)} &= \frac{1}{E_d}\left(\frac{L_b \pi}{72} - \int_{\theta_L^{sky(\phi)}}^{\theta_H^{sky(\phi)}} \int_{\phi-2.5}^{\phi+2.5} L_b \cos^2\theta \cos\phi d\phi d\theta\right) \\ &= \frac{9L_b}{7\pi L_Z}\left(\frac{\pi}{72} - g^{\,sky(\phi)}\right) \end{aligned} \tag{5.23}$$

where

$$\begin{aligned} g^{\,sky(\phi)} &= [\sin(\phi+2.5) - \sin(\phi-2.5)]\left(\frac{\theta_H^{sky(\phi)} - \theta_L^{sky(\phi)}}{2} \times \frac{\pi}{180}\right. \\ &\quad \left. + \frac{\sin 2\theta_H^{sky(\phi)} - \sin 2\theta_L^{sky(\phi)}}{4}\right) \end{aligned} \tag{5.24}$$

Then the obstruction reflected component due to the obstructions in all segments above the horizontal (ORC_{above}) is calculated to be:

$$\begin{aligned} ORC_{above} &= \frac{9L_b}{7\pi L_Z} \sum_{\substack{\phi=-87.5 \\ (Step=5)}}^{87.5} \left(\frac{\pi}{72} - g^{\,sky(\phi)}\right) \\ &= \frac{9L_b}{7\pi L_Z}\left(\frac{\pi}{2} - \sum_{\substack{\phi=-87.5 \\ (Step=5)}}^{87.5} g^{\,sky(\phi)}\right) \end{aligned} \tag{5.25}$$

It is assumed that the effective mean direct skylight illuminance on the obstructions is the same as on the centre of the window and their surfaces are uniformly diffusing.

Then the luminance of the obstructing building L_b can be calculated by the following expression:

$$L_b = \frac{L_Z \rho_b}{\pi} \times \sum_{\substack{\phi=-87.5 \\ (Step=5)}}^{87.5} f^{\,sky(\phi)} \qquad (5.26)$$

In this way, the obstruction reflected component due to the obstructions in all segments above the horizontal (ORC_{above}) can be found by the following equation:

$$ORC_{above} = \frac{9\rho_b}{7\pi^2} \sum_{\substack{\phi=-87.5 \\ (Step=5)}}^{87.5} f^{\,sky(\phi)} \left(\frac{\pi}{2} - \sum_{\substack{\phi=-87.5 \\ (Step=5)}}^{87.5} g^{\,sky(\phi)} \right) \qquad (5.27)$$

<u>5.2.3.4 Illuminance ratio C</u>

It is assumed that the light flux is distributed uniformly to the cavity between the building and the ground. Then the illuminance ratio C can be expressed as:

$$\begin{aligned} C &= \left(DSC + \frac{ORC_{above}}{1-\rho_o} \right) \times 100\% \\ &= \left[\frac{9}{7\pi} \sum_{\substack{\phi=-87.5 \\ (Step=5)}}^{87.5} f^{\,sky(\phi)} + \frac{9\rho_b}{7\pi^2 (1-\rho_o)} \sum_{\substack{\phi=-87.5 \\ (Step=5)}}^{87.5} f^{\,sky(\phi)} \left(\frac{\pi}{2} - \sum_{\substack{\phi=-87.5 \\ (Step=5)}}^{87.5} g^{\,sky(\phi)} \right) \right] \times 100\% \qquad (5.28) \\ &= \frac{9}{7\pi} \sum_{\substack{\phi=-87.5 \\ (Step=5)}}^{87.5} f^{\,sky(\phi)} \left[1 + \frac{\rho_b}{\pi(1-\rho_o)} \left(\frac{\pi}{2} - \sum_{\substack{\phi=-87.5 \\ (Step=5)}}^{87.5} g^{\,sky(\phi)} \right) \right] \times 100\% \end{aligned}$$

5.2.3.5 Average and vertical daylight factors

As explained earlier, C and $D \times \rho_g$ are the illuminance ratios due to the flux from above and below the horizontal. The value of *VDF* can be found out by adding up these two illuminance ratios.

$$VDF = C + D \times \rho_g$$

$$= \frac{9}{7\pi} \sum_{\substack{\phi=-87.5 \\ (Step=5)}}^{87.5} f^{sky(\phi)} \left[1 + \frac{\rho_b}{\pi(1-\rho_o)} \left(\frac{\pi}{2} - \sum_{\substack{\phi=-87.5 \\ (Step=5)}}^{87.5} g^{sky(\phi)} \right) \right] \times 100\% + \frac{\rho_g}{4} \times 100\% \quad (5.29)$$

Then the average daylight factor over all interior room surfaces ($\overline{DF}_{all}$) and the average daylight factor on the working plane ($\overline{DF}_{wp}$) can be evaluated by the following expressions:

$$\overline{DF}_{all} = \frac{tA_{win} VDF}{A(1-\rho)} \text{ (Lynes, 1979)} \quad (5.30)$$

$$\overline{DF}_{wp} = \frac{2tA_{win} VDF}{A(1-\rho^2)} \text{ (Littlefair, 1984)} \quad (5.31)$$

$$\overline{DF}_{wp} = tA_{win} \left[\frac{C}{A_{fw}} + \frac{C\rho_{fw} + D\rho_{cw}\rho_g}{A(1-\rho)} \right] \text{ (Tregenza, 1989b)} \quad (5.32)$$

5.2.3.6 Calculation example

An example was prepared to demonstrate the calculation of average and vertical daylight factors in a dense urban environment. Figure 5.8 shows the site layout and the room under concern. Point X indicates the location of the window centre. The room height, width and length are equal to 3 m, 3m and 6 m respectively. The height of all building blocks above point X is equal to 100 m. In order to calculate $\overline{DF}_{all}$, $\overline{DF}_{wp}$ and *VDF*, the illuminance ratio C has to be first calculated. With reference to the calculation procedures explained above, the semi-circle view from point X is first divided azimuthally into 36 segments, like that shown in Figure 5.9. Then the external environment of the window is defined by 36 pairs of altitude angles: $\theta_H^{sky(\phi)}$ and $\theta_L^{sky(\phi)}$. The angle $\theta_L^{sky(\phi)}$, which defines the lower limit of the visible sky, can be calculated from the height and distance of the obstruction from point X in every segment. If no obstruction is encountered in a segment, the angle should be equal to zero. In this example, the window is installed with external shading devices of overhang and both right and left sidefins. The depth of the overhang and sidefins are equal to 0.2 m and 0.1 m respectively. Then the value of $\theta_H^{sky(\phi)}$, which defines the upper limit of the visible sky, can be calculated by trigonometric equations. The values of $\theta_H^{sky(\phi)}$ and $\theta_L^{sky(\phi)}$ in every segment are calculated for point X. They are tabulated in Table 5.1. Then 36 pairs of $f^{sky(\phi)}$ and $g^{sky(\phi)}$ can be computed from the values of $\theta_H^{sky(\phi)}$ and $\theta_L^{sky(\phi)}$ according to Equations (5.21) and (5.24). After that, the values of DSC and ORC_{above} can be calculated from Equations (5.22) and (5.27). Finally, the value of illuminance ratio C is computed by Equation (5.28). In this way, $\overline{DF}_{all}$ and $\overline{DF}_{wp}$ (Tregenza, 1989b) were calculated to be 1.9% and 2.4% respectively and *VDF* was calculated to be 27.3%.

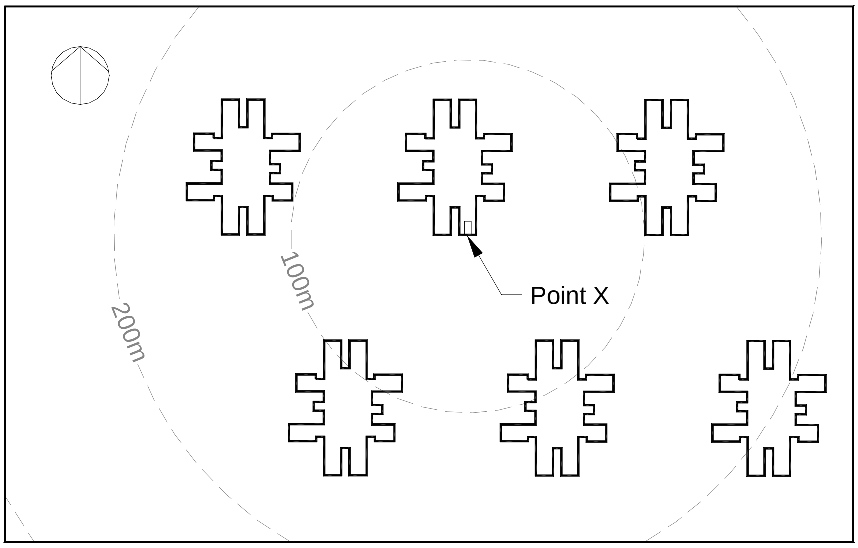


Figure 5.8 Site layout plan for the example

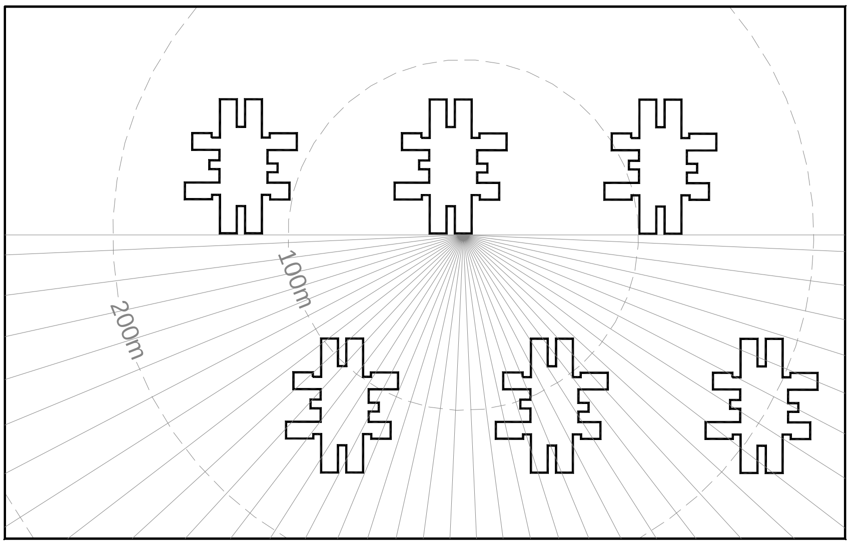


Figure 5.9 Semi-circle view from point X is divided azimuthally into 36 segments.

Table 5.1 Altitude angles defining the external environment of point X

ϕ	$\theta_H^{sky(\phi)}$	$\theta_L^{sky(\phi)}$
-87.5	0.0	0.0
-82.5	44.8	0.0
-77.5	47.3	0.0
-72.5	56.4	0.0
-67.5	62.4	30.3
-62.5	66.6	30.5
-57.5	69.6	29.0
-52.5	71.8	29.7
-47.5	73.5	0.0
-42.5	74.8	51.3
-37.5	75.9	53.3
-32.5	76.7	54.3
-27.5	77.3	50.1
-22.5	77.8	49.7
-17.5	78.2	50.6
-12.5	78.4	42.5
-7.5	78.6	0.0
-2.5	78.7	0.0
2.5	78.7	0.0
7.5	78.6	0.0
12.5	78.4	0.0
17.5	78.2	0.0
22.5	77.8	40.9
27.5	77.3	48.5
32.5	76.7	47.1
37.5	75.9	46.8
42.5	74.8	49.8
47.5	73.5	48.9
52.5	71.8	45.9
57.5	69.6	0.0
62.5	66.6	0.0
67.5	62.4	0.0
72.5	56.4	0.0
77.5	47.3	0.0
82.5	44.8	0.0
87.5	0.0	0.0

5.2.3.7 Calculation spreadsheet

The above calculation method involves many repeated calculations of the same equation with different inputs. Therefore it would be convenient if all the equations are input to a calculation spreadsheet for fast evaluation of average daylight factors and vertical daylight factor. A calculation spreadsheet was developed in the format of Microsoft Excel and its user interface page is shown in Figure 5.10. For the calculation of vertical daylight factor, the inputs include the 36 obstruction angles ($\theta_L^{sky(\phi)}$) defining the lower limits of the visible sky, the dimensions of the external shadings as well as the surface reflectances of external obstruction and ground. The values of $\theta_H^{sky(\phi)}$ are automatically calculated by the spreadsheet with the input of the external shading configurations. If the average daylight factors are going to be calculated, the room and window dimensions, interior surface reflectances as well as the window transmittance have to be input to the calculation spreadsheet. The parameters of the above calculation example are input to the spreadsheet for demonstration and the outputs are shown in the user interface page. This spreadsheet calculates both the average daylight factor over all interior surfaces ($\overline{DF}_{all}$) and the average daylight factor on the working plane ($\overline{DF}_{wp}$). The calculation of $\overline{DF}_{all}$ is based on Lynes's (Lynes, 1979) equation, while the calculation of $\overline{DF}_{wp}$ is based on Tregenza's (1989b) equations.

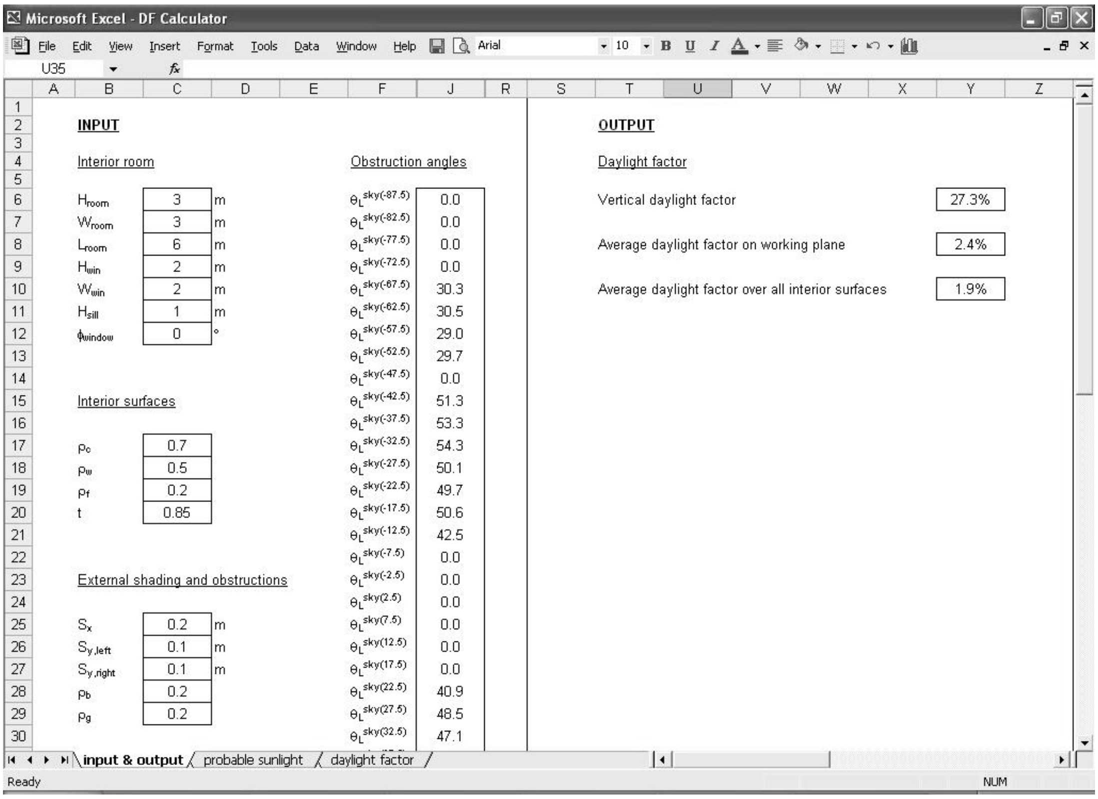


Figure 5.10 User interface of the calculation spreadsheet for the calculations of average daylight factors and vertical daylight factor

5.3 Calculation of probable sunlight duration

The sunlight availability of a window can be quantified by the probable sunlight duration which includes the summer, winter and annual probable sunlight duration. They are the long-term average of the number of hours during summer, winter and the whole year respectively in which direct sunlight reaches a surface. When they are represented by percentages of the total probable sunlight duration received by an unobstructed horizontal plane, they are called the summer sunlight duration factor, winter sunlight duration factor and annual sunlight duration factor respectively in this thesis. Winter is defined as the period between 23 September and 20 March inclusive. A review of the published literature suggests that there is no calculation method which is suitable to be adopted in a dense urban environment. The sunlight penetration to a window on a particular day can be observed by the sunpath diagram, but the sunpath diagram gives no numerical value of sunlight hours. The summer and winter probable sunlight duration can be estimated graphically by the Stereographic Sunlight Probability Diagram (e.g. BSI, 1992) and the Sunlight Availability Indicator (BRE, 1991). However, in the context of a densely packed building environment, they give too coarse results which may lead to unacceptable error. Therefore, a new method was developed for the calculation of summer, winter and annual sunlight duration factors received at a window in a dense urban environment.

5.3.1 Review of calculation methods of probable sunlight duration

5.3.1.1 Sunpath diagrams

A sunpath diagram gives no numerical values of probable sunlight duration, but it illustrates clearly the extent of sunlight penetration to a window in a year. It can be used to find the times of the day and year for which sunlight is available at a point. It is usually labelled with solar time. The sun's position at any time is represented by two angles: solar azimuth (ϕ_s) and solar altitude (γ_s). There are generally two types of sunpath indicator which are widely adopted for sunlight availability assessment. They include the Stereographic Sunpath Diagram (e.g. BSI, 1992) and the Sunpath Indicator (BRE, 1991) which are widely adopted for sunlight availability assessment. The Stereographic Sunpath Diagram is based on the stereographic projection of the sky vault. The projection method is illustrated in the left drawing of Figure 5.11.

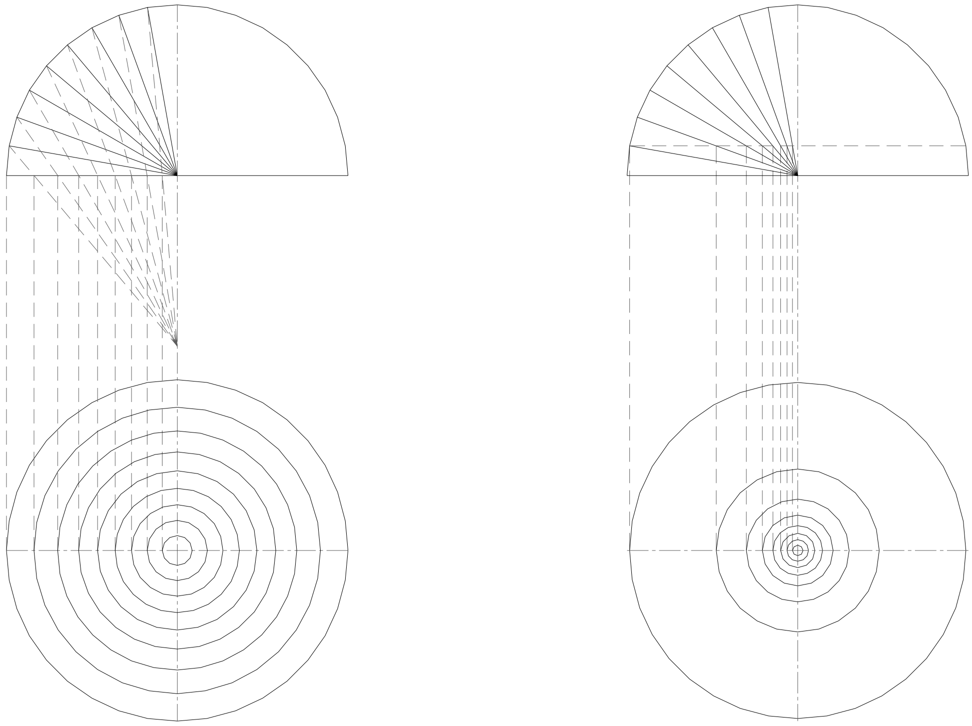


Figure 5.11 Sky vault projection method of the stereographic sunpath diagram (left) and the sunpath indicator (right)

This type of projection is first introduced by Pleijel (1954). The advantage of this kind of projection is that sunpaths and time-of-day curves are arcs of circles on the diagram and therefore can be drawn easily. A fairly easy and quick construction method of the Stereographic Sunpath Diagram is discussed by Szokolay (1980). A Stereographic Sunpath Diagram is constructed for Hong Kong based on this method and it is shown in Figure 5.12. The concentric circles represent the solar altitudes and the scales around the perimeter represent the solar azimuths. Each of the long curved arcs gives the sunpath for a particular day. The shorter converging curves show the apparent solar time of the day. External shading and obstructions can be plotted onto the diagram for sunlight availability study. However, the plotting procedures are rather complicated. Therefore, this sunpath diagram is usually used for presentation of the sunpath.

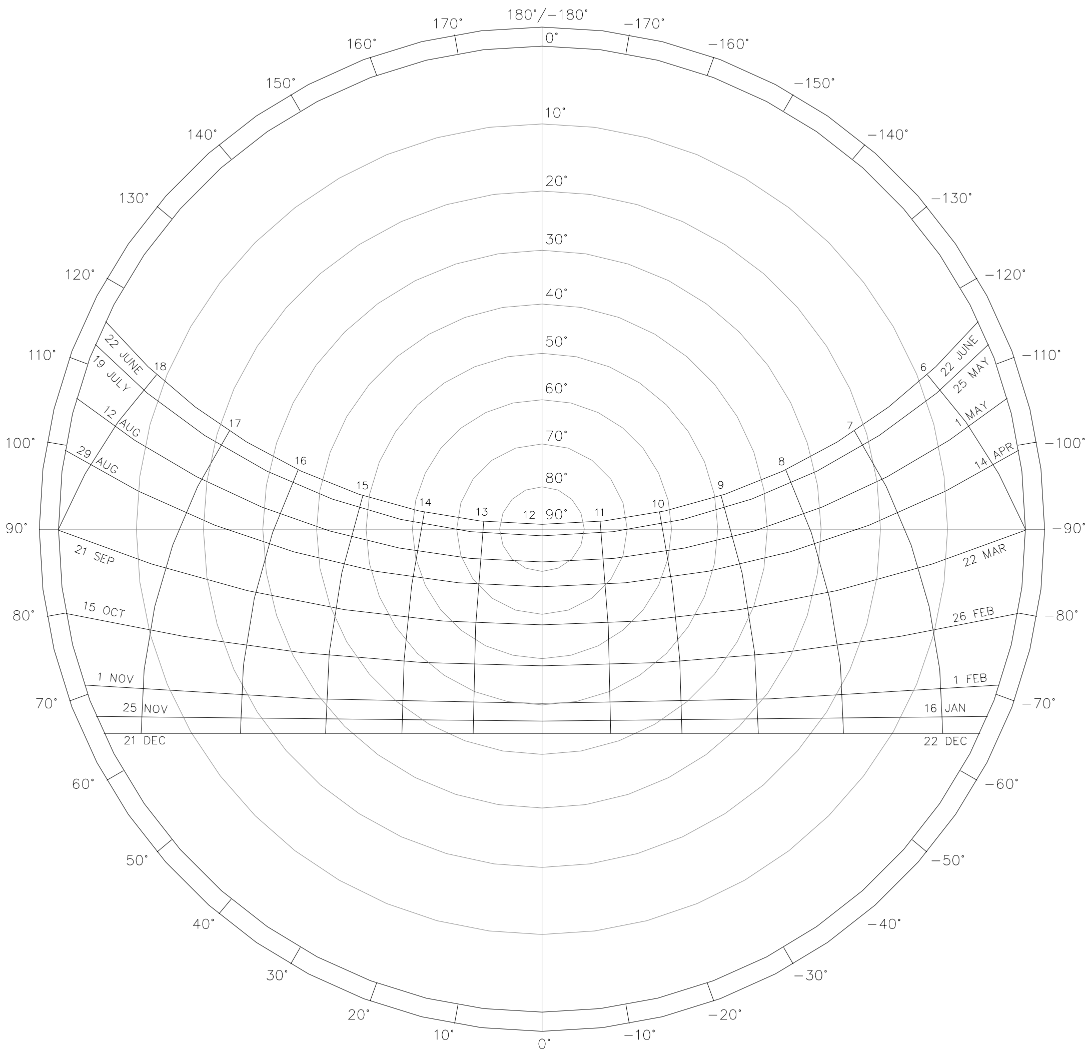


Figure 5.12 Stereographic sunpath diagram for Hong Kong (22.3° N)

Another type of sunpath diagram is called the Sunpath Indicator. The points of the hemisphere are first projected onto a horizontal plane and then further projected orthographically to the horizon circle. The sunpaths on the indicator actually show the locations of the sun on plan when the height of the sun is fixed at a constant value. The projection method is illustrated in the right drawing of Figure 5.11. As 0° altitude would be projected in the infinity, it is not shown in the Sunpath Indicator. One of the advantages of the Sunpath Indicator is that it can be used in conjunction with the site layout plan. The Sunpath Indicator can be overlaid onto the layout plan of correct scale so that the durations of insolation on the façade at different times of the year can be assessed quickly and easily. As explained earlier, sunpaths in the Sunpath Indicator show the locations of the sun on plan when the height of the sun is fixed at a constant value. Then the sunpath can also be treated as the boundary of an obstruction of a particular height so that the obstruction should block the sunlight if it moves near to the reference point from this boundary. The Sunpath Indicator can be overlaid onto a site layout plan to observe the sunpath for sunlight availability design. Before overlaying the indicator onto the layout plan, it is important that they are of the same scale. The Sunpath Indicator was originally developed by Littlefair (BRE, 1999a). It is used to find the times of the day and year for which sunlight is available on a window wall or at a point in a layout. A Sunpath Indicator for Hong Kong was constructed as shown in Figure 5.13. The bold curves which run across the indicator are the sunpaths. Each sunpath is divided into hours by lighter time-of-day curves. Different to the original Sunpath Indicator developed by Littlefair, the time scale for the proposed Sunpath Indicator is local clock time of Hong Kong. Therefore, the hour lines are asymmetrical. The hour lines for January to June are different to that for June to December. The hour lines for the former months are indicated with arrows pointing up and that for the latter months are indicated with arrows pointing down. The concentric circles in hidden line are the ratios of the distance over height above the reference point. The ratios have the same value as the tangent of the angle (90 - γ_s)°.

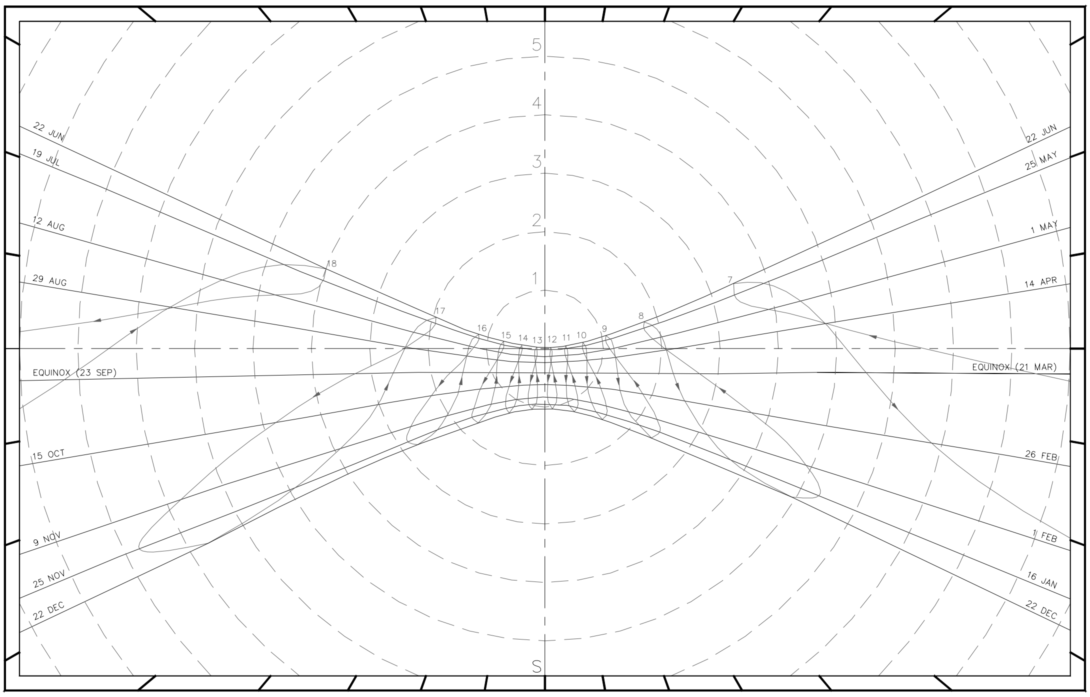


Figure 5.13 Sunpath Indicator for Hong Kong (22.3° N)

5.3.1.2 Sunlight availability indicator

The sunpath diagrams give the times of day and year for which sunlight is possibly available at a point. It does not give any quantity of the probable sunlight availability. Moreover, it does not take the local weather condition into consideration. Another graphical tool, called the Sunlight Availability Indicator, which was originally developed by Littlefair (BRE, 1991,1999a) assesses the sunlight availability received at a window quantitatively. It is adopted by the BRE (1991) for sunlighting assessment. It is used to find the summer and winter sunlight duration factors received by a point in a site layout. The Sunlight Availability Indicator was constructed for Hong Kong as shown in Figure 5.14. It uses the bright sunshine hour recorded by the Hong Kong Observatory as the base data. The measurement of bright sunshine hour is based on the apparent solar time. It represents the fraction of an hour that sunlight is received by an unobstructed horizontal plane. The data are recorded hourly with a Campbell Stokes recorder at King’s Park by the Hong Kong Observatory. A total of 31 years of data from 1970 to 2000 were used for the generation of the spots. In the original Sunlight Availability Indicator by the Building Research Establishment, there are totally 100 spots on the indicator and each of these represents 1% of the annual probable sunlight duration received by an unobstructed ground. However, due to the densely packed building environment in Hong Kong, 100 spots may not be sufficiently accurate. Therefore, the data were transformed into 200 spots (denoted by the symbol ‘•’) each representing 0.5% of the annual total probable sunlight duration. The method of generating the spots is described in the Appendix E1.

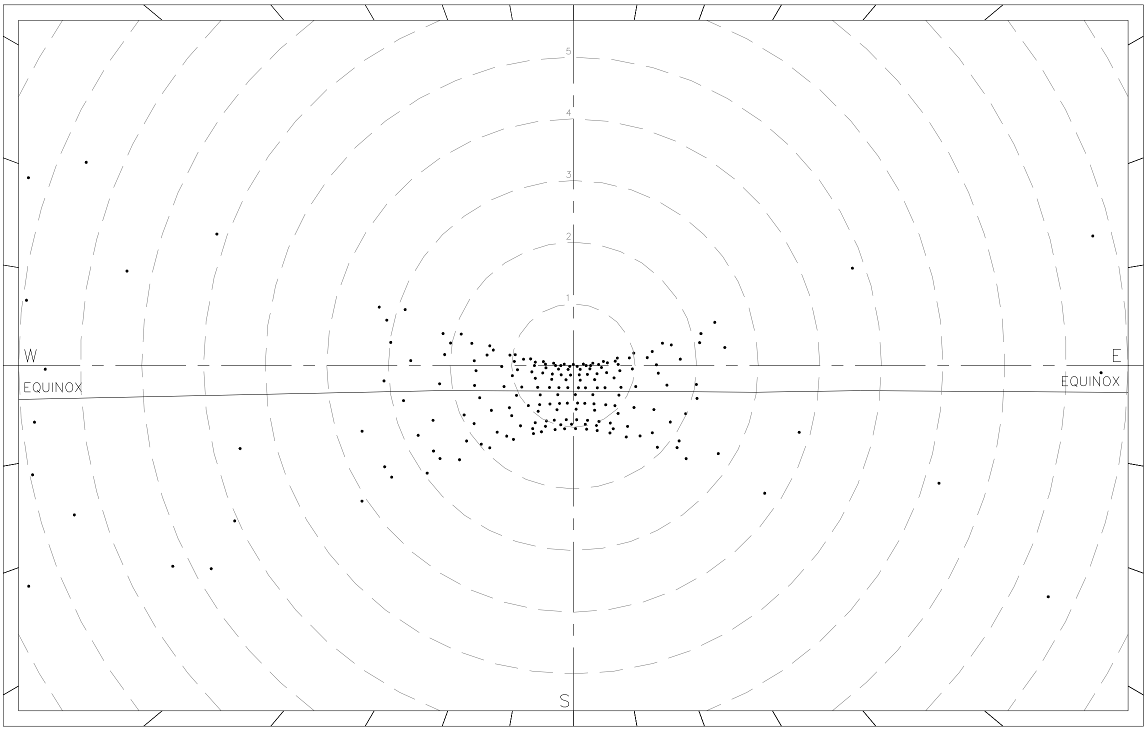


Figure 5.14 Sunlight Availability Indicator for Hong Kong (22.3° N)

Similar to the Sunlight Indicator, the Sunlight Availability Indicator can be overlaid onto a site layout plan of correct scale to analyze the access of sunlight to a point on the external surface of a building. The indicator is first overlaid onto the layout plan with the centre of the indicator over the reference point. The south point of the indicator should be parallel to the south of the site layout plan, regardless of which way the building faces. The effect of the external obstruction on the sunlight availability can be demonstrated by projecting the obstruction onto the indicator based on the site layout plan. Construction lines are drawn from the reference point to the edge of the obstruction and extended outwards. The area bounded by these lines will be obstructed from sunlight. The sunlight from behind of the wall will also be obstructed. To estimate the probable sunlight duration, the number of unobstructed spots is counted. As mentioned previously, the sunlight availability indicator has 200 spots on it, each spot represents 0.5% of the annual total probable sunlight duration received by an unobstructed ground. The annual sunlight duration factor at the reference point would be equal to 0.5% multiplied by the number of unobstructed spots. The annual probable sunlight duration is then estimated by multiplying this percentage to the annual total probable sunlight duration of an unobstructed horizontal plane. For Hong Kong the average annual probable sunlight duration received by an unobstructed ground over the 31 years (1970-2000) were calculated to be about 1,844 hrs. In the sunlight availability indicator, an equinox line is drawn. It differentiates between the periods of summer and winter. Then the number of unobstructed spots above the equinox line will calculate the summer sunlight duration factor and those below will calculate the winter sunlight duration factor.

In the Sunlight Availability Indicator, the probable sunlight from all part of the sky where the sun will pass is simplified into 200 spots. The number of unobstructed spots has to be counted manually to evaluate the sunlight duration factors received by a point. Using 200 spots to represent all the sunlight from the sky hemisphere may reduce the accuracy of the calculation method and counting the number of unobstructed spots may be laborious. Another problem with the Sunlight Availability Indicator is the implicit definition of unobstructed spot. There is no clear guideline for the case that a spot is partly obstructed in the BRE Report BR209 (1991) in which the sunlight availability indicator is originally developed. Besides, the external shading device of the window is not taken into account. In passive solar design, an overhang has an important role to block the summer direct sunlight while allowing the low-angle winter sunlight to penetrate. Nevertheless, in a dense urban environment, the building blocks are so densely packed that the probable sunlight duration are relatively difficult to be estimated using the Sunlight Availability Indicator which involves overlaying it on the site layout plan and counting the unobstructed spots. In order to study the effect of external shading device and obstruction, a new calculation method was developed for detailed calculations of probable sunlight duration and sunlight duration factor.

5.3.2 New calculation method for dense urban environment

The summer, winter and annual probable sunlight duration are useful parameters in the sunlighting performance evaluation. A new method was developed for the evaluation of the probable sunlight duration and sunlight duration factors. This method relies on the concept of dividing the sky hemisphere into small patches and the probable sunlight hour contribution from every sky patch is analyzed individually. Then the probable sunlight duration from different portion of sky can be illustrated numerically by a set of data or graphically by a diagram called the sky map of annual cumulative probable sunlight duration. This sky map illustrates the total amount of probable sunlight available from every portion of sky in a year. By studying the geometric relationship of the window with the external building environment (including the external shading devices), the values of summer and winter probable sunlight duration can be evaluated. It offers a clear approach of spacing the building blocks so that the valuable winter sunlight is not overshadowed by the external obstruction. A sky map of annual cumulative probable sunlight duration was constructed for Hong Kong as an example. In order to study the effect of external shading, a graphical tool for designing external shading was also developed to be used in conjunction with the sky map. Optimum external shading configurations for different orientations are also suggested with the aim of minimizing summer sunlight and at the same time maximizing the winter sunlight and diffuse skylight. In order to save the time of computation, a calculation spreadsheet was developed for calculation of summer, winter and annual sunlight duration factors.

5.3.2.1 Sky hemisphere division

The sky hemisphere division method had been explained in chapter 4. The sky hemisphere is first divided azimuthally into 36 subdivisions. After that each subdivision is divided altitudinally into 18 sky patches. In this way, the sky hemisphere is divided into 1,296 (18 × 72 = 1,296) sky patches. A sky patch is represented by its centre whose location is defined by the azimuth angle (ϕ) and altitude angle (γ). The angular width of the azimuthal subdivisions and the angular height of the altitudinal sky patches are both set to be equal to 5°. The angular width and height of all the sky patches are arranged to be equal so that the procedures of defining the external environment would be simpler and clearer.

5.3.2.2 Sky map of annual cumulative probable sunlight duration

Similar to the Sunlight Availability Indicator, the sky map of annual cumulative probable sunlight duration uses the bright sunshine hour data recorded by the Hong Kong Observatory as the base data. A total of 31 years of data from 1970 to 2000 was used for the sky map development. The bright sunshine hours of the same hour in a month were averaged over the 31 years. Then a set of average hourly bright sunshine duration for the whole year was obtained. As the sky hemisphere is divided into many sky patches, the contribution of probable sunlight duration from every sky patch is analyzed individually.

The average hourly bright sunshine data are allocated to the corresponding sky patches by studying the location of the sun. As bright sunshine hour is the fraction of an hour that sunlight is received, the sun which is responsible for this hour of bright sunshine may then belong to more than one sky patch. In order to allocate a correct proportion of bright sunshine duration to the sky patch, the fraction of bright sunshine duration in an hour is divided by 60. In other words, this assumes that the sky condition during the entire hour remains unchanged and every minute in the hour is allocated the simple arithmetic average of the fraction of bright sunshine duration in the hour. For the hour h on the day d, the average bright sunshine duration recorded for this hour is represented by $P_{d,h}$. If the sky condition at that hour is assumed to remain unchanged, the bright sunshine duration for each minute in the hour would be equal to $P_{d,h}$ divided by 60. For every minute in the hour, the sun's location, which is represented by the solar azimuth ($\phi_{d,h,m}$) and solar altitude ($\gamma_{d,h,m}$), can be found from the day (d), hour (h) and minute (m). Then the bright sunshine duration for every minute can be allocated to the corresponding sky patch at which the sun appears at that minute. A sky patch is represented by its centre whose location is defined by the azimuth angle (ϕ) and altitude angle (γ). Then the sky patch is bounded by the azimuth angles $(\phi + 2.5^\circ)$ and $(\phi - 2.5^\circ)$ and altitude angles $(\gamma + 2.5^\circ)$ and $(\gamma - 2.5^\circ)$. The fact whether the sun, which is responsible for the bright sunshine in a particular minute, appears in a patch is verified by the parameter $A_{d,h,m}$ given by:

$$A_{d,h,m} = \begin{cases} 1 & \text{if } (\phi - 2.5) < \phi_{d,h,m} < (\phi + 2.5) \text{and} (\gamma - 2.5) < \gamma_{d,h,m} < (\gamma + 2.5) \\ 0 & \text{otherwise} \end{cases} \tag{5.33}$$

The annual cumulative probable sunlight duration for each sky patch is then produced by adding up all the probable sunlight duration in each minute with the sun located in this sky patch in the whole year. For a sky patch bounded by azimuth angles $(\phi + 2.5^\circ)$ and $(\phi - 2.5^\circ)$, and altitude angles $(\gamma + 2.5^\circ)$ and $(\gamma - 2.5^\circ)$, the annual cumulative probable sunlight duration, $P_{\phi\gamma}$, is expressed in the following equation:

$$P_{\phi\gamma} = \sum_{d=1}^{365} \left[\sum_{h=1}^{24} \left[\left(\sum_{m=1}^{60} A_{d,h,m} \right) \times \frac{P_{d,h}}{60} \right] \right] \tag{5.34}$$

Using the above procedures, the sky map of annual cumulative probable sunlight duration for Hong Kong was developed as shown in Figure 5.15. The x-axis is the azimuth angle which is measured from the south. It is negative when sky patches are to the east of south, while it is positive when they are to the west of south. The sunpath of 23 September and 21 March is indicated on the sky map as the “23 SEP / 21 MAR” line. It differentiates the sky patches which are responsible for the summer sunlight and winter sunlight. The sky patches above and below the “23 SEP / 21 MAR” line are responsible for the summer sunlight and winter sunlight respectively. The sunpaths of some selective days are also shown on the sky map in Figure 5.15. Figure 5.16 illustrates the sky map in a polar graph. The numerical values of the summer, winter and annual cumulative probable sunlight duration for every sky patch are tabulated in Appendix E2.

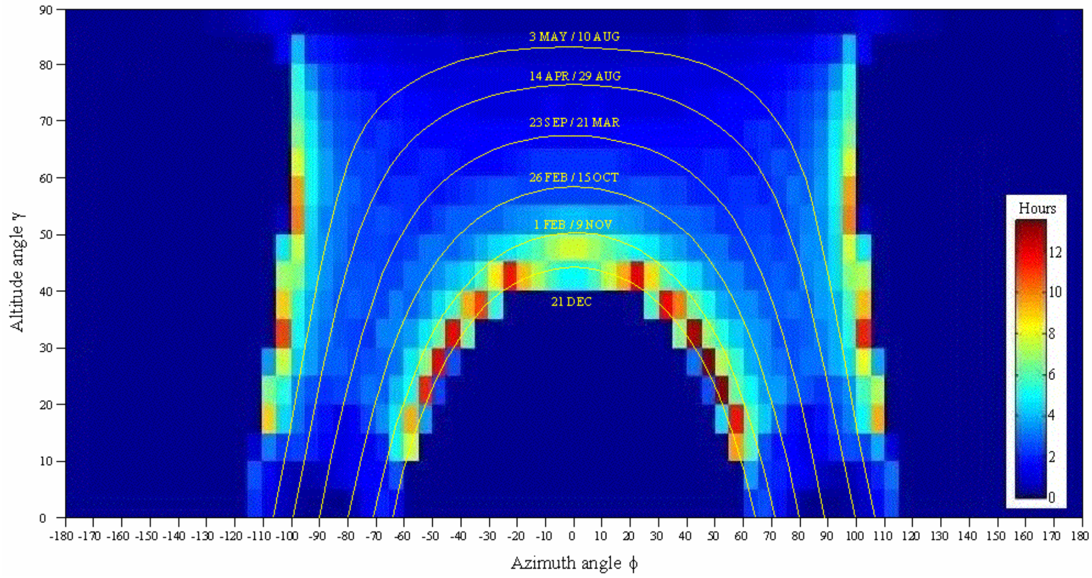


Figure 5.15 Sky map of annual cumulative probable sunlight duration for Hong Kong

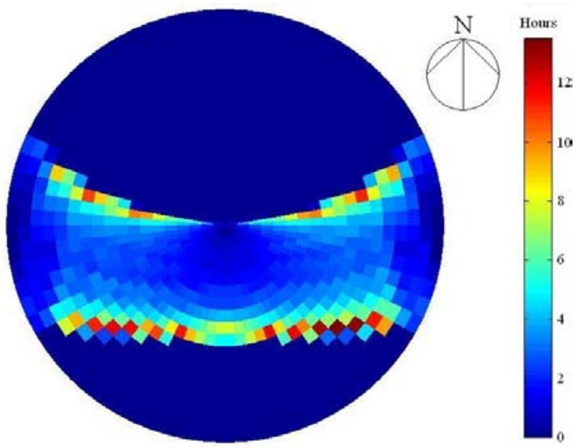


Figure 5.16 Polar graph of sky map of annual cumulative probable sunlight duration for Hong Kong

In the northern hemisphere, all winter sunlight comes in the southern direction (from $\phi = -90^\circ$ to $\phi = 90^\circ$). The sun altitude angle is relatively low compared to the summer sun. In Hong Kong, the highest solar altitude in winter is around 68°, while that in summer is 90°. With reference to the sky maps in Figure 5.15 and Figure 5.16, the annual cumulative probable sunlight duration are not uniform. It is observed that the winter probable sunlight duration is the highest in November and December, while that of summer probable sunlight duration peaks around June and July. It may be explained by the relative movement of the sun and the characteristics of the local weather conditions. The relative angular movement of the sun is constant at 15° per hour every day, while the daily sunpath "shifts" from south to north in the period starting 21 December to 22 June and from north to south in the rest of the days. The speed of this "shifting" motion is not constant throughout the year. The movement is the slowest around June and December, while it is the fastest around March and October. This "shifting" motion as reflected by the rate of change in solar altitude at the same solar time across the year is illustrated in Figure 5.17 for the case of Hong Kong. The increasing rate and decreasing rate are the slowest on 21 December and 22 June respectively. It results that more bins are allocated to the sky patches belonging to the sunpaths around those two days. Apart from the relative movement of the sun, the sky conditions around June, July, November and December are fine and clear in Hong Kong. Therefore, the hourly bright sunshine durations of these months are expected to be higher.

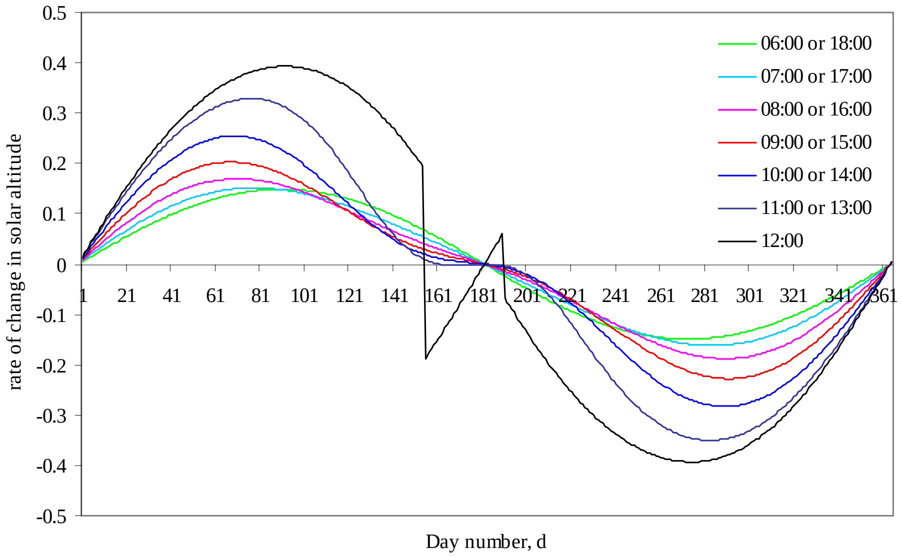


Figure 5.17 Rate of change in solar altitude for Hong Kong

5.3.2.3 Shadowing effect of obstruction

With the aid of the sky map of annual cumulative probable sunlight duration, the overshadowing effect due to external obstructions can be studied. In winter, sunlight comes from low angle and it is easily blocked by external obstructions. If a window is targeted to acquire a desirable amount of winter sunlight, buildings should be so spaced that the sky patches of high cumulative winter sunlight hours are not obstructed. In summer time, sunlight is less welcome as it brings along the undesirable heat to the interior. It may be beneficial in the thermal comfort and energy conservation point of view to prevent direct sunlight to enter the interior in the cooling seasons. With reference to the sky map of Hong Kong, it is noticed that the sky patches in two ranges of azimuth angle: -105° to -85° and +85° to +105° are responsible for a large amount of summer sunlight, which accounts for more than half (52%) of the total summer probable sunlight duration from the whole sky hemisphere. In order to reduce the summer sunlight exposure, the window can be so oriented to avoid facing these sky patches. During the site layout planning of a building development, the building blocks can also be so spaced that some of the blocks shadow the others from overheating by summer sunlight. The shadowing effect of obstruction can be studied by plotting the obstruction onto the sky map. Then the sky patches which are blocked by the external buildings can be identified.

In the external view division method for the calculations of average and vertical daylight factors, the semi-circle view of a window is divided azimuthally into 36 segments of 5° angular width. A set of obstruction angles ($\theta_L^{sky(\phi)}$) are used to define the external environment of a window. It can also be used to plot the external obstruction onto the sky map, but the azimuth angle ϕ should be measured from the south instead of the normal to the window. In this way, the same set of obstruction angles can be plotted onto the sky map to identify the portion of obstructed sky. An example is prepared for demonstration of the use of the sky map to study the shadowing effect of obstruction to a window in a dense urban environment. The same site layout as the calculation example of average and vertical daylight factors is used for demonstration. The shadowing effect by obstruction to point X in Figure 5.8 is going to be studied. The 36 obstruction angles $\theta_L^{sky(\phi)}$ were calculated previously and the results are shown in Table 5.1. Then the angles can be plotted onto the sky map and the area bounded under curve should be shadowed by surrounding buildings. In this way, the portions of visible and obstructed sky as seen from point X can be illustrated in the sky map presented in Figure 5.18. The shaded areas are the portion of sky blocked by the external obstructions. The sky behind the vertical wall, at which point X is located, is certainly invisible to the window and therefore it is shaded.

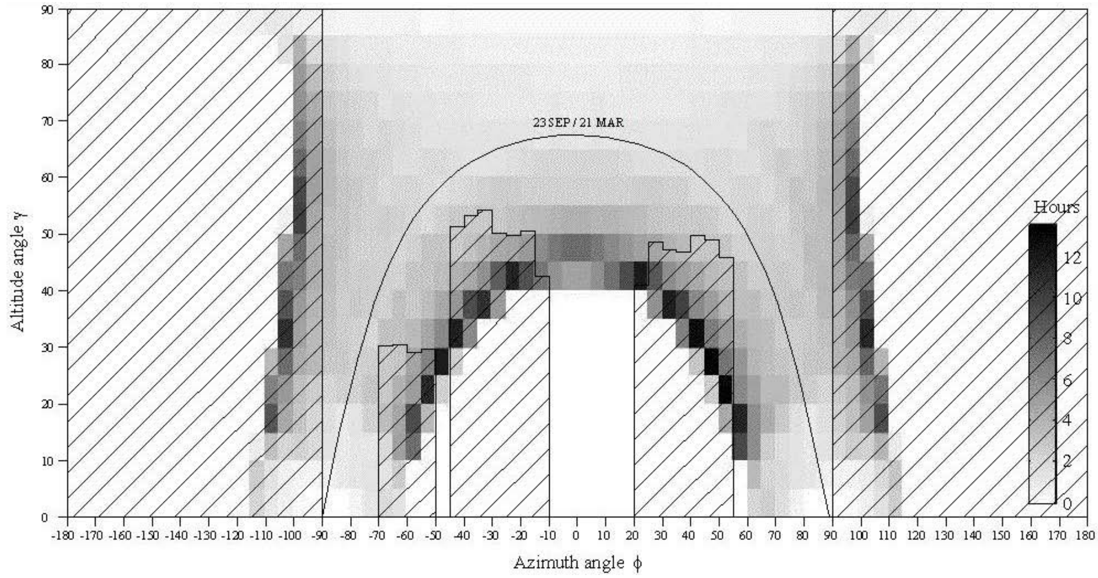


Figure 5.18 The external obstruction (shaded area) being plotted onto the sky map

By plotting the 36 obstruction angles on the sky map of annual cumulative probable sunlight duration, the sunlighting performance at point X can be analyzed. With reference to the sky map, although some sky patches which are responsible for winter sunlight are shadowed by the external buildings, there should still be a considerable amount of winter sunlight reaching point X. If no external shading is installed for the window, summer sunlight penetration should be so severe that all of the summer sunlight from the southern sky hemisphere can reach point X.

5.3.2.4 External shading analysis

The shadowing effect by other building blocks can shade the window from the intense summer sun. Another method of preventing the space from overheating by summer sunlight is to design a shading device to obstruct the summer sunlight. Then the solar cooling load due to the summer sunlight can be reduced. In the above example, if the window at point X is installed with an overhang or sidefin, the summer sunlight penetration should be different from that without external shading.

The external shading can be projected onto the sky map to illustrate the portion of sky obstructed by it. The projection of the shading depends on its geometrical relationship with the reference point. Overhangs and sidefins are characterized by the parameters shown in the following diagram.

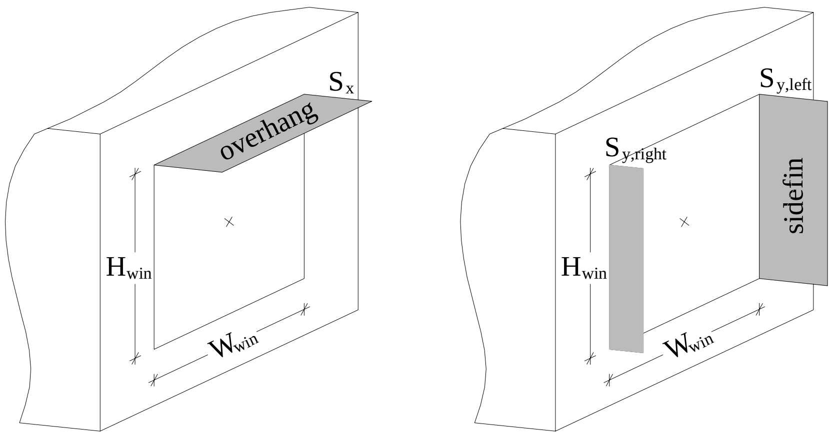


Figure 5.19 Parameters characterizing overhangs and sidefins

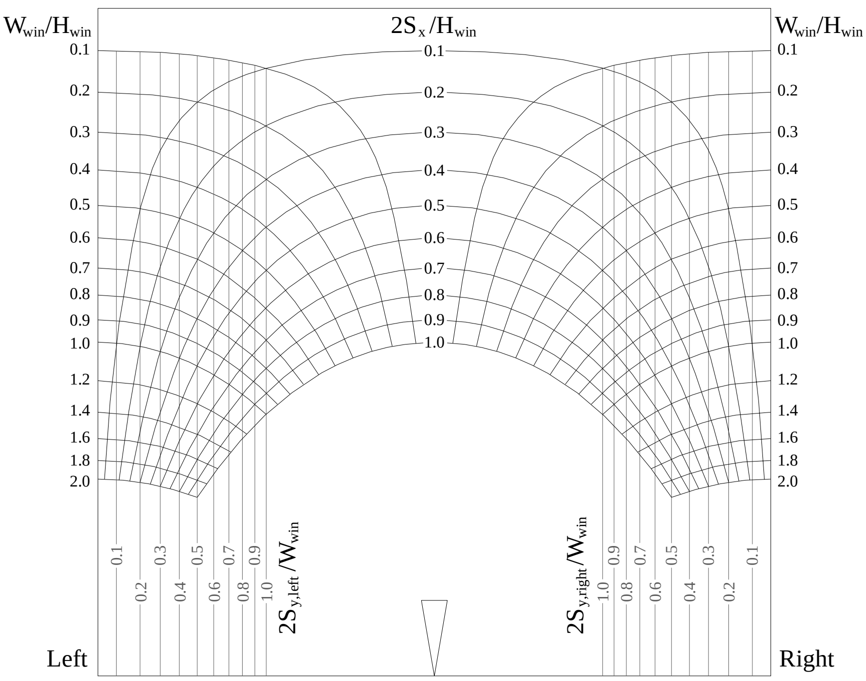


Figure 5.20 External shading design tool

The centre point of the window is chosen to be the reference point. The overhang is assumed to be full-width, i.e. its width is equal to that of the window, while the sidefin is assumed to be full-height, i.e. its height is equal to that of the window. In this way, the configurations of the overhang and sidefins are defined by their depths (S_x, $S_{y,left}$ and $S_{y,right}$), window width (W_{win}) and window height (H_{win}). To project the overhang onto the sky map, it means that the three edges of the overhang have to be projected on the sky map. The edge in front of the window is a horizontal line parallel to the window. It can be defined by the ratio of $\frac{2S_x}{H_{win}}$. The relationship between the azimuth and altitude angles of this horizontal line projection is expressed by the following curve:

$$\frac{2S_x}{H_{win}} \tan\gamma = \cos\phi \tag{5.35}$$

Then the portion of sky above this curve on the sky map should be obstructed by the overhang. As for the two edges on the two sides of the overhang, they are horizontal lines perpendicular to the window. They can be characterized by the ratio of $\frac{W_{win}}{H_{win}}$. The relationship between the azimuth and altitude angles of the projection of these two horizontal lines on the sky map is expressed by this equation:

$$\frac{W_{win}}{H_{win}} \tan\gamma = \sin\phi \tag{5.36}$$

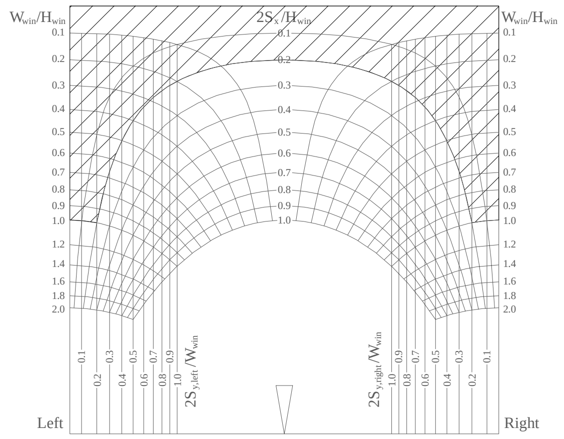
Similarly, the portion of sky above this curve will also be blocked by the overhang. The matching points of these two curves should indicate the two external corners of the overhang. As a result, the portion of sky bounded by these lines will become the projection of the overhang. As for the sidefin, its projection is defined by its upper edge and its vertical edge. The upper edge is represented by the same horizontal line perpendicular to the window as the overhang. The projection of the vertical edge of the sidefin can be found by a simple equation. The projection of the horizontal and vertical lines can be found by the following two equations respectively:

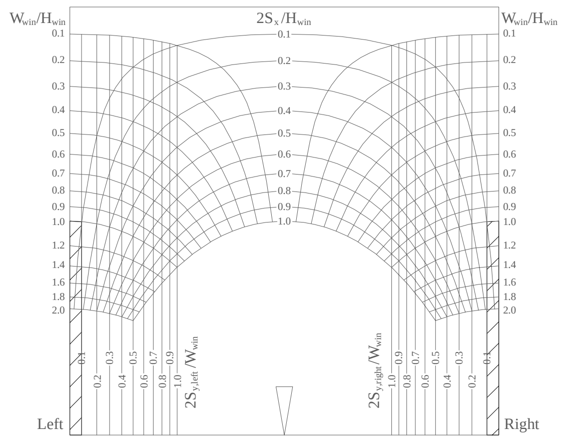
$$\frac{W_{win}}{H_{win}} \tan\gamma = \sin\phi \tag{5.37}$$

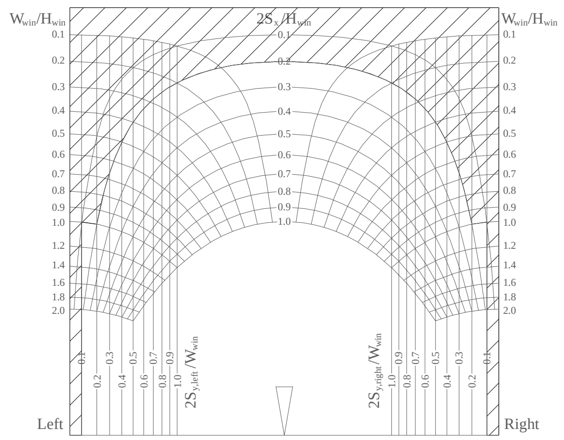
$$\phi = \tan^{-1}\frac{W_{win}}{2S_{y,left}} \text{ and } \phi = \tan^{-1}\frac{W_{win}}{2S_{y,right}} \tag{5.38}$$

The portion of sky below the first curve and away from the second line will be obstructed by this sidefin. The projections of the horizontal and vertical edges of the overhang and sidefin with various $\frac{2S_x}{H_{win}}$, $\frac{W_{win}}{H_{win}}$, $\frac{2S_{y,left}}{W_{win}}$ and $\frac{2S_{y,right}}{W_{win}}$ ratios can be plotted onto a graph. Then the projections can be overlaid onto the sky map of annual cumulative probable sunlight duration for external shading analysis. In this way, an external shading design tool is developed as shown in Figure 5.20. This design tool can be overlaid onto the sky map to study the effect of the external shading to the probable sunlight duration received by a window. The arrow at the bottom centre of the external shading design tool should point to the value of the wall azimuth angle of the window in the sky map. If the window faces south, the arrow should point to 0°. If the window faces west, the arrow should then point to 90°. The projection of the overhang and sidefin can be found out by the procedures described in Table 5.2.

Table 5.2 Procedures for finding the projections of overhang and sidefins

<table>
<tr>
<td>1.</td>
<td>Let's say the window width is 2m (i.e. W_{win} = 2m) and window height is 2m (i.e. H_{win} = 2m). The depth of the overhang is 0.2m. Then the $\frac{2S_x}{H_{win}}$ and $\frac{W_{win}}{H_{win}}$ ratios are calculated to be:
$\frac{2S_x}{H_{win}} = \frac{2 \times 0.2}{2} = 0.2$
$\frac{W_{win}}{H_{win}} = \frac{2}{2} = 1$</td>
<td>

The curves representing the edges of the overhang are identified. Then the portion of sky obstructed by the overhang is found. (The obstructed sky is shaded.)</td>
</tr>
<tr>
<td>2.</td>
<td>The $\frac{W_{win}}{H_{win}}$, $\frac{2S_{y,left}}{W_{win}}$ and $\frac{2S_{y,right}}{W_{win}}$ ratios are then found for the sidefins. Let's say the depth of the sidefins on left and right are both 0.1m. Then the ratios are calculated to be:
$\frac{W_{win}}{H_{win}} = \frac{2}{2} = 1$
$\frac{2S_{y,left}}{W_{win}} = \frac{2 \times 0.1}{2} = 0.1$
$\frac{2S_{y,right}}{W_{win}} = \frac{2 \times 0.1}{2} = 0.1$</td>
<td>

The curves and lines representing the edges of the sidefin are identified. The portion of sky obstructed by the sidefin is found. (The obstructed sky is shaded.)</td>
</tr>
<tr>
<td>3.</td>
<td>Finally, the overall portion of sky obstructed by the overhang and sidefin is identified.</td>
<td>
</td>
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</table>

If the window at point X in the example demonstrating the shadowing effect of obstruction is installed with external shadings which have the same configurations as in Table 5.2, the effect of the overhang and sidefin on the probable sunlight duration received at point X can be assessed using the external shading projection produced in Step 3 in Table 5.2. It can be overlaid onto the sky map of annual cumulative probable sunlight duration developed for point X. It is illustrated in Figure 5.21. The blank area shows the portion of visible sky as seen from point X. It is noticed that the external shading blocks a large amount of summer probable sunlight. The problem due to overheating by direct summer sunlight should not be serious. The sunlighting performance is therefore expected to be quite satisfactory in summer.

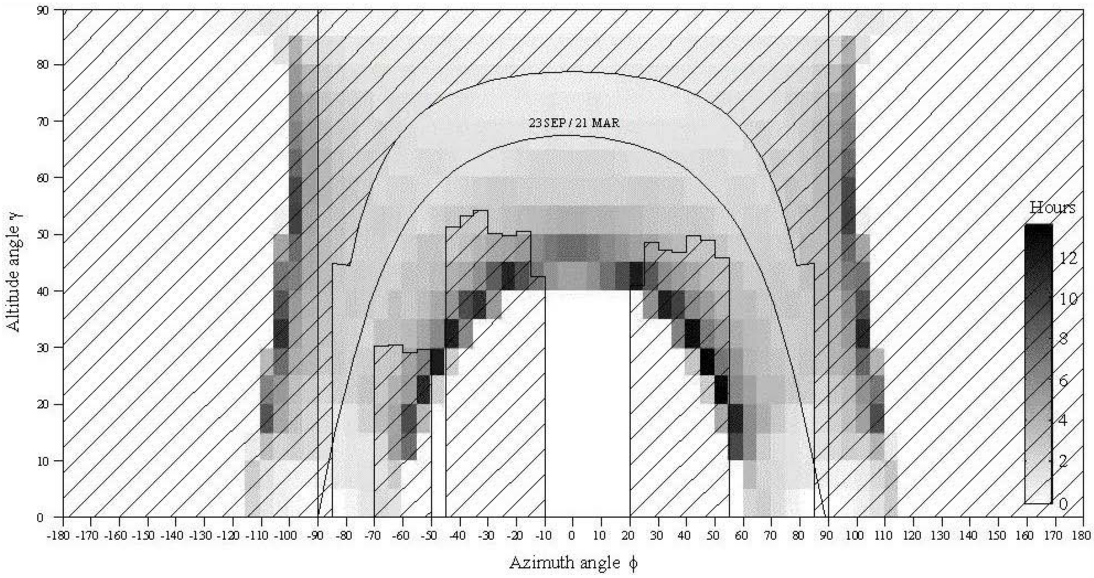


Figure 5.21 The external obstruction and shadings (shaded area) being plotted onto the sky map

Recent researches on the external shading design make use of computer graphics and simulation programs to generate the optimum setting of fixed external shading. The simulation programs include the SHADESIGN (Francisco, 1996) and SHADING MASK (Kensek et al., 1996). Both of the programs output the optimum geometric configurations of the external shading based on the possible occurrences of the sun. However, the local weather conditions are not taken into account in both methods. Besides, the relations between the shading design alternatives with the effectiveness of blocking the summer sunlight can not be easily understood by the users. With the aid of the sky map of annual cumulative probable sunlight duration together with the external shading design tool, the effectiveness of the external shadings in terms of their capability to shade the probable summer sunlight can be easily compared. The performance of external shading for different window orientations can also be compared. Figure 5.22 to Figure 5.25 show the sky maps for windows facing south, north, east and west with the external shading design tools overlaid on them. It is noticed that the orientation of a window is critical to the sunlighting performance. A south-facing window can easily block the summer sunlight with an overhang and acquire a large amount of winter sunlight. However, it will be much more difficult for windows facing other orientations, especially east and west, to shade the summer sunlight. No matter how good an external shading design program we have, we cannot simply rely on the program to design an external shading device to block the summer sunlight. Besides, one should note that a shading device will reduce the winter sunlight and diffuse skylight availability at the same time. In the context of Hong Kong, it is suggested that the windows should avoid facing the directions: -105° to -85° and 85° to 105° if the summer sunlight is going to be minimized.

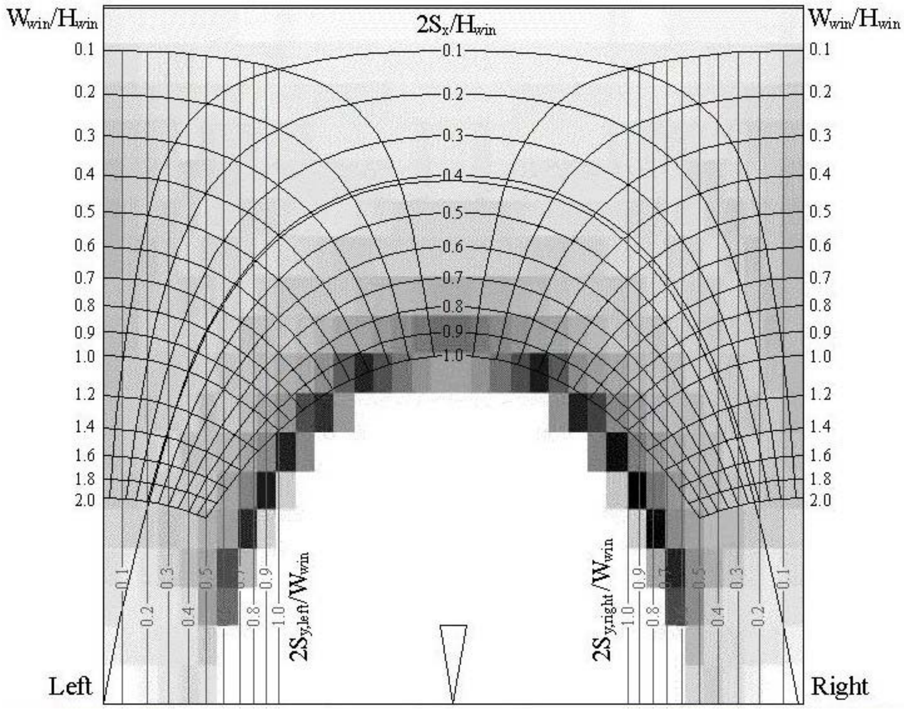


Figure 5.22 Sky map of annual cumulative probable sunlight duration for south facade

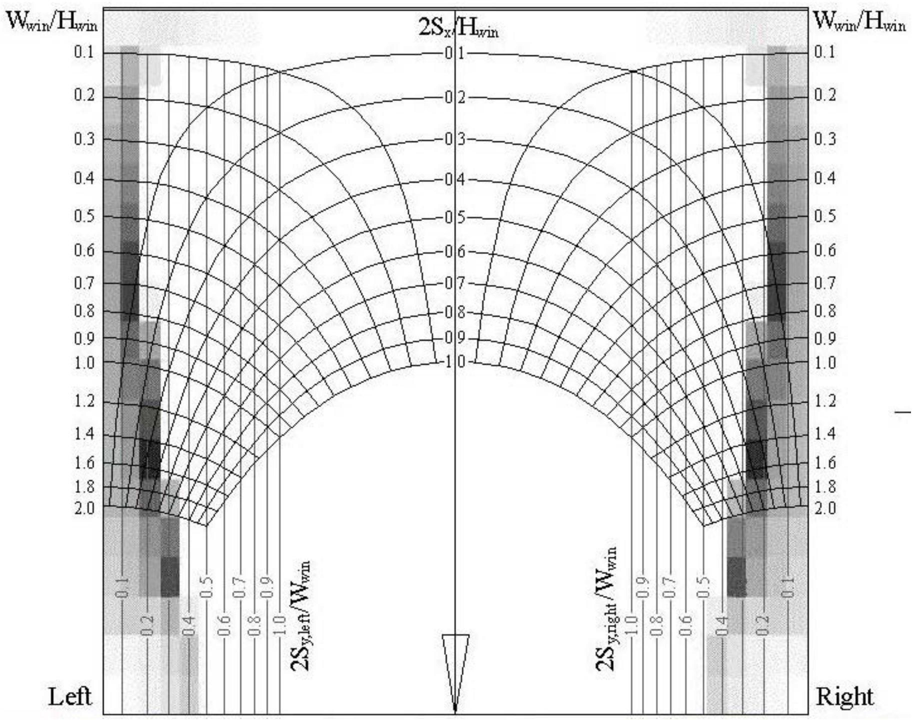


Figure 5.23 Sky map of annual cumulative probable sunlight duration for north facade

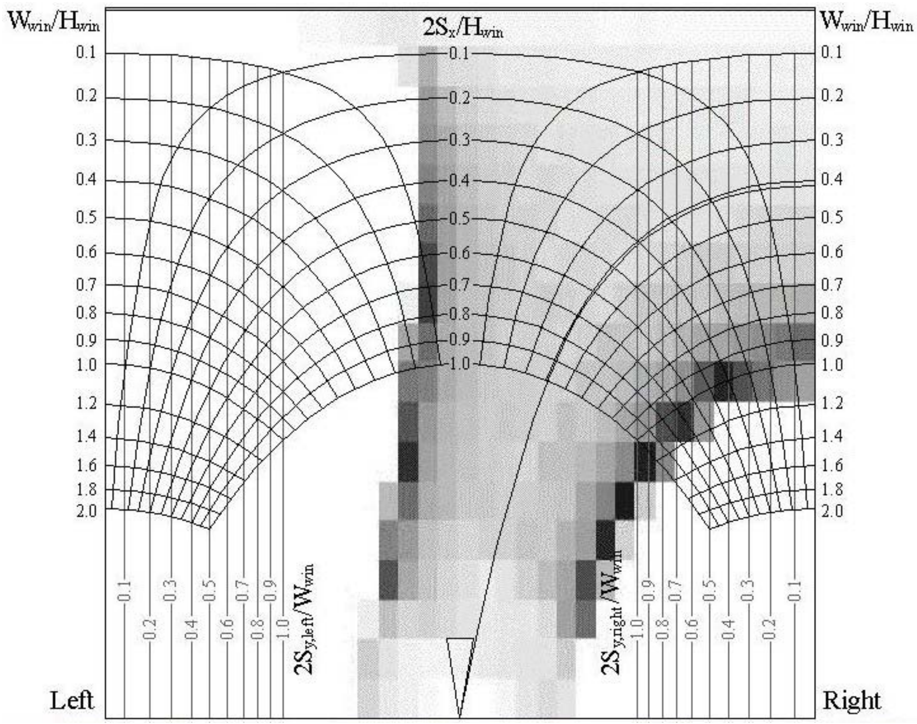


Figure 5.24 Sky map of annual cumulative probable sunlight duration for east facade

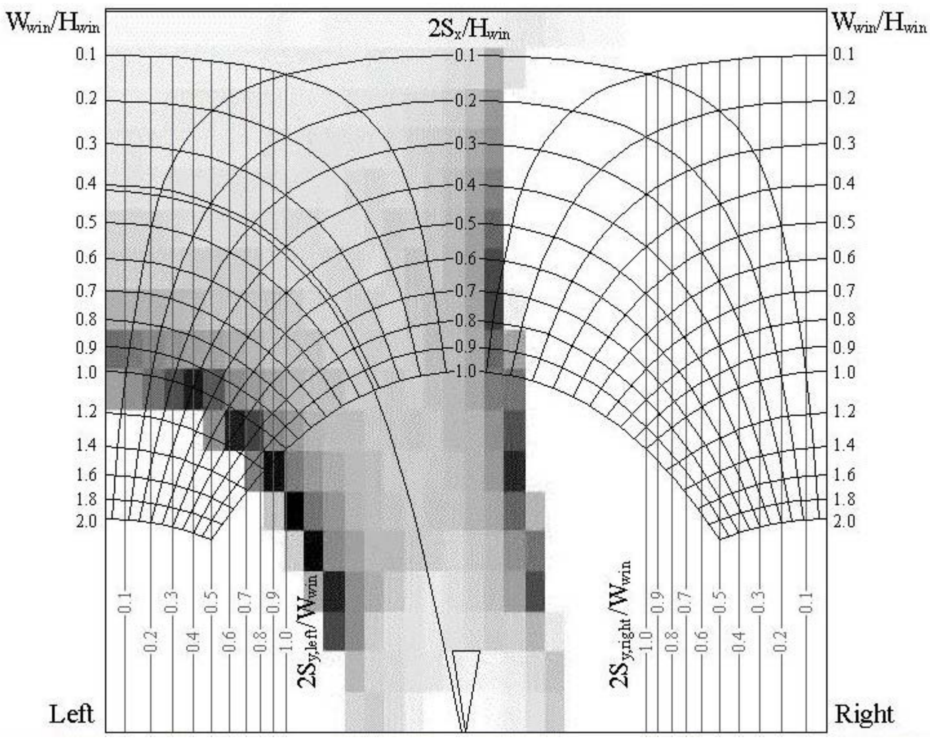


Figure 5.25 Sky map of annual cumulative probable sunlight duration for west facade

5.3.2.5 Calculation spreadsheet

As mentioned previously, the sky map of annual cumulative probable sunlight duration was developed from a set of probable sunlight duration data of all sky patches in the whole sky hemisphere. The data can be input to a calculation spreadsheet for fast evaluation of the probable sunlight duration received by a window. Then the summer, winter and annual probable sunlight duration received by a window can be evaluated with the input of the window azimuth angle, 36 obstruction angles ($\theta_L^{sky(\phi)}$) defining the lower limits of the visible sky and the dimensions of the external shadings. The calculation spreadsheet introduced previously for the calculations of average daylight factors and vertical daylight factor was revised to compute the probable sunlight duration also. It was based on the average bright sunshine conditions in Hong Kong. The calculation procedures of probable sunlight duration in the calculation spreadsheet are presented in Appendix E3. The user interface page of the spreadsheet is shown in Figure 5.26. The parameters of the window at point X are input to the calculation spreadsheet for demonstration and the outputs are shown in the user interface page. By using this calculation spreadsheet, the summer, winter and annual sunlight duration factors can be calculated instantly. Then the sunlighting performance of different windows can be compared and analyzed in detail.

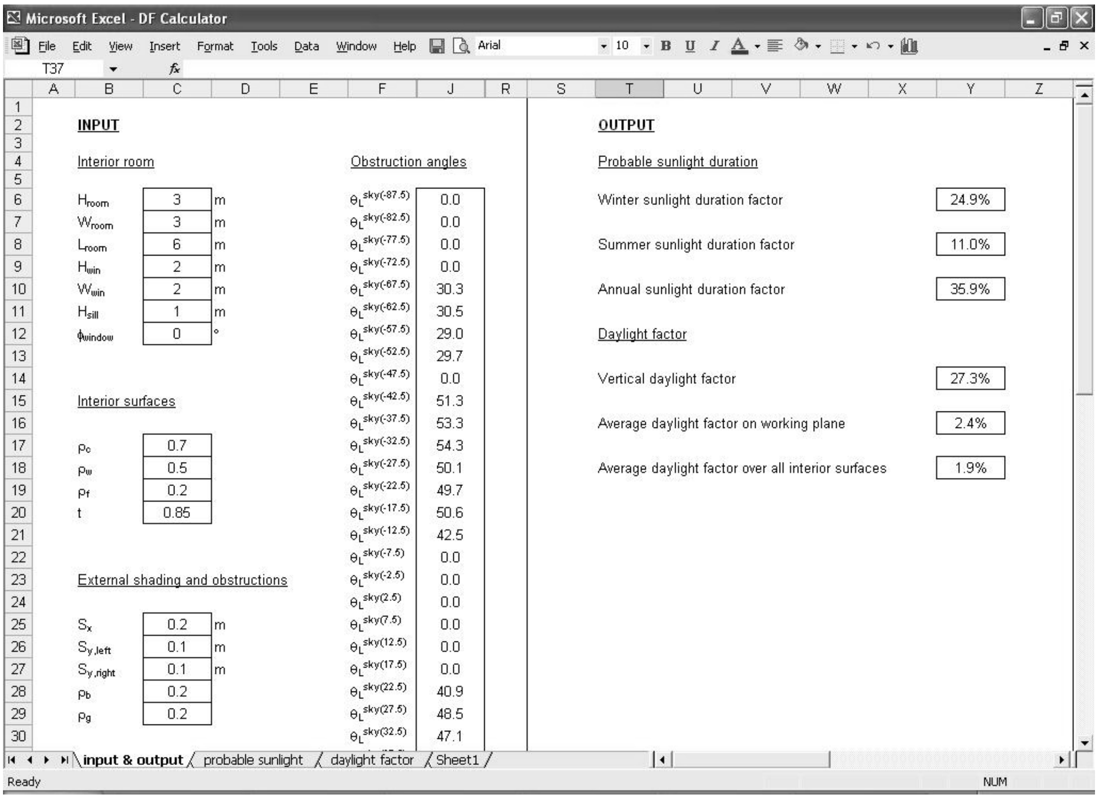


Figure 5.26 User interface of the calculation spreadsheet for the calculations of average daylight factors, vertical daylight factor and sunlight duration factors

Case studies were conducted to show the effect of external obstruction to the sunlighting performance of a window. Values of sunlight duration factors were computed by the calculation spreadsheet. Figure 5.27 shows three building layouts and their respective sky maps. The buildings are of equal height. The spacing between the building blocks is shown by a semi-circle whose radius is equal to the height of the buildings. The window under concern is located in the room which is represented by a small rectangle in the building on the right. The windows are all facing south-west with window azimuth equal to 40°. In the first layout, the window's view at azimuth angle from 50° to 80° is obstructed. The summer and winter sunlight duration factors are calculated to be 28.2% and 29.8% respectively. As seen from the sky map, the external obstruction blocks a certain amount of winter sunlight and the window is exposed to a large amount of summer sunlight. In order to increase the winter sunlight exposure, the external buildings should be located away from the sky patches with high value of winter sunlight. Therefore, in the second layout, the obstructing building is relocated such that its projection on the sky map is moved to the azimuth angle of 80° to 110°. Then the winter sunlight duration factor is increased by 9.2% to 39.0% while the summer sunlight duration factor is reduced by 9.7% to 18.5%. The summer sunlight may also be blocked by self-shadowing as shown in the third layout. In this way, the summer sunlight duration factor is further decreased to 14.7%.

For an unobstructed window in Hong Kong, the summer sunlight duration factors received by windows facing south, east, west and north are calculated to be 26.0%, 25.8%, 26.6% and 26.4% respectively, while the winter sunlight duration factors are calculated to be 47.6%, 22.7%, 25.0% and 0.0% respectively. As the summer sunlight usually comes from a high angle. It has a high probability to reach the window even in the high-rise building environment. In order to reduce the summer sunlight exposure, external shading device is suggested to be installed. In the following section, optimal external shading configurations for various window orientations will be studied.

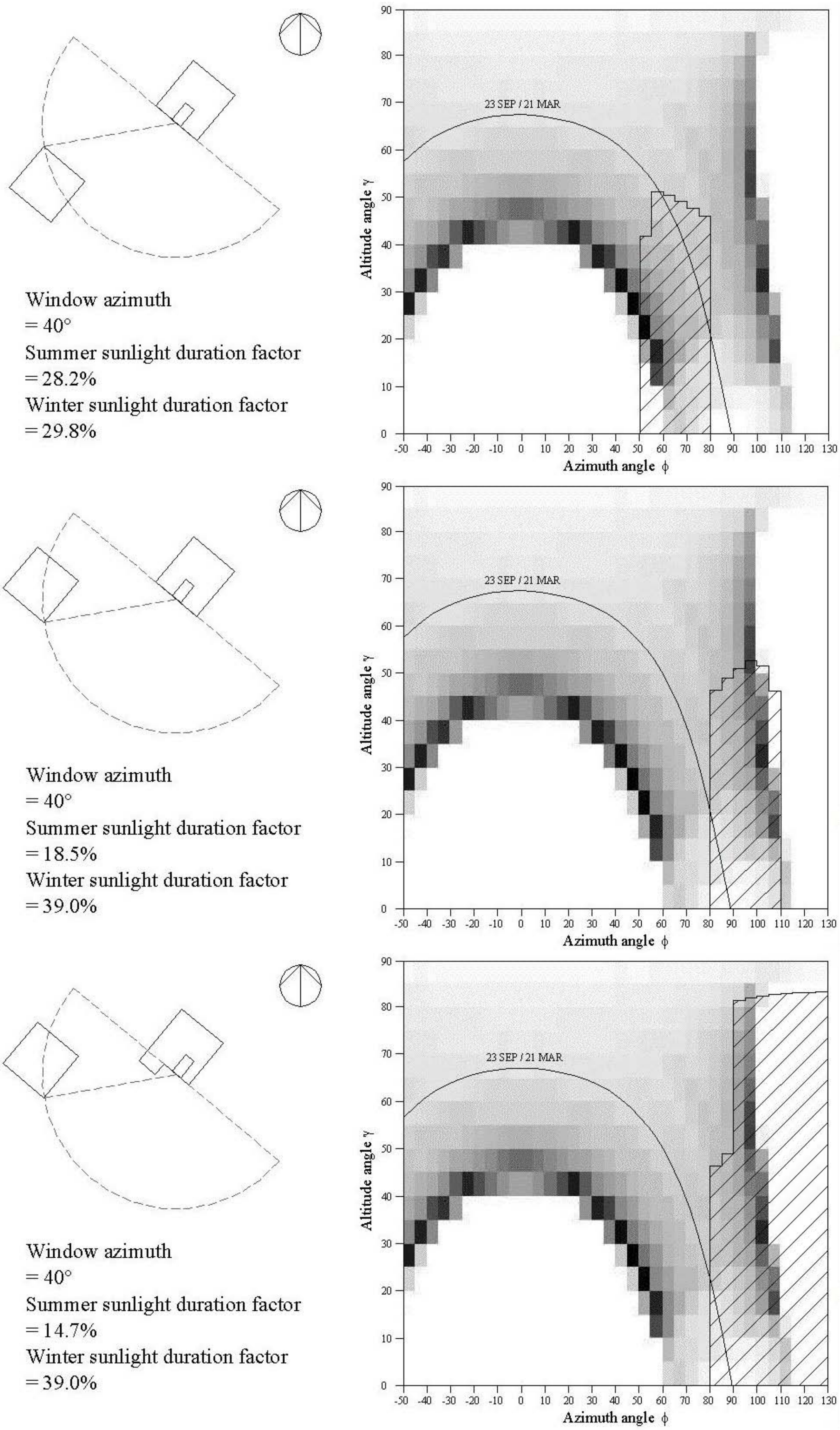


Figure 5.27 Site layouts and their respective annual cumulative sky map

5.3.2.6 Optimal external shading configurations

In passive solar design, summer sunlight should be minimized down below a certain level in order not to overheat the space. The summer sunlight exposure should be minimized, while the winter sunlight exposure should be maximized. It is mentioned earlier that the sunlight duration factors (summer or winter) received at a window depend very much on its orientation. Figure 5.28 shows the summer sunlight duration factor received by a window of various orientations and depths of overhang. For windows facing south and north, the window azimuths are equal to 0° and 180°/ -180° respectively. For windows facing east and west, the window azimuths are equal to -90° and 90° respectively. The bold curve represents the summer sunlight duration factor variation for a window without any external shading device. The other curves represent the variations for windows installed with overhangs of various $\frac{2S_x}{H_{win}}$ ratios. It is noticed that overhangs can effectively reduce the summer sunlight duration factor, especially for the windows facing south (window azimuth = 0°). Figure 5.29 shows the winter sunlight duration factor received by a window of various orientations and depths of overhang. In this figure, it is observed that overhangs have less effect on the winter sunlight duration factor. On the other hand, the winter sunlight exposure is very dependent on the window orientations. The sunlight duration factors received by windows of various orientations and other external shading configurations are presented in Appendix E4.

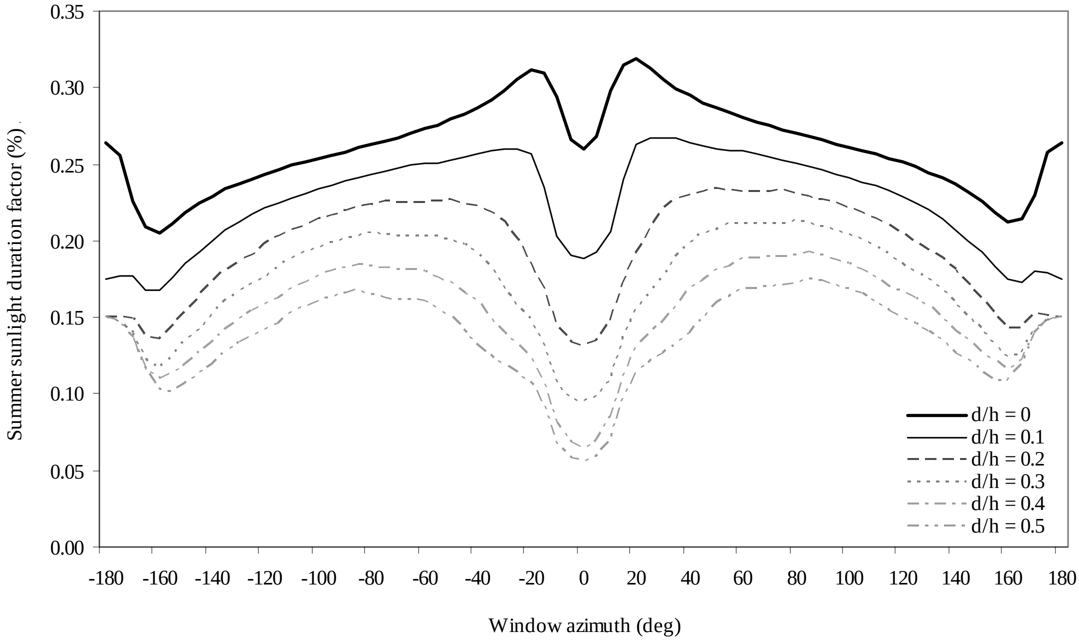


Figure 5.28 Summer sunlight duration factor received by windows of various orientations and depths of overhang

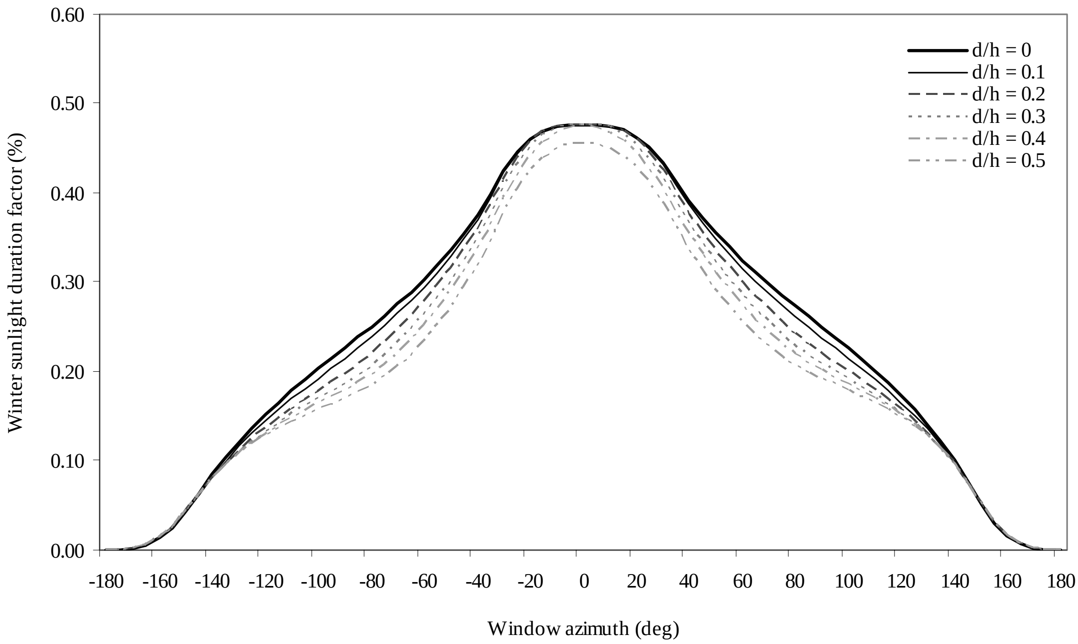


Figure 5.29 Winter sunlight duration factor received by windows of various orientations and depths of overhang

In order to minimize the summer sunlight exposure and maximize the winter sunlight availability, the external shadings should block the summer sunlight down to an acceptable level and at the same time they should also provide as much access as possible for the winter sunlight. Using the calculation spreadsheet introduced earlier, optimum configurations of external shading can be evaluated to block the summer sunlight down to a certain level while maximizing the winter sunlight exposure for different window orientations. In this analysis, the types of fixed external shading device included overhang, sidefin and a combination of both. The overhang was set to be of equal width with the window, while the sidefin was of equal height with the window. The window width and height were assumed to be equal, so that the $\frac{W_{win}}{H_{win}}$ ratio was equal to 1. Different depths of overhang were tested with different depths of left sidefin as well as different depths of right sidefin. The ratios $\frac{2S_x}{H_{win}}$, $\frac{2S_{y,left}}{W_{win}}$ and $\frac{2S_{y,right}}{W_{win}}$ were tested with values of 0.1, 0.2, 0.3, 0.4 and 0.5. All combinations of configuration settings were tested for every orientation in a 5° azimuth angle interval. The window was assumed to be free from any obstruction. The optimum external shading setting was selected for a direction if it is able to reduce the summer sunlight duration factor below a certain predetermined value and provides maximum access of winter sunlight among the other settings. For some orientations like north, no winter sunlight could be received. Then, optimum setting was selected based on the highest vertical daylight factor value in order to maximize the diffuse skylight exposure. The predetermined limits of summer sunlight duration factor were chosen to be 25%, 20%, 15%, 10% and 5%. It enables a wide range of limits for sunlighting performance design. The results of the optimum external shading configurations for various orientations are shown in Table 5.3.

Table 5.3 Optimum external shading configurations for various orientations

Window azimuth	Upper limit of summer sunlight duration factor					Window azimuth	Upper limit of summer sunlight duration factor				
	25%	20%	15%	10%	5%		25%	20%	15%	10%	5%
-180	0/1/1	1/0/0	1/1/1	1/3/2	1/4/3	0	1/0/0	1/0/0	2/0/0	3/0/0	4/1/1
-175	0/1/0	0/3/0	1/2/0	2/3/0	1/4/4	5	1/0/0	1/0/0	2/0/0	3/0/0	4/0/2
-170	0/0/0	0/1/0	1/1/0	3/2/0	2/1/5	10	1/0/0	1/0/1	2/0/0	3/0/1	4/0/3
-165	0/0/0	0/1/0	1/2/0	4/2/0	4/1/5	15	1/0/0	1/0/2	2/0/1	2/0/5	4/0/4
-160	0/0/0	1/0/0	2/0/0	5/1/0	n/a	20	0/0/4	1/0/4	2/0/2	3/0/3	4/0/5
-155	0/0/0	1/0/0	2/0/0	5/0/2	n/a	25	0/0/4	1/0/5	2/0/4	3/0/5	5/0/5
-150	0/0/0	1/0/0	3/0/0	5/0/4	n/a	30	0/0/5	2/0/4	3/0/4	4/0/5	n/a
-145	0/0/0	1/0/0	3/0/0	n/a	n/a	35	1/0/4	2/0/5	3/0/5	5/0/5	n/a
-140	0/0/0	1/0/0	4/0/0	n/a	n/a	40	1/0/5	3/0/0	4/0/5	n/a	n/a
-135	0/0/0	2/0/0	4/0/0	n/a	n/a	45	2/0/0	4/0/0	5/0/0	n/a	n/a
-130	0/0/0	2/0/0	4/0/0	n/a	n/a	50	2/0/0	4/0/0	n/a	n/a	n/a
-125	0/0/0	2/0/0	5/0/0	n/a	n/a	55	2/0/0	4/0/0	n/a	n/a	n/a
-120	0/0/0	2/0/0	5/0/0	n/a	n/a	60	2/0/0	4/0/0	n/a	n/a	n/a
-115	0/0/0	3/0/0	5/0/0	n/a	n/a	65	2/0/0	4/0/0	n/a	n/a	n/a
-110	0/0/0	3/0/0	n/a	n/a	n/a	70	2/0/0	4/0/0	n/a	n/a	n/a
-105	1/0/0	3/0/0	n/a	n/a	n/a	75	2/0/0	4/0/0	n/a	n/a	n/a
-100	1/0/0	3/0/0	n/a	n/a	n/a	80	2/0/0	4/0/0	n/a	n/a	n/a
-95	1/0/0	3/0/0	n/a	n/a	n/a	85	1/0/0	4/0/0	n/a	n/a	n/a
-90	1/0/0	4/0/0	n/a	n/a	n/a	90	1/0/0	4/0/0	n/a	n/a	n/a
-85	1/0/0	4/0/0	n/a	n/a	n/a	95	1/0/0	4/0/0	n/a	n/a	n/a
-80	1/0/0	4/0/0	n/a	n/a	n/a	100	1/0/0	4/0/0	n/a	n/a	n/a
-75	1/0/0	4/0/0	n/a	n/a	n/a	105	1/0/0	4/0/0	n/a	n/a	n/a
-70	1/0/0	4/0/0	n/a	n/a	n/a	110	1/0/0	3/0/0	n/a	n/a	n/a
-65	1/0/0	4/0/0	n/a	n/a	n/a	115	1/0/0	3/0/0	n/a	n/a	n/a
-60	2/0/0	4/0/0	n/a	n/a	n/a	120	1/0/0	3/0/0	n/a	n/a	n/a
-55	2/0/0	4/0/0	n/a	n/a	n/a	125	0/0/0	2/0/0	5/0/0	n/a	n/a
-50	2/0/0	3/0/0	n/a	n/a	n/a	130	0/0/0	2/0/0	5/0/0	n/a	n/a
-45	2/0/0	3/0/0	5/0/0	n/a	n/a	135	0/0/0	2/0/0	5/0/0	n/a	n/a
-40	1/5/0	3/0/0	4/5/0	n/a	n/a	140	0/0/0	2/0/0	4/0/0	n/a	n/a
-35	0/5/0	2/5/0	3/5/0	5/5/0	n/a	145	0/0/0	2/0/0	3/0/0	n/a	n/a
-30	0/5/0	1/5/0	3/4/0	4/4/0	n/a	150	0/0/0	1/0/0	3/0/0	5/5/0	n/a
-25	0/4/0	1/4/0	2/4/0	3/4/0	5/5/0	155	0/0/0	1/0/0	3/0/0	5/3/0	n/a
-20	0/4/0	1/3/0	2/2/0	3/3/0	4/5/0	160	0/0/0	1/0/0	2/0/0	5/2/1	n/a
-15	1/0/0	1/2/0	2/1/0	2/5/0	4/4/0	165	0/0/0	0/0/2	2/0/0	4/1/2	4/5/2
-10	1/0/0	1/1/0	2/0/0	3/1/0	4/3/0	170	0/0/0	0/0/2	1/0/2	3/0/3	2/5/1
-5	1/0/0	1/0/0	2/0/0	3/0/0	4/2/0	175	0/0/1	0/0/4	1/0/2	2/0/3	1/4/4

With reference to Table 5.3, the results of the optimum external shading configurations for various orientations are shown in a text of three numbers. The first number stands for the $\frac{2S_x}{H_{win}}$ ratio of the overhang while the second and third numbers stand for the $\frac{2S_{y,left}}{W_{win}}$ and $\frac{2S_{y,right}}{W_{win}}$ ratios of the sidefins on the left and right respectively. The number “1” represents a ratio of 0.1, “2” represents a ratio of 0.2 and so on. If the optimal configuration is in form of an overhang, the second and the third numbers would be equal to zero. If the optimal configuration is only a right sidefin, then the first and second numbers will be zero. A combination of overhang and sidefin is expressed by at least two numbers. It is observed from the table that overhang is favorable to most of the orientations. Left sidefin is an advantage to windows facing SSE, while right sidefin is favorable to windows facing SSW. For the requirement of summer sunlight duration factor to be lower than 15%, only the windows, whose azimuth angles are in the ranges between -180° and -115°, -45° and 45° as well as 125° and 180°, can achieve this goal. For the other directions, no combination of overhang and sidefins is able to block the summer sunlight below this value. Then the external shading configurations for these directions are expressed by “n/a”.

5.4 Conclusion

In this chapter, the calculation methods of average daylight factors ($\overline{DF}_{wp}$ and $\overline{DF}_{all}$), vertical daylight factors and probable sunlight duration in the context of dense urban environment are introduced. The calculation methods of average and vertical daylight factors depend on the concept that the external view of the window is divided into 36 segments so that the exterior obstruction can be defined by 36 pairs of obstruction angles. As for the computation of probable sunlight duration received at a window, a sky map of annual cumulative probable sunlight duration was constructed by dividing the whole sky hemisphere into 1,296 sky patches and analyzing their contributions to the probable sunlight duration. A calculation spreadsheet was developed to calculate the average and vertical daylight factors as well as the summer, winter and annual probable sunlight duration received by a window. The input parameters include the room and window dimensions, interior surface reflectances, obstruction and ground reflectances, window transmittance and azimuth angle, 36 obstruction angles and dimensions of external shading. It offers a clear approach of site layout planning and external shading design to block the summer sunlight and maximize the winter sunlight exposure at the same time.

CHAPTER 6

DEVELOPMENT OF DAYLIGHTING DESIGN CRITERIA FOR GENERAL EVALUATION OF DAYLIGHTING PERFORMANCE

6.1 Introduction

This chapter aims to develop a daylighting design criteria for general evaluation of daylighting performance of buildings in a dense urban environment. The criteria are based on the quantitative assessment parameters: vertical daylight factor and probable sunlight duration received at the window. The relation between these assessment parameters and subjective user satisfaction of a daylight environment was investigated by conducting a questionnaire survey. A daylighting performance assessment method was developed for residential buildings in an environment of high building density.

6.2 Questionnaire survey of human satisfaction to daylight environment

A questionnaire survey was conducted to study the relation between user satisfaction of a daylighting environment and the values of vertical daylight factor and probable sunlight duration. The survey was generally divided into two stages. At the first stage, the subjective sensation of the respondents to the daylighting environment of their households was collected from the questionnaire survey. The influence of each sensation to the overall satisfaction with the daylighting environment was studied using a correlation analysis. At the second stage, the daylight environment was evaluated using the assessment parameters: summer sunlight duration factor (*SSDF*), winter sunlight duration factor (*WSDF*), annual sunlight duration factor (*ASDF*) and vertical daylight factor (*VDF*). Another correlation analysis was carried out to study the relation between the subjective sensations and the four quantitative assessment parameters. A set of daylighting design criteria was developed by studying the critical values of the assessment parameters which result in different ratings of user satisfaction.

The questionnaire survey was administered by postal questionnaire. Two housing estates: Tin Shing Court in Tin Shui Wai and Choi Ming Court in Tseung Kwan O were identified as survey sites. The questionnaire contained 15 closed questions and 1 open-ended question. Please refer to chapter 4 for the development and details of the questionnaire. The questionnaires were delivered to and collected from the residential flats during June and July in 2002. Totally 2,000 copies of the questionnaires were distributed to the two housing estates. A total of 652 completed copies returned, 321 of the copies were returned from Tin Shing Court and the rest was returned from Choi Ming Court. The response rate was about 33%.

6.2.1 Results of questionnaire survey at the first stage

Among the 652 respondents, 49% of them were male and 51% were female. The age of the respondents ranged from 20 to over 60. In Question 1, respondents were asked for the habit of using blinds or curtains of the windows in their living rooms. The percentages for Question 1 are shown in Figure 6.1. More than half (57%) of the respondents in Tin Shing Court replied that they did not usually draw the curtain in their living rooms. The percentage for the respondents not drawing curtains in Choi Ming Court was 37%. The results suggest that most of the respondents did not usually draw or drew less than a half of the curtains in the living room. This fact may imply that daylight coming from the window is welcomed by most of the respondents. It is consistent with the previous findings that daylight is desirable to the inhabitants of residential building (Day & Creed, 1996; Iwata et al., 1994).

Question 2 asked for the reasons for the respondents to draw the curtains in their living rooms. About 23% of the respondents in Tin Shing Court and 25% in Choi Ming Court reported that they drew the curtains because the daylight was too bright or too glaring. Another 19% in Tin Shing Court and 26% in Choi Ming Court drew the curtains because of the reflected glare. The results suggest that the visual discomfort due to daylight was responsible for about half of the reasons to draw curtains in living rooms. As the size of the living room is not large, it limits the furniture layout. It is common for the occupants to put the television near to the wall which is adjacent to the window in the living room. Then the image of the bright sky projected on the television would cause reflected glare to the occupants. The degree of discomfort due to the bright sky and the reflected glare can be very different among different flats. The occupants' sensation to daylight glare was studied in Question 4.

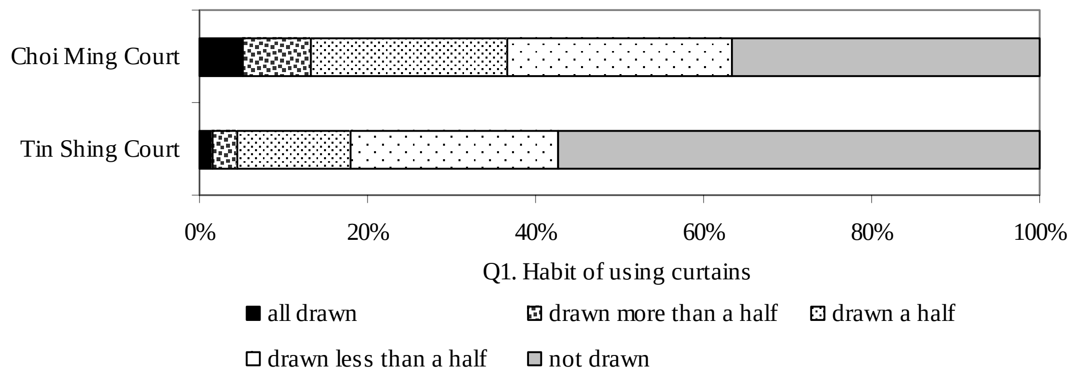


Figure 6.1 Results of Question 1

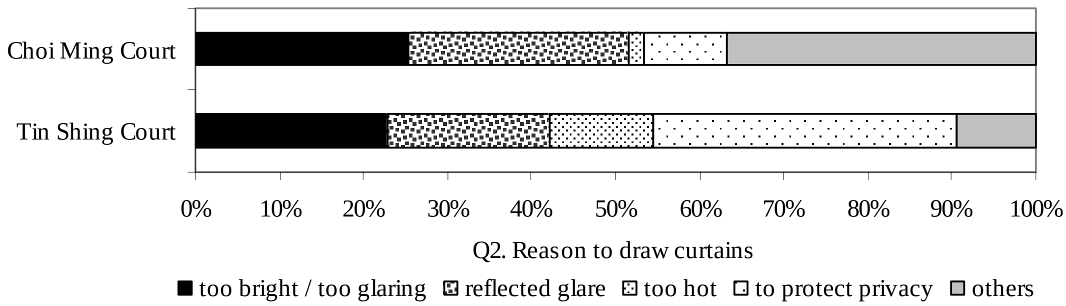


Figure 6.2 Results of Question 2

In Question 3, the occupants were asked whether they needed to switch on electrical lighting for reading in the living rooms in the daytime. The results of the two estates are very similar. About 40% and 38% of the respondents in Tin Shing Court and Choi Ming Court respectively claimed that they had never switched on electrical lighting for reading in the daytime. Another 37% and 40% of the occupants in these two estates reported that they rarely switched on electrical lighting. As a large portion of the occupants rarely or even never required supplementary lighting for reading in the daytime, it implies that the amount of daylight in most of the living rooms in the two estates is adequate for task performance like reading. In Question 4, daylight glare sensation was studied. The problem of daylight glare can be classified into discomfort glare and disability glare. Discomfort glare is resulted from the presence of an excessively bright light source in the visual field causing discomfort to a person (Robbins, 1986). It could be due to the bright sky as seen from the window or the large brightness contrast between the window and the dark interior wall. When the sky is very bright, it may cause discomfort glare by the saturation and contrast effects. The degree of daylight glare was claimed to be related to the luminance of the sky, window size, position of the patch of sky relative to the direction of view and the adaptation conditions in the room (Petherbridge & Hopkinson, 1950). Similar to discomfort glare, disability glare is also resulted from the presence of an excessively bright light source (Robbins, 1986). Disability glare will interfere a person's ability to perform a task. One important type of disability glare is reflected glare. It occurs when the image of a light source, which is brighter than the task luminance, is projected on the task. One example of reflected glare occurs when the image of the bright sky is projected on the television. When the respondents were asked for the frequency of encountering the daylight glare problem in their living rooms in Question 4, nearly half of the respondents (41% in Tin Shing Court and 48% in Choi Ming Court) reported that they encountered this problem rarely. Only a small portion of them claimed that the glare problem occurred often. It implies that this problem is not serious in the two estates. It could be explained by several reasons. As the building blocks are densely packed, the visible sky (excessively bright light source) could enter the visual field only from a high angle so that it does not cause significant daylight discomfort glare to the occupants. Besides, previous research (Chauvel et al., 1982) showed that window, whose area is larger than 2% of the floor area, increases the surround luminance so that the adapting effect on the eye is higher. As the window to floor area ratios for the living rooms in these two estates are quite high (about 23%), it increases the respondents' adaptation to bright light source such that the problem of daylight glare is not very serious. Nevertheless, when the occupants find the window too glaring, they can react to it by drawing the curtains, as reflected from Question 2. It could reduce complaints about glare in some ways. In Question 5, respondents were asked for the frequency that they felt uncomfortable because of the heat brought by the sunlight coming from the windows in their living rooms. Nearly half of the occupants (41% in Tin Shing Court and 46% in Choi Ming Court) reported that they rarely encountered this problem. About 34% of the respondents in Tin Shing Court and 35% in Choi Ming Court claimed that this problem occurred sometimes.

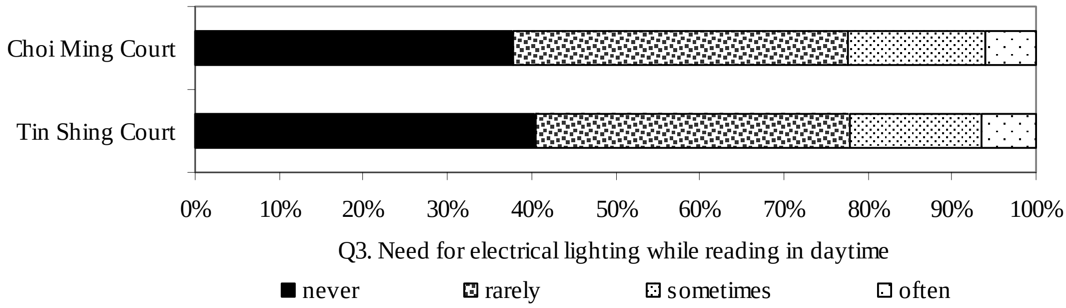


Figure 6.3 Results of Question 3

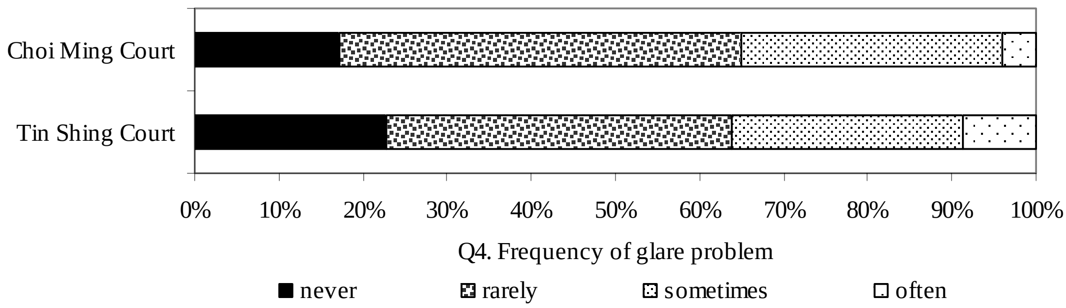


Figure 6.4 Results of Question 4

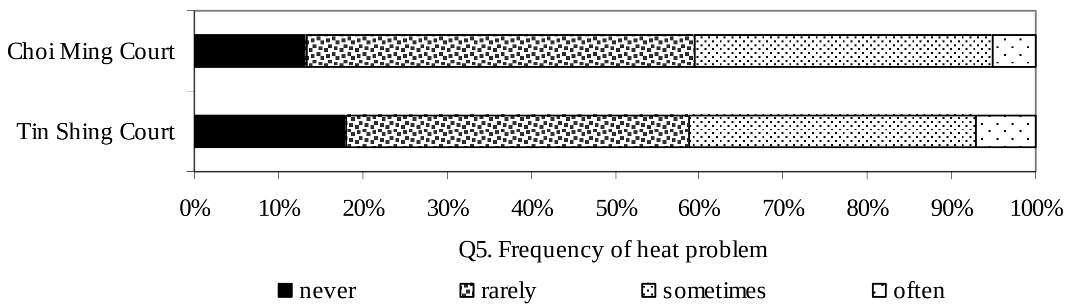


Figure 6.5 Results of Question 5

When the occupants were asked for their opinions on the comfort sensation and brightness sensation of their living rooms, most of them expressed positive sensations to these two questions. More than half of them (57% in Tin Shing Court and 62% in Choi Ming Court) claimed that the daylight environment was very comfortable. Similarly, more than half of the respondents (57% in Tin Shing Court and 57% in Choi Ming Court) reported the daylight environment was very bright. It is quite surprising that the occupants on the lower floors also expressed that the natural lighting environment was very bright. Question 8 asked for the amount of daylight in living rooms. About 70% of the respondents in Choi Ming Court reported that the amount of daylight in their living rooms was just right. As for Tin Shing Court, 27% of them claimed it to be just right and 44% claimed it to be too much. The conclusion that the occupants are satisfied with the daylight performance of their flats is supported by the findings in Question 9 and Question 10. A large portion of the occupants reported that there was no need to improve the daylight environments of the living rooms. Nevertheless, nearly all of them (90% in Tin Shing Court and 91% in Choi Ming Court) agreed that the daylight environment was satisfactory. When they were asked to give a mark (maximum is 10) for the overall evaluation of the daylight environment in Question 11, about 34% and 35% of the respondents in the two estates gave a mark of 7. The mean value for the overall evaluation mark is 7.71. The standard deviation of the ratings is 1.55. The high mean value agrees with the conclusion that most of the respondents are satisfied with the daylight environment.

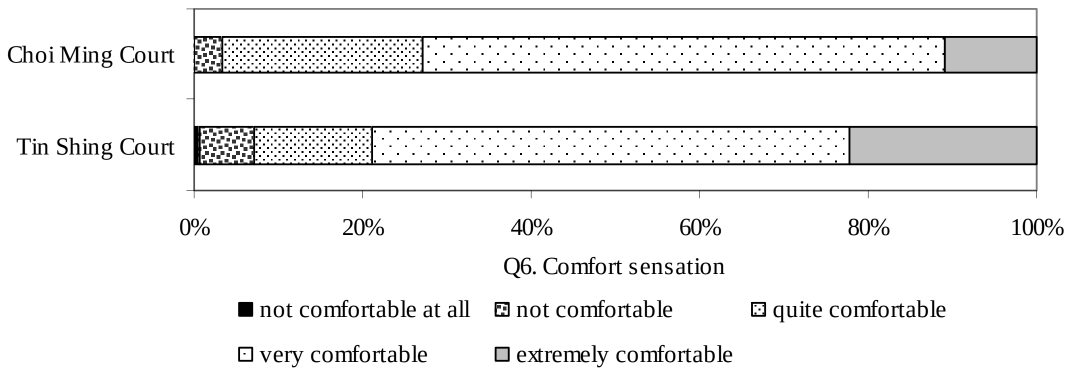


Figure 6.6 Results of Question 6

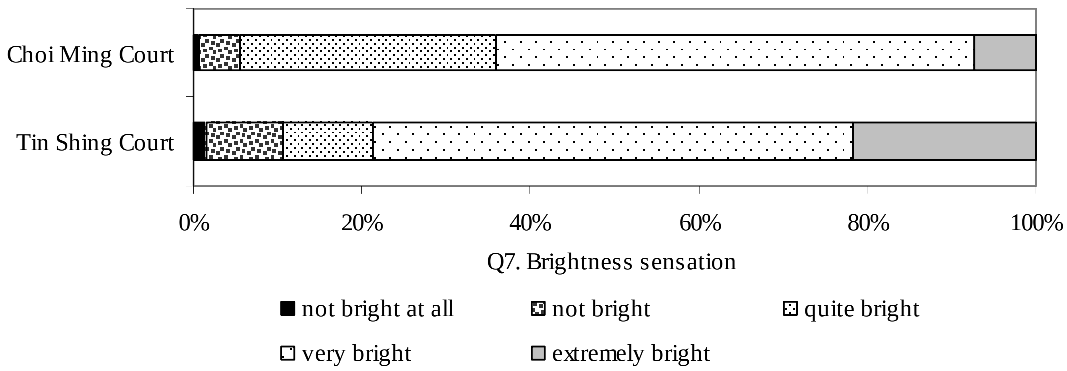


Figure 6.7 Results of Question 7

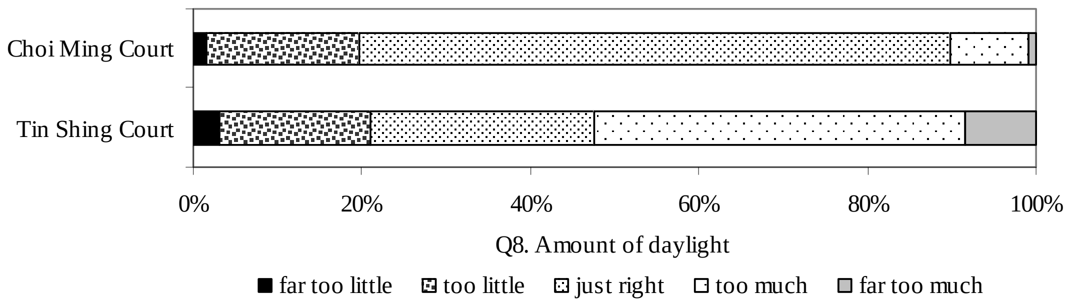


Figure 6.8 Results of Question 8

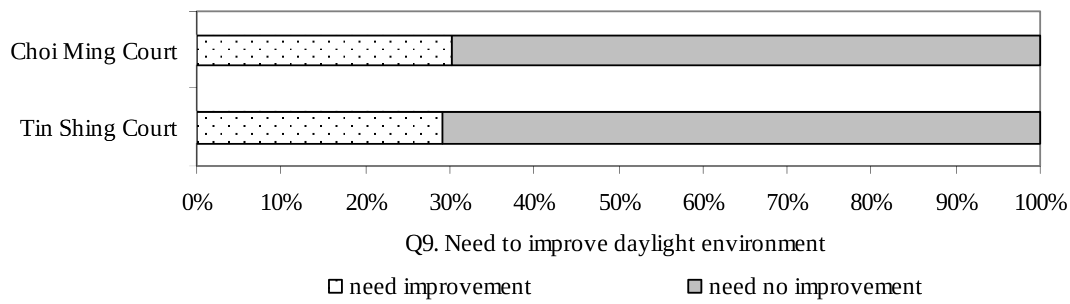


Figure 6.9 Results of Question 9

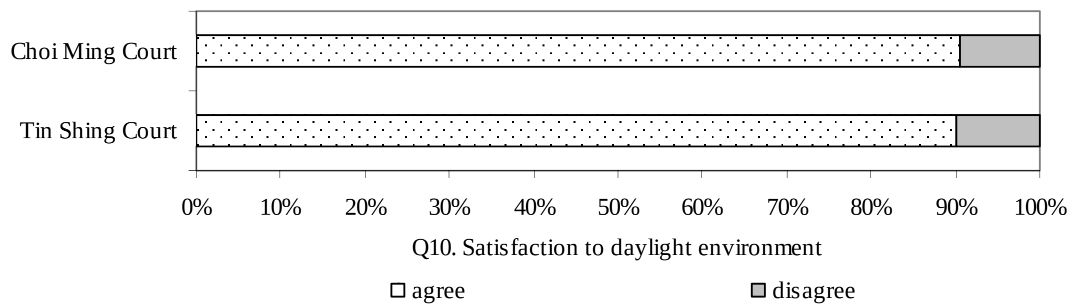


Figure 6.10 Results of Question 10

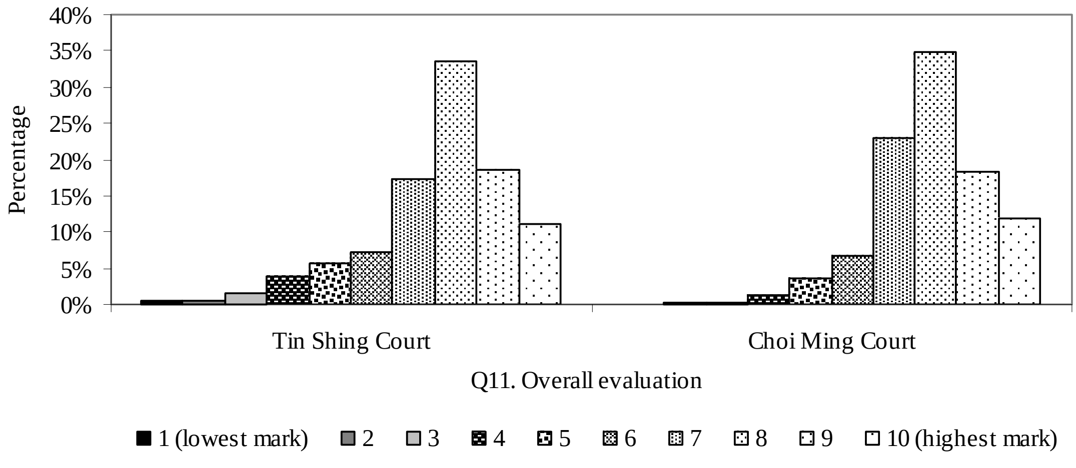


Figure 6.11 Results of Question 11

Question 12 sought information of the time preferences to sunlight for different rooms. The results of the two estates are similar. They are shown in Figure 6.12 and Figure 6.13. Most of the respondents preferred sunlight to enter the space in the morning (06:00 to 10:00) for living rooms, dining rooms and bedrooms. As for the kitchen and bathroom, most of them reported that they had no special preference to the time having sunlight. In Question 13, the occupants were asked to rank the importance of sunlight to different rooms. Nearly all of them ranked the living room as the room to which sunlight was most important. The mean values of the ratings are 1.19, 2.53, 3.28, 3.63 and 4.36 in the order of living room, dining room, bedroom, kitchen and bathroom. The smaller mean values refer to a higher rank of importance of sunlight. The corresponding standard deviations are 0.62, 0.87, 1.14, 0.85 and 1.02.

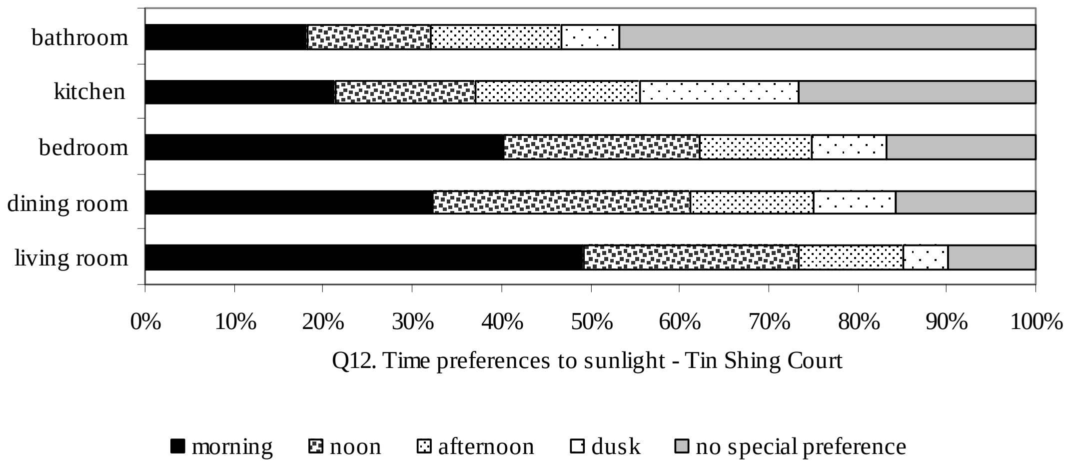


Figure 6.12 Results of Question 12 for Tin Shing Court

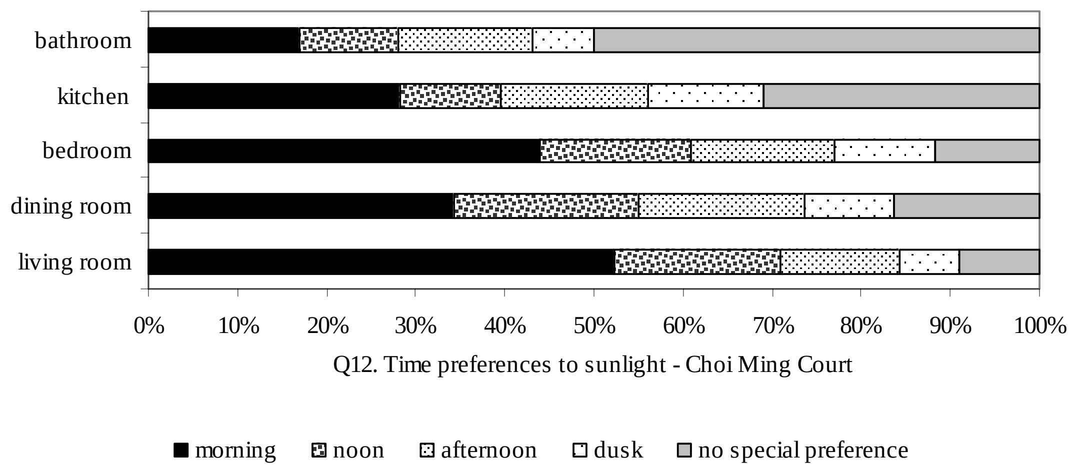


Figure 6.13 Results of Question 12 for Choi Ming Court

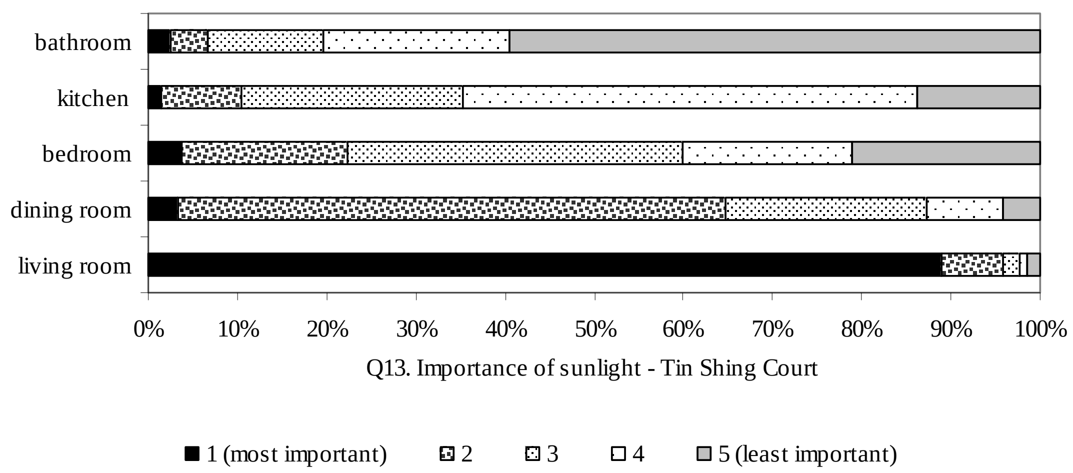


Figure 6.14 Results of Question 13 for Tin Shing Court

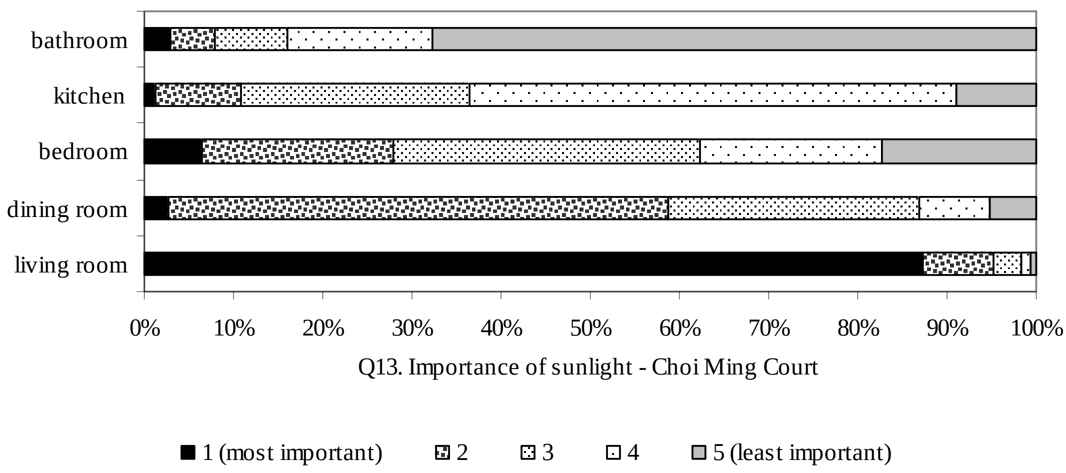


Figure 6.15 Results of Question 13 for Choi Ming Court

In Question 14, the respondents were asked to express any ideas about the daylight environment in their living rooms. 135 occupants responded to this question. About 27 of them expressed that they preferred to have more sunlight to enter their flats, especially in winter. About 20 of the occupants claimed that the building-to-building distance was too close that it obstructed the available daylight to their flats. Besides, 15 of them complained that the locations for hanging clothes had too little sunlight so that they had to hang their clothes on the windows in the living rooms. Then the clothes hanging on the windows would block the available daylight. Nevertheless, 11 of them preferred to have larger windows or more windows in the living rooms.

In order to study the influence of each sensation to the overall satisfaction with the daylighting environment, the results of Question 3 to Question 8 and Question 11 were studied under a correlation analysis. Question 3 sought information about the frequency that the occupants switch on lighting for reading in the daytime. It aims to study the task performance under daylight in the respondents' living rooms. Question 4 and Question 5 concerned about the glare and heat problem due to the sunlight entering the space. In Question 6 and Question 7, the occupants were asked for their opinions on the comfort and brightness sensation of the daylight environment. Question 8 asked for the amount of daylight in the living rooms. In Question 11, the respondents were asked for the overall evaluation of the daylight environment in their living rooms. The relations between the results from these seven questions were studied under a correlation matrix. The non-parametric (Spearman's) rank order correlation coefficients (r_s) were evaluated for every set of results. The results are tabulated in Table 6.1. The frequency of switching on lighting for reading (Q3) is found to be significantly correlated with the comfort sensation (Q6), brightness sensation (Q7) and overall evaluation (Q11). The correlation coefficients were calculated to be -0.375, -0.362 and -0.384 respectively. Negative correlations indicate that the frequency of switching on lighting is higher when the daylight environment is less comfortable and bright. The frequency of switching on lighting is also higher for lower mark of overall evaluation. Besides, the problem of glare (Q4) is found to be strongly correlated with the problem of heat (Q5) due to the sunlight entering the space (r_s = 0.573). The comfort sensation (Q6) correlates highly with the brightness sensation (Q7) (r_s = 0.552). It suggests that a comfortable daylight environment is usually coupled with a brightly lit interior. The sensation to the amount of daylight (Q8) is also found to be strongly correlated with the brightness sensation (Q7) (r_s = 0.576). It suggests that the occupants' attitude towards the amount of daylight is highly dependent on the sensation to the brightness of the environment. The correlations of overall evaluation (Q11) with comfort sensation (Q6), brightness sensation (Q7) and amount of daylight (Q8) are also very high. The correlation coefficients are calculated to be 0.466, 0.564 and 0.462 respectively. It is concluded that the comfort sensation, brightness sensation and the amount of daylight are the critical parameters determining the overall evaluation of a daylight environment, while the overall evaluation is affected most significantly by the brightness sensation. The comfort sensation is coupled with the brightness sensation, while the brightness sensation is coupled with the amount of daylight. However, the correlation between comfort sensation and amount of daylight is less significant ($r_s = 0.309$).

Table 6.1 Correlation matrix for questionnaire results

		Q3	Q4	Q5	Q6	Q7	Q8	Q11
Q3	Correlation Coefficient	1.000	0.029	0.001	-0.375	-0.362	-0.250	-0.384
	Sig. (2-tailed)	-	0.455	0.985	0.000	0.000	0.000	0.000
Q4	Correlation Coefficient	0.029	1.000	0.573	-0.057	0.164	0.280	0.146
	Sig. (2-tailed)	0	-	0.000	0.146	0.000	0.000	0.000
Q5	Correlation Coefficient	0.001	0.573	1.000	-0.091	0.089	0.254	0.085
	Sig. (2-tailed)	1	0.000	-	0.020	0.024	0.000	0.031
Q6	Correlation Coefficient	-0.375	-0.057	-0.091	1.000	0.552	0.309	0.466
	Sig. (2-tailed)	0	0.146	0.020	-	0.000	0.000	0.000
Q7	Correlation Coefficient	-0.362	0.164	0.089	0.552	1.000	0.576	0.564
	Sig. (2-tailed)	0	0.000	0.024	0.000	-	0.000	0.000
Q8	Correlation Coefficient	-0.250	0.280	0.254	0.309	0.576	1.000	0.462
	Sig. (2-tailed)	0	0.000	0.000	0.000	0.000	-	0.000
Q11	Correlation Coefficient	-0.384	0.146	0.085	0.466	0.564	0.462	1.000
	Sig. (2-tailed)	0	0.000	0.031	0.000	0.000	0.000	-

The major findings of the questionnaire survey at the first stage are summarized below:

1. More than half of the respondents reported that the curtains in their living room were drawn less than a half or not drawn. One of the main reasons for the respondents to draw the curtains is visual discomfort due to daylight glare.

2. The respondents rarely switched on electrical lighting for reading in the daytime.

3. Nearly half of the respondents claimed that they rarely encountered the problem of glare and heat due to daylight.

4. More than half of them reported that the daylight environment of their living room was very comfortable and very bright, and the amount of daylight was just right.

5. A large portion of the respondents reported that there was no need to improve the daylight environment of the living rooms. Nearly all of them agreed that the daylight environments were satisfactory.

6. When they were asked to give a mark (maximum is 10) for the overall evaluation, the mean value is equal to 7.71. The standard deviation of the ratings is 1.55.

7. Most of the respondents preferred sunlight to enter the space in the morning for living rooms, dinning rooms and bedrooms. As for the kitchen and bathroom, they showed no special preference.

8. A large portion of them ranked the living room as the room to which sunlight was most important, followed by the dinning room, bedroom, kitchen, and finally bathroom.

9. The comfort sensation, brightness sensation and the amount of daylight are the critical parameters determining the overall evaluation of a daylight environment, while the overall evaluation is affected most significantly by the brightness sensation.

6.2.2 Results of questionnaire survey at the second stage

Using the calculation methods developed in chapter 5, *SSDF*, *WSDF*, *ASDF* and *VDF* were calculated for the window centres of respondents' living room. Figure 6.16 shows the window directions of the eight flats on a typical floor of the two estates. The window azimuth is measured from the south. It is positive when it is measured to the west and it is negative when it is measured to the east. If this typical building block is located on a horizontal plane without external obstruction, the values of *VDF* for the windows of the eight living rooms at the same floor will be the same due to the symmetrical floor layout. However, the results of *SSDF*, *WSDF* and *ASDF* can be very different, because they are very dependent on the window orientations. For an unobstructed vertical plane facing north, *WSDF* will be equal to 0%, but for the same vertical plane but facing south, *WSDF* can be as high as 47%. Among the eight flats on each floor, the probable sunlight duration of the two flats facing the same direction can also be different. In the layout plan as shown in Figure 6.16, it is noticed that a portion of sky is self-obstructed by the external wall of the adjacent flat for the window in every living room. The relative location of this external wall to the window will affect the results of the probable sunlight duration even if the windows face the same direction. The overhanging canopy will also block a large portion of the summer sunlight from reaching the centre of a window due north and south. In order to study the effect of window orientation and self obstruction to *SSDF*, *WSDF* and *ASDF*, the values were calculated for the window centres of the eight typical flats in each estate without any external obstruction. The results for Tin Shing Court and Choi Ming Court are shown in Figure 6.17 and Figure 6.18 respectively.

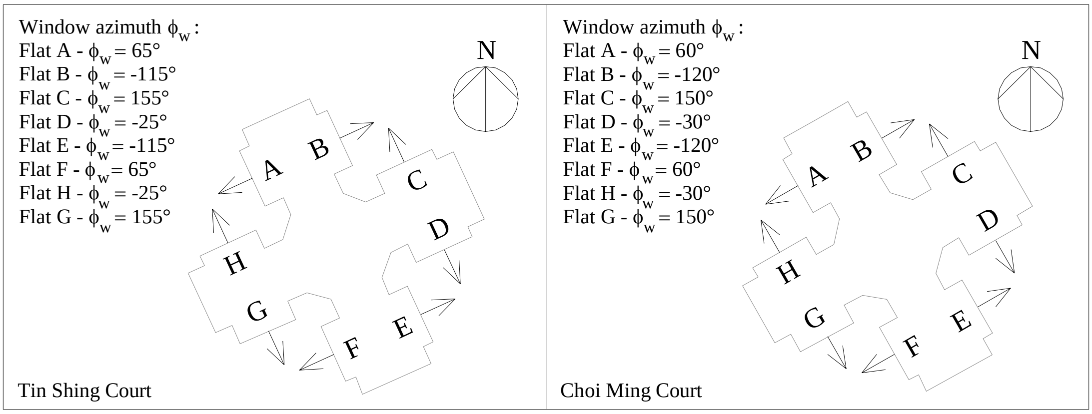


Figure 6.16 Window directions of the eight flats on a typical floor of Tin Shing Court and Choi Ming Court

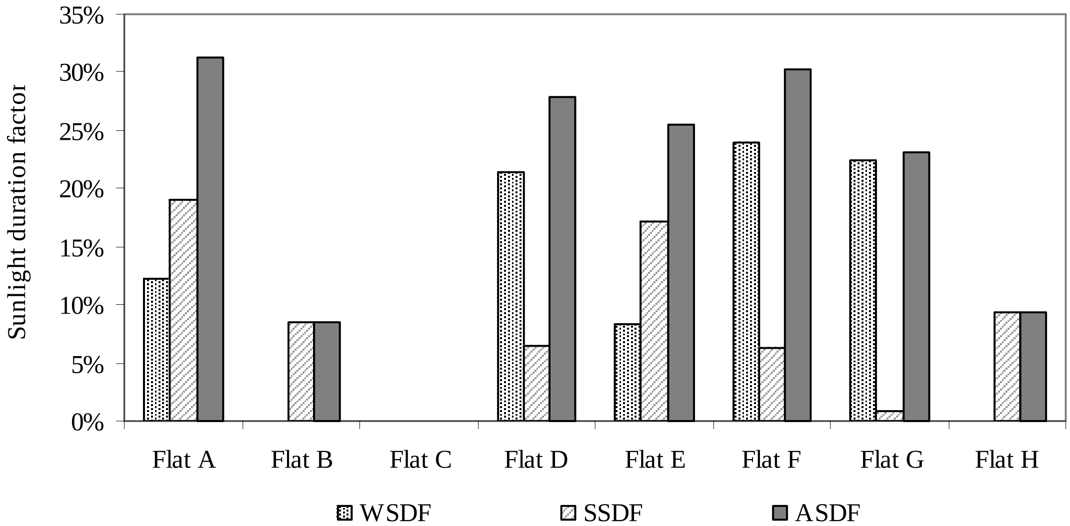


Figure 6.17 Probable sunlight duration of the eight flats in Tin Shing Court (without external obstruction)

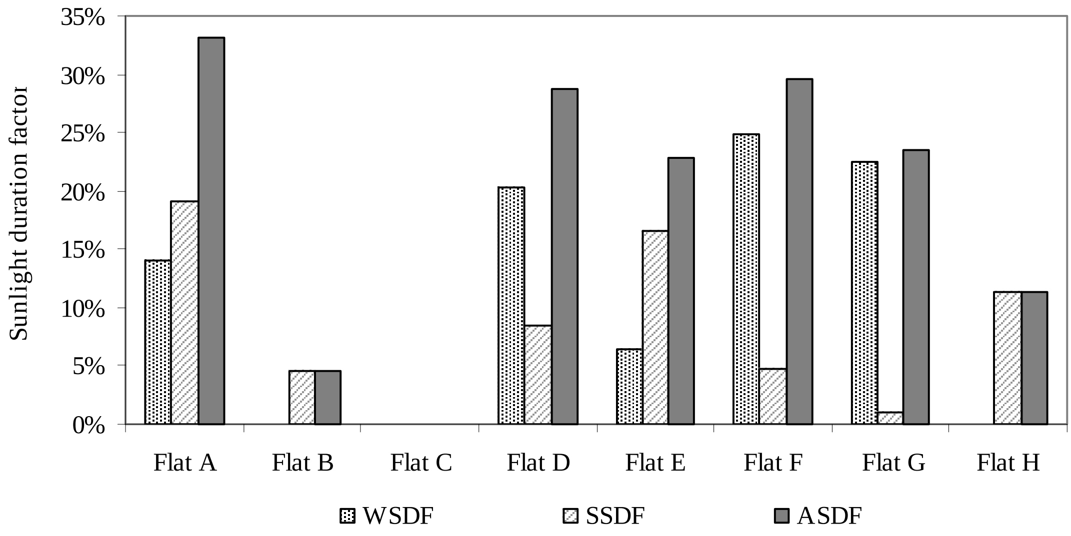


Figure 6.18 Probable sunlight duration of the eight flats in Choi Ming Court (without external obstruction)

In the typical floor layout, Flat A and Flat F face the same direction, but the *SSDF* values of Flat A is much larger than that of Flat F. It is because the external wall of Flat G obstructs a large portion of sky which is responsible for the summer sunlight. Flat B and Flat E face the same orientation. The *WSDF* value of Flat B is equal to zero, while that of Flat E is equal to about 8% for Tin Shing Court and 6% in Choi Ming Court. The difference is mainly due to the fact that the external wall of Flat C blocks all the available winter sunlight from entering Flat B from the south-east direction. When a building block is located in a dense urban environment, instead of an unobstructed horizontal plane, the *VDF* and probable sunlight duration of the corresponding flats will be reduced as the surrounding building becomes denser and higher. Two flats of Tin Shing Court, as shown in Figure 6.19, are chosen to illustrate the effect of obstructions to *VDF*, *SSDF*, *WSDF* and *ASDF*. Location X corresponds to Flat F while Location Y corresponds to Flat A in Figure 6.16. The values of *SSDF*, *WSDF* and *VDF* for flats at Location X and Location Y are shown in Figure 6.20 and Figure 6.21 respectively. The curves for the corresponding typical flats without external obstruction are included in the graphs for comparison.

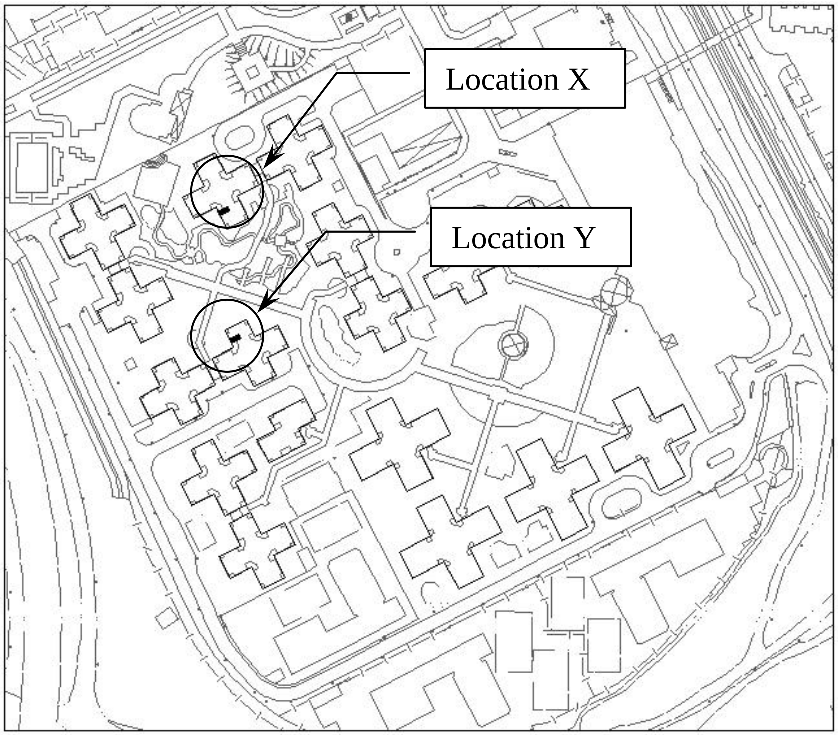


Figure 6.19 Location X and Location Y

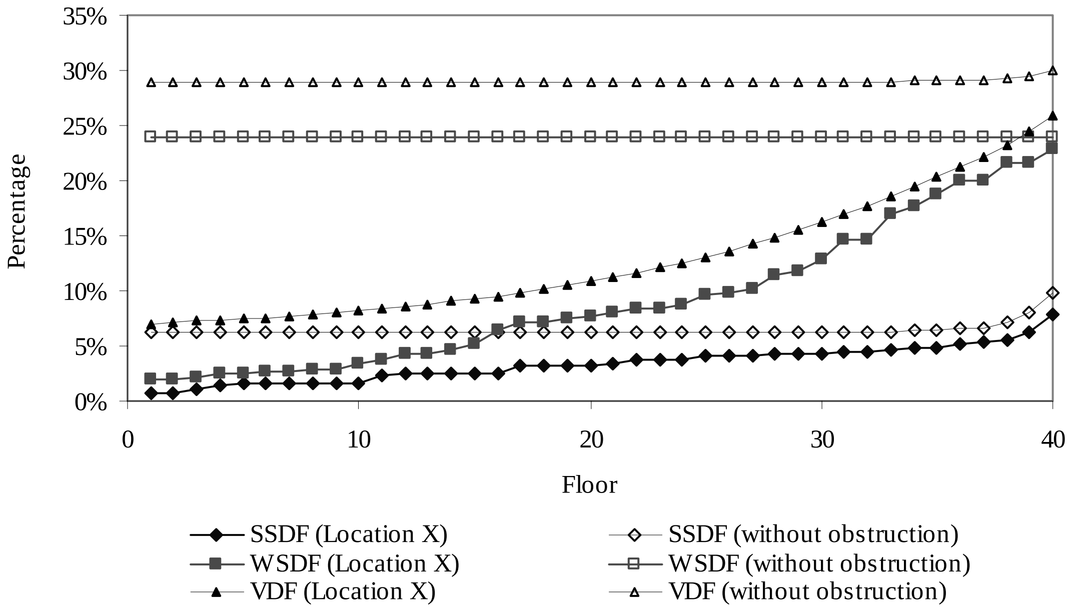


Figure 6.20 *VDF*, *SSDF* and *WSDF* for flats at Location X

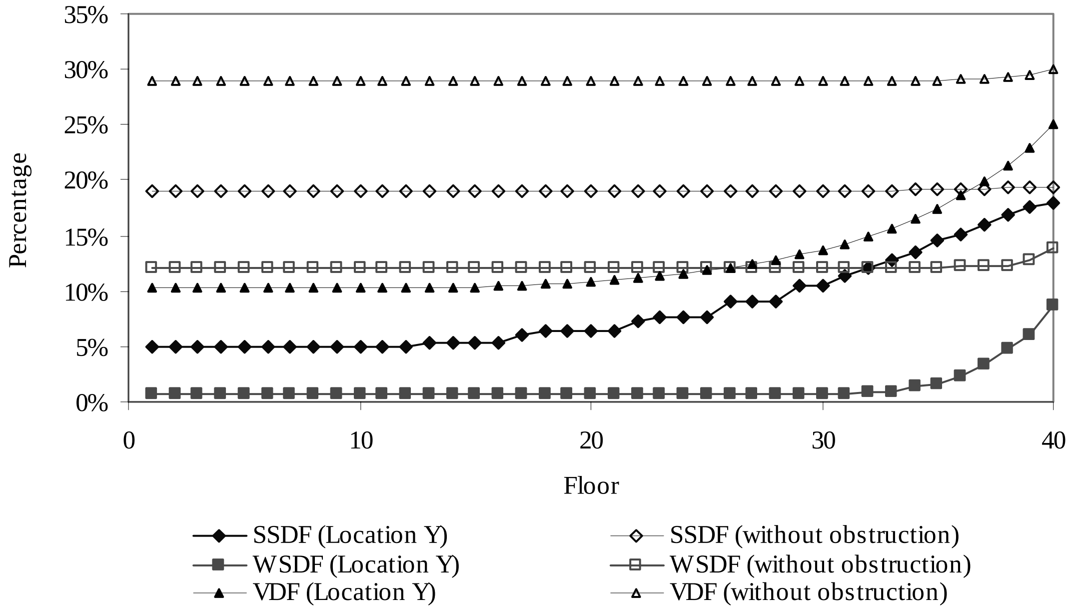


Figure 6.21 *VDF*, *SSDF* and *WSDF* for flats at Location Y

For location X, the external obstruction blocks so much skylight that the *VDF* decreases from 25% at the highest floor to 7% at the lowest floor. The value of *WSDF* also decreases dramatically from 23% at the highest floor to 2% at the lowest floor. As for the *SSDF*, the effect of external obstruction is smaller. The values of *SSDF* decrease from 8% at the highest floor to 1% at the lowest floor. As summer sunlight usually comes from high altitude angle, it is less probable to be obstructed by external buildings. Shading devices, like overhang, are effective to shadow the summer sunlight. In the two estates, the external shading configurations for all the flats are about the same. Much of the summer sunlight is already blocked by the shadings. Besides, the external wall of the adjacent flat of Location X also blocks a large amount of summer sunlight. It results that the decrease of *SSDF* due to external obstruction is smaller compared to *WSDF*.

For Location Y, similar results are found. However, the *VDF* at the lowest floor is higher than that at Location X. It is because there is a gap between the buildings opposite to Location Y, such that skylight can reach the windows at the lowest floor from this gap. It is noticed that the decrease of *SSDF* (from 18% to 5%) is larger than the decrease of *WSDF* (from 9% to 1%) for Location Y. It is explained by the fact that the summer sunlight exposure for Location Y is larger than the winter sunlight exposure, because the external wall of the adjacent flat blocks a large amount of winter sunlight, but not summer sunlight. As a result, although the opposite building blocks both summer and winter sunlight, the decrease is more significant for the summer sunlight. There are a lot of factors affecting the shading effect of external obstruction to the values of *SSDF*, *WSDF* and *VDF*. They include the relative location of the obstruction to the reference point, the external shading configuration and window orientation. In winter, sunlight comes from the southern hemisphere at lower altitude angles (smaller than 68°). As winter sunlight comes at low angle, it is easily blocked by external obstruction. A densely packed building environment will probably result in very low value of *WSDF*.

At the second stage of questionnaire survey, the daylight environment of the respondents' living rooms was assessed quantitatively using four assessment parameters. The values of *SSDF*, *WSDF*, *ASDF* and *VDF* were calculated for the window in the living room of every respondent in the two estates. In Tin Shing Court, the calculated values of *SSDF* range from 0.0% to 19.4%, while *WSDF* ranges from 0.0% to 23.7%. Although *ASDF* is the sum of *SSDF* and *WSDF*, its maximum value is not simply the sum of the maximum values of *SSDF* and *WSDF*. The flat which gives the highest value of *SSDF* may not be the flat which results the highest value of *WSDF*. In this quantitative survey, *ASDF* ranges from 0.0% to about 32.6%. Unlike probable sunlight duration, *VDF* is independent on the window azimuth. It is mainly dependent on the height and layout of the external obstruction. The smallest and largest values of vertical daylight factor were calculated to be 5.2% at the lowest floor and 30.1% at the highest floor.

In Choi Ming Court, *SSDF* ranges from 0.0% to 18.2%, while *WSDF* ranges from 0.0% to 26.3%. The range of *ASDF* is from 0.0% to 35.2%. As for *VDF*, the minimum value was calculated to be 5.0%, while the maximum value was calculated to be 29.6%. Table 6.2 summarizes the minimum and maximum values, means, and standard deviations of *SSDF*, *WSDF*, *ASDF* and *VDF* results of the two estates. The distributions of different ranges of the four reference parameters for Tin Shing Court and Choi Ming Court are illustrated in Figure 6.22 and Figure 6.23 respectively.

Table 6.2 Summary of quantitative assessment results

	Tin Shing Court				Choi Ming Court			
	Minimum value	Maximum value	Mean	Standard deviation	Minimum value	Maximum value	Mean	Standard deviation
SSDF	0.0%	19.4%	5.1%	5.1%	0.0%	18.2%	4.2%	4.8%
WSDF	0.0%	23.7%	7.2%	8.2%	0.0%	26.3%	5.9%	7.2%
ASDF	0.0%	32.6%	12.3%	10.1%	0.0%	35.2%	10.2%	8.9%
VDF	5.2%	30.1%	16.4%	7.5%	5.0%	29.6%	15.9%	6.9%

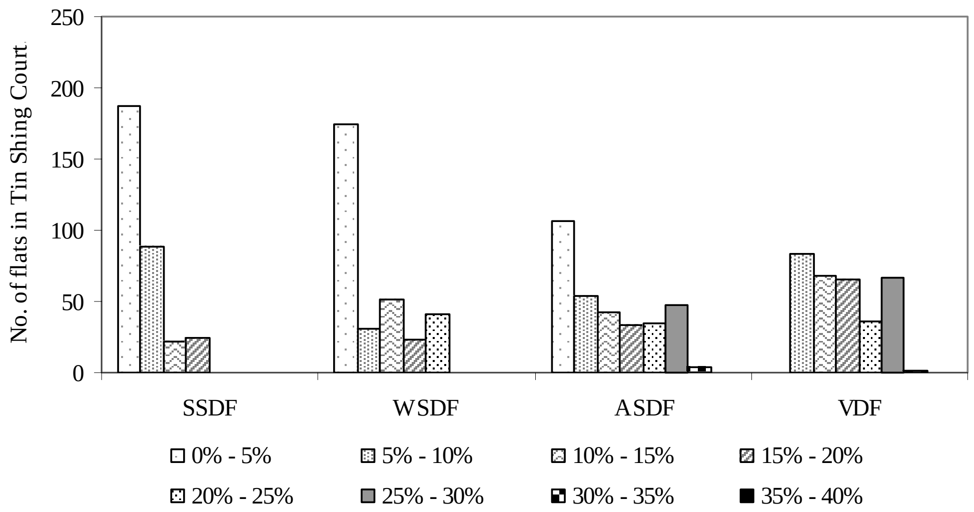


Figure 6.22 Distributions of *SSDF*, *WSDF*, *ASDF* and *VDF* for Tin Shing Court

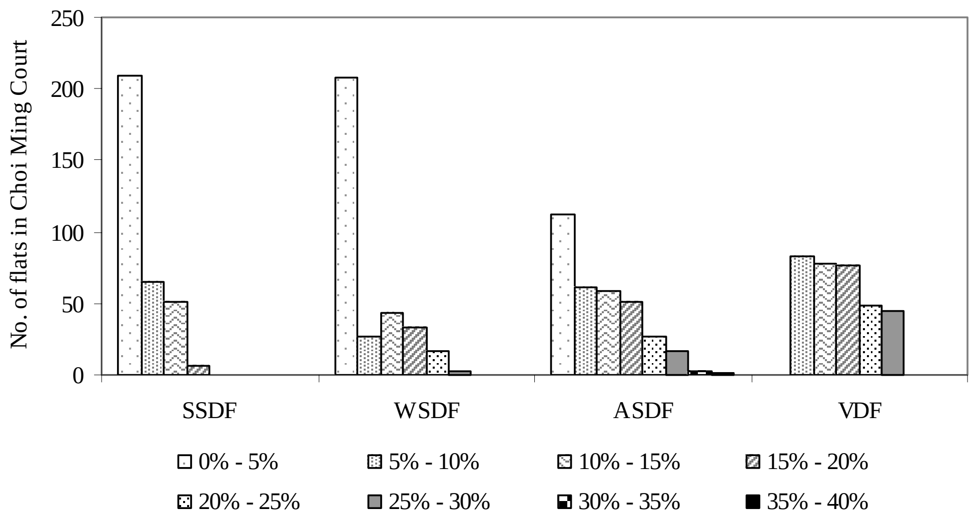


Figure 6.23 Distributions of *SSDF*, *WSDF*, *ASDF* and *VDF* for Choi Ming Court

The major findings of the quantitative assessment for the living rooms of the respondents are summarized in the following:

1. The four quantitative assessment parameters include summer sunlight duration factor (*SSDF*), winter sunlight duration factor (*WSDF*), annual sunlight duration factor (*ASDF*) and vertical daylight factor (*VDF*).

2. The values of *SSDF*, *WSDF* and *ASDF* are affected by the window orientation, self-obstruction by the external wall of the adjacent flat and the external obstruction layout. The value of *VDF* is affected by the self-obstruction and the external obstruction layout, but not by the window orientation.

3. In Tin Shing Court, *SSDF* ranges from 0.0% to 19.4%. Its mean value is equal to 5.1%. *WSDF* ranges from 0.0% to 23.7%. Its mean value is equal to 7.2%. *ASDF* ranges from 0.0% to 32.6%. Its mean value is equal to 12.3%. *VDF* ranges from 5.2% to 30.1%. Its mean value is equal to 16.4%.

4. In Choi Ming Court, *SSDF* ranges from 0.0% to 18.2%. Its mean value is equal to 4.2%. *WSDF* ranges from 0.0% to 26.3%. Its mean value is equal to 5.9%. *ASDF* ranges from 0.0% to 35.2%. Its mean value is equal to 10.2%. *VDF* ranges from 5.0% to 29.6%. Its mean value is equal to 15.9%.

A correlation analysis was carried out to study the statistical relations between the subjective occupants' preferences and quantitative assessment of daylight environment using *SSDF*, *WSDF*, *ASDF* and *VDF*. The values of these four parameters for the living room of every respondent were calculated in the previous section. The correlation coefficients were evaluated and summarized in Table 6.3. No significant correlation is found between the need for electrical lighting while reading in the daytime (Q3) and any quantitative assessment parameters. It is found that the problem of glare (Q4) and problem of heat (Q5) due to the sunlight entering the space correlate highly with *SSDF*. The correlation coefficients were calculated to be 0.387 and 0.377 respectively. It suggests that summer sunlight should cause more problems of glare and heat. Besides, high correlation is found between the sensation towards the amount of daylight (Q8) and *ASDF* (r_s = 0.371). The correlation between the amount of daylight and *VDF* is less significant (r_s = 0.287). It implies that the respondents' perception of the amount of daylight in an interior is more dependent on the sunlight availability. No significant correlation is found between the overall evaluation (Q11) of the daylight environment and *SSDF*, *WSDF*, *ASDF* or *VDF* (r_s = 0.179, 0.234, 0.278 and 0.275 respectively). However, significant correlations are observed for the brightness sensation (Q7) and the two quantitative assessment parameters: *ASDF* (r_s = 0.320) and *VDF* (r_s = 0.342). As brightness sensation was concluded to be the most critical factor to the overall evaluation of a daylight environment in previous section, *ASDF* and *VDF* should be effective parameters to assess the overall performance of a daylight environment quantitatively.

Table 6.3 Correlation coefficients (r_s) between the subjective and quantitative assessment

		Q3	Q4	Q5	Q6	Q7	Q8	Q11
SSDF	Correlation Coefficient	-0.112	0.387	0.377	0.068	0.218	0.309	0.179
	Sig. (2-tailed)	0	0.000	0.000	0.084	0.000	0.000	0.000
WSDF	Correlation Coefficient	-0.104	0.165	0.137	0.117	0.232	0.264	0.234
	Sig. (2-tailed)	0	0.000	0.000	0.003	0.000	0.000	0.000
ASDF	Correlation Coefficient	-0.156	0.287	0.274	0.140	0.320	0.371	0.278
	Sig. (2-tailed)	0	0.000	0.000	0.000	0.000	0.000	0.000
VDF	Correlation Coefficient	-0.232	0.146	0.178	0.222	0.342	0.287	0.275
	Sig. (2-tailed)	0	0.000	0.000	0.000	0.000	0.000	0.000

It was mentioned previously that the window orientation and the effect of self obstruction would affect the summer and winter sunlight availability significantly. In order to study the effect of window orientation to the correlations between the human subjective sensation and quantitative assessment, the questionnaire data was divided into eight groups according to the window orientations and the relative location of the external wall of the adjacent flat. All flats in the two survey estates generally face four directions: north-east (NE), north-west (NW), south-east (SE) and south-west (SW). The two flats facing the same direction were further differentiated by the relative location of the external wall of the adjacent flat. Then the data were divided into eight groups namely NE(N), NE(S), NW(N), NW(S), SE(N), SE(S), SW(N) and SW(S). For a flat facing north-east, if the external wall of the adjacent flat obstructed the southern portion of sky, then this flat was grouped to NE(N). Similarly, for a flat facing south-west, if the external wall of the adjacent flat obstructed the northern portion of sky, then this flat was grouped to SW(S). Figure 6.24 illustrates the relative location of the flat in each group. After dividing the data into eight groups, a correlation analysis between the subjective sensations towards the daylight environment and the quantitative assessment using *SSDF*, *WSDF*, ASDF and *VDF* was carried out for each group of data. In order to illustrate the differences of sunlight availability among different groups of flats, the maximum value, minimum value and mean of *SSDF*, *WSDF* and *ASDF* for each group are shown in Figure 6.25, Figure 6.26 and Figure 6.27 respectively. The range of *VDF* for each group of flats is also shown in Figure 6.28.

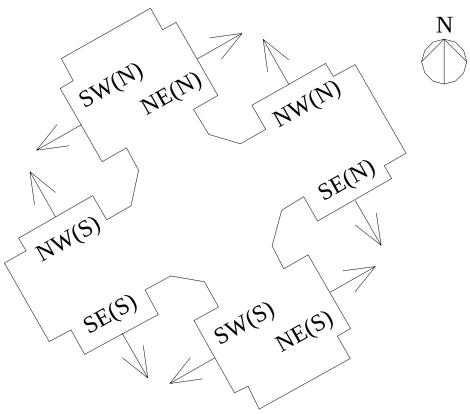


Figure 6.24 Group division by window orientation

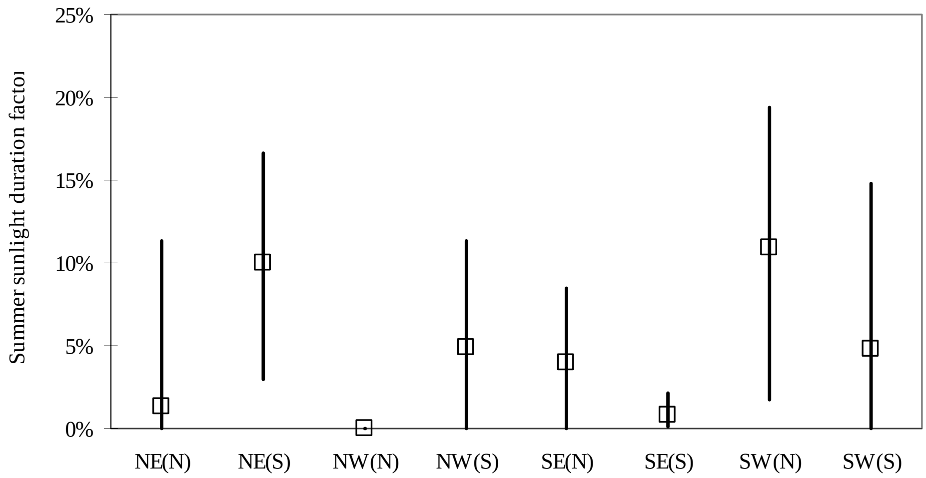


Figure 6.25 *SSD*F results for each group

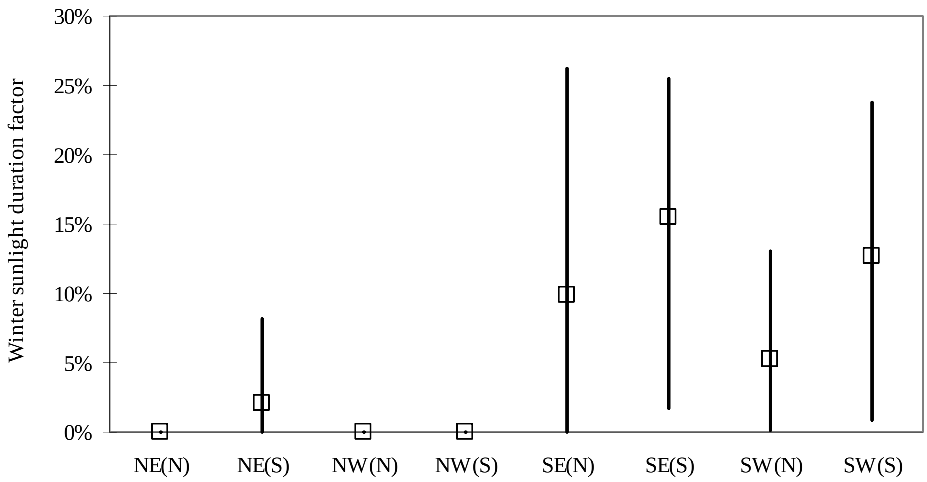


Figure 6.26 *WSDF* results for each group

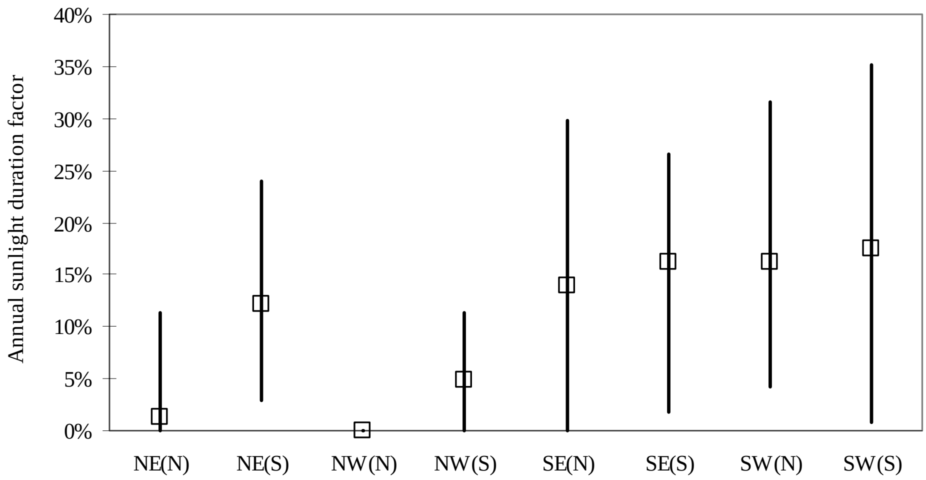


Figure 6.27 *ASDF* results for each group

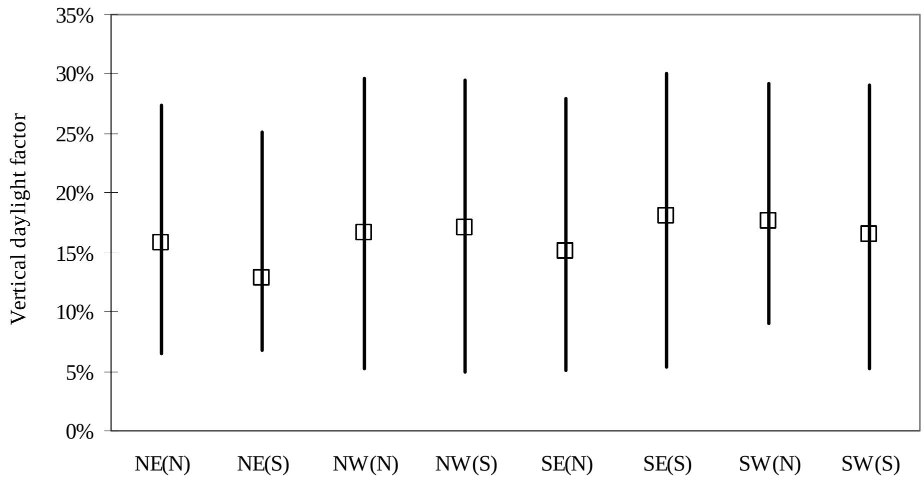


Figure 6.28 *VDF* results for each group

As the daylighting performance of the flats in the eight groups varies significantly, there should be some discrepancies in the questionnaire survey results of the eight groups. The mean values of the answers to Q3 to Q8 for the eight groups are summarized in Table 6.4 . The highest mean value of Q3 is resulted for group SE(N) (mean value = 2.1), followed by the group NW(N) (mean value = 2.0). The result implies that the frequency of switching on electrical lighting for reading during daytime is the highest in these two groups. For group NW(N), it may be explained by the fact that windows in this group receive zero *SSDF*, *WSDF* and *ASDF*. The daylight level of the living room in this group is therefore expected to be relatively low. As for group SE(N), the sunlight availability is generally good among the eight groups, but the frequency of switching on electrical lighting for reading during daytime is the highest. It suggests that the relation between sunlight availability and the frequency of switching on lights is small. This conclusion is supported by the poor correlations of Q3 with *SSDF*, *WSDF* or *ASDF* as shown in Table 6.3. In questions Q4 and Q5, the respondents were asked for the frequency that they encountered the glare and heat problem due to the daylight entering the interior. The groups NE(N), NW(N) and SE(S) have the lowest mean values of Q4 and Q5, while high mean values of Q4 and Q5 are resulted in groups SW(N) and SW(S). Low values of Q4 and Q5 indicate that the occupants rarely encounter the problem of glare and heat. The values of *SSDF* in the groups NE(N), NW(N) and SE(S) are very low and the values of *SSDF* in groups SW(N) and SW(S) are high. It suggests that the problems of glare and heat are related to the values of *SSDF*. It also agrees with the correlation analysis results as shown in Table 6.3. As for the comfort sensation (Q6), the mean values peaks at 5.6 in group SE(S) which has very low value of *SSDF* and very high value of *WSDF*. It indicates that the daylight environment in group SE(S) is the most comfortable compared to the other groups. However, the differences in the mean values of Q6 are small. No conclusion is drawn for the rest of the groups. In question Q7, the respondents were asked for the brightness sensation in their living rooms. The group SW(S) is responsible for the highest mean value (mean value = 5.4) and the groups NE(N) and NW(N) are responsible for the lowest mean values (mean value = 4.9). A high value indicates the sensation of a brighter daylight environment. With reference to Figure 6.27, the values of *ASDF* are very high in group SW(S), while the values of *ASDF* are very low in group NE(N) and NW(N). It suggests that the brightness sensation could be related to the annual sunlight availability. In question Q8, the respondents were asked for their subjective feelings on the amount of daylight in their living rooms. High mean values of Q8 are resulted for groups SW(N) and SW(S) (mean value = 4.8 and 4.6 respectively). Low mean values are resulted for groups NE(N) and NW(N) (mean value = 3.7 and 3.8 respectively). A high value indicates the sensation of large amount of daylight. With reference to Figure 6.27, the values of *ASDF* are high in the groups SW(N) and SW(S), while the values of *ASDF* are very low in group NE(N) and NW(N). This result implies a significant relation between the values of *ASDF* and the sensation to the amount of daylight. As for the overall evaluation of the daylight environment (Q11), group NW(S) is responsible for the highest mean value and the groups NE(N) and NW(N) are responsible for the lowest mean value. As all the groups NW(S), NE(N) and NW(N) have low sunlight availability, no conclusion is drawn for the correlation between the overall evaluation of daylight environment and the probable sunlight durations. Further correlation analyses were carried out to study the relationships between the questionnaire results and the quantitative assessment parameters.

Table 6.4 Mean values of questionnaire results for each group division

	Mean values						
	Q3	Q4	Q5	Q6	Q7	Q8	Q11
NE(N)	1.8	2.0	2.0	5.3	4.9	3.7	7.3
NE(S)	1.9	2.5	2.4	5.2	5.2	4.3	7.7
NW(N)	2.0	1.6	1.9	5.2	4.9	3.8	7.3
NW(S)	1.9	2.1	2.4	5.3	5.2	4.0	8.8
SE(N)	2.1	2.1	2.2	5.5	5.2	4.1	8.5
SE(S)	1.8	1.9	2.0	5.6	5.2	4.2	8.0
SW(N)	1.9	2.7	2.9	5.2	5.2	4.8	7.7
SW(S)	1.8	2.6	2.6	5.2	5.4	4.6	8.0

After dividing all the data into eight groups according to the window orientation and the relative location of the external wall of the adjacent flat, a correlation analysis between the subjective sensations towards the daylight environment (Q3 to Q8 and Q11) and the quantitative assessment using *SSDF*, *WSDF*, *ASDF* and *VDF* was carried out for each group of data. Firstly, the correlation coefficients between the questionnaire results and the quantitative assessment results for group NE(N) are summarized in Table 6.5. As the values of *WSDF* are equal to zero for all flats in this group, no correlation coefficients could be found for *WSDF* and other parameters. In this group, the correlation of the sensation to the amount of daylight (Q8) with *ASDF* is quite high (r_s = 0.327), but the correlation with *VDF* is not very significant (r_s = 0.259). It could be explained by the fact that sunlight is scarce for the flats in this group. The mean value of *ASDF* is equal to 1.3%. Then the subjective sensation of the amount of daylight could be dominated by the duration of the occasional sunlight. Strong correlation is found between the overall evaluation of daylight environment (Q11) and *VDF* (r_s = 0.494), but not for *SSDF* or *ASDF*. As the sunlight availability is very low for the flats in this group, the occupants' expectation of sunlight might not be strong. It could lead to the result that the overall performance of the daylight environment depends on the amount of visible sky, thus *VDF*.

For the group NE(S), the correlation coefficients are tabulated in Table 6.6. In this group, *SSDF* is quite high (Mean = 10.0%), while *WSDF* is low (Mean = 2.1%). It is unexpected that no significant correlation is found between the glare and heat sensation (Q4 and Q5) and *SSDF*. One possible reason is that all summer sunlight enters the interior in the morning. It may be more acceptable to the occupants if sunlight comes in the morning. The brightness sensation (Q7) correlates highly with *ASDF* and *VDF* (r_s = 0.387 and 0.392 respectively). No significant correlations are found for the comfort sensation, amount of daylight or overall evaluation of daylight environment with the assessment parameters.

Table 6.5 Correlation coefficients (r_s) between the subjective and quantitative assessment for group NE(N)

NE(N)		Q3	Q4	Q5	Q6	Q7	Q8	Q11
SSDF	Correlation Coefficient	-0.075	0.335	0.292	0.114	0.298	0.327	0.203
	Sig. (2-tailed)	1	0.008	0.023	0.381	0.020	0.010	0.117
WSDF	Correlation Coefficient	-	-	-	-	-	-	-
	Sig. (2-tailed)	-	-	-	-	-	-	-
ASDF	Correlation Coefficient	-0.075	0.335	0.292	0.114	0.298	0.327	0.203
	Sig. (2-tailed)	1	0.008	0.023	0.381	0.020	0.010	0.117
VDF	Correlation Coefficient	-0.273	0.379	0.422	0.179	0.292	0.259	0.494
	Sig. (2-tailed)	0	0.003	0.001	0.168	0.022	0.044	0.000

Table 6.6 Correlation coefficients (r_s) between the subjective and quantitative assessment for group NE(S)

NE(S)		Q3	Q4	Q5	Q6	Q7	Q8	Q11
SSDF	Correlation Coefficient	-0.100	0.126	0.037	0.279	0.324	0.192	0.232
	Sig. (2-tailed)	0	0.265	0.748	0.012	0.003	0.088	0.039
WSDF	Correlation Coefficient	-0.064	0.071	0.029	0.066	0.239	0.080	0.107
	Sig. (2-tailed)	1	0.533	0.796	0.559	0.033	0.480	0.346
ASDF	Correlation Coefficient	-0.129	0.105	0.021	0.253	0.387	0.216	0.252
	Sig. (2-tailed)	0	0.353	0.850	0.023	0.000	0.055	0.024
VDF	Correlation Coefficient	-0.142	0.083	-0.005	0.279	0.392	0.208	0.265
	Sig. (2-tailed)	0	0.463	0.967	0.012	0.000	0.064	0.017

In group NW(N), the values of *SSDF*, *WSDF* and *ASDF* are all equal to zero. The correlation coefficients are tabulated in Table 6.7. No correlation coefficient could be found for these three parameters. For the flats in this group, the glare and heat problem should not be serious, because no sunlight could enter the space at all. It might lead to the result that no significant correlation is found for the results of Q4 and Q5 with *VDF*. The sensation results of the problem of glare and heat could be affected by other subjective sensations, personal expectations and experience. High correlation is resulted between the comfort sensation (Q6) and *VDF* (r_s = 0.418). A higher value of *VDF* generally results in a brighter daylight environment. A brighter environment could lead to a more comfortable living condition. However, no significant correlation is found between the brightness sensation and *VDF*. Nevertheless, no significant correlations are found between *VDF* and Q8 as well as between *VDF* and Q11 (r_s = 0.028 and 0.167).

For group NW(S), the value of *WSDF* is zero, while the mean value of *SSDF* is about 4.9%. The sunlight availability in summer is medium among other groups.

With reference to the table of correlation coefficients as shown in Table 6.8, the glare and heat sensations (Q4 and Q5) correlate highly with *SSDF*. For the flats in this group, summer sunlight always comes in the afternoon. It could cause disturbances to the occupants, thus causing problems of glare and heat. Significant correlations are also found between brightness sensation (Q7) and *ASDF* as well as between the amount of daylight (Q8) and *ASDF*. The correlation coefficients were calculated to be 0.371 and 0.334 respectively. The correlations between these two subjective sensations (Q7 and Q8) with *VDF* are comparatively not very significant (r_s = 0.291 and 0.241). As the sunlight availability is not high in this group, the subjective sensations of brightness and amount of daylight may be dominated by the presence of the occasional sunlight. It leads to the high correlations between the subjective sensations and *ASDF*. Significant correlations are found between the overall evaluation (Q11) and *ASDF* (r_s = 0.384) as well as between overall evaluation (Q11) and *VDF* (r_s = 0.354). The values of *ASDF*, which is equal to *SSDF* in this case, is also highly correlated with the glare and heat problems.

Table 6.7 Correlation coefficients (r_s) between the subjective and quantitative assessment for group NW(N)

NW(N)		Q3	Q4	Q5	Q6	Q7	Q8	Q11
SSDF	Correlation Coefficient	-	-	-	-	-	-	-
	Sig. (2-tailed)	-	-	-	-	-	-	-
WSDF	Correlation Coefficient	-	-	-	-	-	-	-
	Sig. (2-tailed)	-	-	-	-	-	-	-
ASDF	Correlation Coefficient	-	-	-	-	-	-	-
	Sig. (2-tailed)	-	-	-	-	-	-	-
VDF	Correlation Coefficient	-0.140	0.056	-0.079	0.418	0.131	0.028	0.167
	Sig. (2-tailed)	0	0.655	0.527	0.000	0.293	0.821	0.181

Table 6.8 Correlation coefficients (r_s) between the subjective and quantitative assessment for group NW(S)

NW(S)		Q3	Q4	Q5	Q6	Q7	Q8	Q11
SSDF	Correlation Coefficient	-0.211	0.431	0.452	0.271	0.371	0.334	0.384
	Sig. (2-tailed)	0	0.000	0.000	0.018	0.001	0.003	0.001
WSDF	Correlation Coefficient	-	-	-	-	-	-	-
	Sig. (2-tailed)	-	-	-	-	-	-	-
ASDF	Correlation Coefficient	-0.211	0.431	0.452	0.271	0.371	0.334	0.384
	Sig. (2-tailed)	0	0.000	0.000	0.018	0.001	0.003	0.001
VDF	Correlation Coefficient	-0.177	0.379	0.407	0.286	0.291	0.241	0.354
	Sig. (2-tailed)	0	0.001	0.000	0.012	0.011	0.036	0.002

Table 6.9 shows the correlation coefficients between the subjective sensation ratings and the quantitative assessment parameters for group SE(N). The sunlight availability for flats in this group is quite satisfactory. The values of *SSDF* and *WSDF* are both medium among the other groups. The mean values of *SSDF* and *WSDF* are 4.0% and 9.9% respectively. No significant correlations are found for the problems of glare and heat with *SSDF* values (r_s = 0.006 and -0.067 respectively). It may be explained by the fact that sunlight enters the living room in the morning. The problems could be more acceptable when sunlight comes in the morning. Besides, as the mean value of *SSDF* is not high for this group, the problem of heat due to the sunlight entering the space should not be serious. Then the subjective sensations of heat may depend mostly on personal feelings and expectations to the daylight environment. The comfort sensation (Q6) is found to be highly correlated with *SSDF* (r_s = 0.392), while the brightness sensation (Q7) is found to be strongly correlated with *WSDF*, *ASDF* and *VDF* (r_s = 0.395, 0.406 and 0.437 respectively). No significant correlations are found between the amount of daylight (Q8) and any quantitative assessment parameters. It suggests that some other critical factors,

which are missing in this study, affect the subjective human sensation to the amount of daylight available in an interior. The factors could be subjective feelings and personal expectations to the daylight environment. Similar to the brightness sensation, the overall evaluation (Q11) of the daylight environment is significantly correlated with *ASDF* and *VDF*. The correlation coefficients were calculated to be 0.325 and 0.340 respectively. In the group SE(N), the *VDF* values are very strongly correlated with the *WSDF* and *ASDF* (r_s = 0.962 and 0.973 respectively). The strong correlations between *VDF* and *WSDF* as well as between *VDF* and *ASDF* may hinder the leading factor to the brightness sensation and overall evaluation.

The sunlighting performance of group SE(S) is the best among the eight groups. The mean value of *SSDF* is very low (0.8%), while the mean value of *WSDF* is very high (15.5%). As the summer sunlight exposure is low and the winter sunlight comes in the morning, the problem of glare and heat due to the sunlight entering the space should not be serious. The correlation coefficients are tabulated in Table 6.10. No significant correlations are found between Q4 and *SSDF* as well as between Q5 and *SSDF*. The sensations to glare and heat should be determined by other subjective factors. Although no significant correlations are found between the comfort sensation (Q6) and the four quantitative assessment parameters, the brightness sensation (Q7) is found to be significantly correlated with *VDF* (r_s = 0.338). As for the sensation to the amount of daylight available in the interior (Q8), it correlates highly with *WSDF*, *ASDF* and *VDF*. Similar to group SE(N), the *VDF* values are very strongly correlated with the *WSDF* and *ASDF* (r_s = 0.924 and 0.924 respectively). A high *VDF* value is usually coupled with high values of *WSDF* and *ASDF*. The strong correlations between *VDF* and *WSDF* as well as between *VDF* and *ASDF* may hinder the leading factor to the sensation to the amount of daylight.

As the windows of the flats in this group face south-east, the occupants should have relatively higher expectations for the daylight environment. It could lead to the result that the overall evaluation (Q11) depends on subjective feelings and personal expectations to the daylight environment, but not on the quantitative assessment parameters.

Table 6.9 Correlation coefficients (r_s) between the subjective and quantitative assessment for group SE(N)

SE(N)		Q3	Q4	Q5	Q6	Q7	Q8	Q11
SSDF	Correlation Coefficient	-0.387	0.006	-0.067	0.392	0.304	0.289	0.317
	Sig. (2-tailed)	0	0.949	0.504	0.000	0.002	0.003	0.001
WSDF	Correlation Coefficient	-0.292	-0.108	-0.055	0.161	0.395	0.181	0.303
	Sig. (2-tailed)	0	0.277	0.583	0.105	0.000	0.068	0.002
ASDF	Correlation Coefficient	-0.340	-0.087	-0.071	0.222	0.406	0.206	0.325
	Sig. (2-tailed)	0	0.380	0.476	0.024	0.000	0.037	0.001
VDF	Correlation Coefficient	-0.351	-0.096	-0.090	0.222	0.437	0.243	0.340
	Sig. (2-tailed)	0	0.334	0.368	0.025	0.000	0.013	0.000

Table 6.10 Correlation coefficients (r_s) between the subjective and quantitative assessment for group SE(S)

SE(S)		Q3	Q4	Q5	Q6	Q7	Q8	Q11
SSDF	Correlation Coefficient	-0.183	0.032	0.115	0.187	0.045	0.144	0.076
	Sig. (2-tailed)	0	0.768	0.289	0.084	0.682	0.182	0.483
WSDF	Correlation Coefficient	-0.278	0.014	0.249	0.245	0.282	0.346	0.229
	Sig. (2-tailed)	0	0.898	0.020	0.022	0.008	0.001	0.033
ASDF	Correlation Coefficient	-0.295	0.010	0.233	0.248	0.286	0.348	0.220
	Sig. (2-tailed)	0	0.928	0.030	0.021	0.007	0.001	0.041
VDF	Correlation Coefficient	-0.406	0.060	0.208	0.245	0.338	0.363	0.230
	Sig. (2-tailed)	0	0.583	0.053	0.022	0.001	0.001	0.032

As the flats in group SW(N) face south-west and the external walls of the adjacent flats block part of the sky which is responsible for the winter sunlight, the mean value of *SSDF* is very high (10.9%), and the mean value of *WSDF* is medium (5.3%). With reference to the table of correlation coefficients in Table 6.11, the heat problem (Q5) is significantly correlated with *SSDF*, *ASDF* and *VDF* (r_s = 0.319, 0.346 and 0.387 respectively). The correlation analysis also shows that the brightness sensation (Q7) correlates strongly with all the four quantitative assessment parameters. The correlation coefficients between Q7 and *SSDF*, *WSDF*, *ASDF* and *VDF* were calculated to be 0.397, 0.470, 0.454 and 0.446 respectively. Similar correlation results were evaluated for the sensation to the amount of daylight (Q8). The correlation coefficients between Q8 and *SSDF*, *WSDF*, *ASDF* and *VDF* were calculated to be 0.503, 0.456, 0.529 and 0.488 respectively. The values of *WSDF* and *ASDF* are concluded to be very effective daylight assessment parameters for group SW(N). However, no significant correlation is found between the overall evaluation and the four assessment parameters.

In group SW(S), the mean value of *SSDF* is medium (4.8%), and the mean value of *WSDF* is high (12.7%). The correlation coefficients are summarized in Table 6.12. It is found that the glare problem (Q4) correlates significantly with *WSDF*, *ASDF* and *VDF* (r_s = 0.359, 0.357 and 0.344 respectively). Besides, the heat problem (Q5) also correlates highly with *SSDF*, *WSDF*, *ASDF* and *VDF* (r_s = 0.398, 0.367, 0.421 and 0.375 respectively). For the windows facing south-west, sunlight usually enters the space in the afternoon. The disturbance due to the incoming sunlight in the afternoon may be less endurable. Strong correlations are concluded between the brightness sensation (Q7) and the quantitative parameters: *WSDF*, *ASDF* and *VDF*. The correlation coefficients were calculated to be 0.405, 0.389 and 0.413 respectively.

Besides, strong correlations are also found between the sensation to the amount of daylight (Q8) and *WSDF*, *ASDF* and *VDF*. The correlation coefficients were evaluated to be 0.410, 0.349 and 0.412 respectively. High correlations are found between *VDF* and *WSDF* as well as between *VDF* and *ASDF* (r_s = 0.962 and 0.975 respectively). The strong correlations of *VDF* with *WSDF* and *ASDF* might hinder the leading factor to Q7 and Q8. No significant correlation is found between the overall evaluation and the four assessment parameters.

Table 6.11 Correlation coefficients (r_s) between the subjective and quantitative assessment for group SW(N)

SW(N)		Q3	Q4	Q5	Q6	Q7	Q8	Q11
SSDF	Correlation Coefficient	-0.080	0.235	0.319	0.230	0.397	0.503	0.179
	Sig. (2-tailed)	1	0.047	0.006	0.053	0.001	0.000	0.139
WSDF	Correlation Coefficient	-0.060	0.221	0.301	0.288	0.470	0.456	0.300
	Sig. (2-tailed)	1	0.062	0.010	0.015	0.000	0.000	0.012
ASDF	Correlation Coefficient	-0.091	0.239	0.346	0.282	0.454	0.529	0.207
	Sig. (2-tailed)	0	0.043	0.003	0.017	0.000	0.000	0.085
VDF	Correlation Coefficient	-0.028	0.266	0.387	0.273	0.446	0.488	0.216
	Sig. (2-tailed)	1	0.024	0.001	0.021	0.000	0.000	0.072

Table 6.12 Correlation coefficients (r_s) between the subjective and quantitative assessment for group SW(S)

SW(S)		Q3	Q4	Q5	Q6	Q7	Q8	Q11
SSDF	Correlation Coefficient	-0.105	0.261	0.398	-0.030	0.171	0.141	0.086
	Sig. (2-tailed)	0	0.007	0.000	0.761	0.079	0.148	0.386
WSDF	Correlation Coefficient	-0.183	0.359	0.367	0.057	0.405	0.410	0.144
	Sig. (2-tailed)	0	0.000	0.000	0.558	0.000	0.000	0.143
ASDF	Correlation Coefficient	-0.189	0.357	0.421	0.037	0.389	0.349	0.158
	Sig. (2-tailed)	0	0.000	0.000	0.707	0.000	0.000	0.106
VDF	Correlation Coefficient	-0.184	0.344	0.375	0.053	0.413	0.412	0.155
	Sig. (2-tailed)	0	0.000	0.000	0.591	0.000	0.000	0.115

Correlation analyses between the subjective questionnaire results and the quantitative assessment parameters were carried out both for the whole set of data and after the data were divided into the eight groups. The major findings are summarized as follows:

1. The glare and heat problems due to the sunlight entering the space are strongly correlated with *SSDF*, but the correlations become not significant when the sunlight comes in the morning.

2. The comfort sensation of a daylight environment is difficult to be predicted by the four selected quantitative assessment parameters. No significant correlation is found. However, for the group of flats receiving zero sunlight duration (group NW(N)), the comfort sensation is highly correlated with *VDF*. It suggests that the comfort sensation is correlated significantly with *VDF* when the sunlight availability is zero. When sunlight is present, the comfort sensation is dependent on the other subjective feelings and personal expectation to the sunlighting environment of a space.

3. In general, the brightness sensation of a daylight environment is highly correlated with *ASDF* and *VDF*. However, for groups NE(N) and NW(N) which receive little or zero sunlight, no significant correlation is found between the brightness sensation and all the four quantitative assessment parameters. The brightness sensation may depend on other subjective sensations. For the rest of the groups, brightness sensation correlates highly with *SSDF*, *WSDF*, *ASDF* and *VDF*.

4. In general, the sensation to the amount of daylight available in an interior is strongly correlated with *ASDF*. However, after the data are divided into groups, poor correlations are found between the sensation to amount of daylight and the four quantitative parameters for some groups (NE(S), NW(N) and SE(N)). For the rest of the groups, the sensation to the amount of daylight is highly correlated with *SSDF*, *WSDF*, *ASDF* or *VDF*.

5. No significant correlations are found between the overall evaluation of the daylight environment and the four quantitative assessment parameters. The advantages associated with the high sunlight availability could be offset by the problem of glare and heat. Significant correlation is found between the overall evaluation and *VDF* for some groups (NE(N), NW(S) and SE(N)). As brightness sensation, which was concluded to be the critical factor to the overall evaluation of the daylight environment, is highly correlated with *ASDF* and *VDF*, then *ASDF* together with *VDF* should generally perform satisfactorily in the assessment of the daylighting performance of a window.

6.2.3 Development of daylighting design criteria

In Q9 of the questionnaire survey, the respondents were asked whether the daylight environments in their living rooms need to be improved. In Q10, they were asked whether they agreed that the daylight environments were satisfactory. As concluded in the previous section, *VDF* and *ASDF* should be effective parameters to assess the general performance of a daylight environment. In this stage of data analysis, daylight design criteria based on *VDF* and *ASDF* were evaluated based on the questionnaire survey results of Q9 and Q10. The data were first divided into groups based on the *VDF* values. Percentage of “need no improvement” and percentage of satisfaction were calculated for each group of data according to the questionnaire results of Q9 and Q10 respectively. A mean value of *VDF* was calculated for every group. Figure 6.29 shows the graph of percentage of satisfaction versus mean value of *VDF*. Figure 6.30 shows the graph of percentage of "need no improvement" versus mean value of *VDF*. Polynomial trendlines to the second order are plotted on the two graphs using regression analysis. They display the trend of the data graphically. Using the regression equations of the trendlines, daylighting design criteria were evaluated according to different percentages of "need no improvement" and different percentages of satisfaction. The criteria are tabulated in Table 6.13 and Table 6.14.

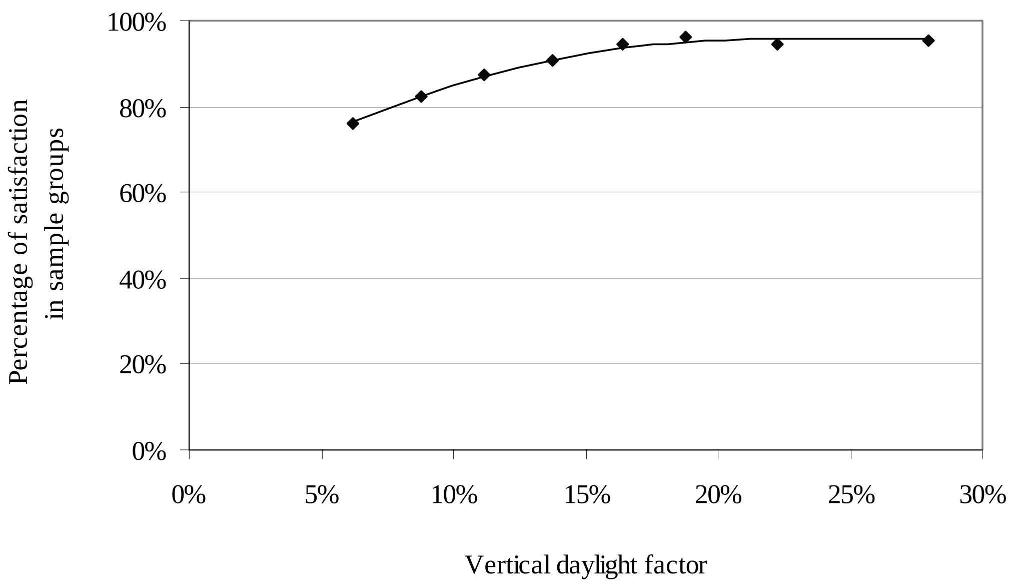


Figure 6.29 Percentage of satisfaction plotted against *VDF*

Table 6.13 *VDF* criteria based on percentage of satisfaction

Percentage of satisfaction	Daylight performance criteria (VDF)
90%	13.1%
80%	7.7%

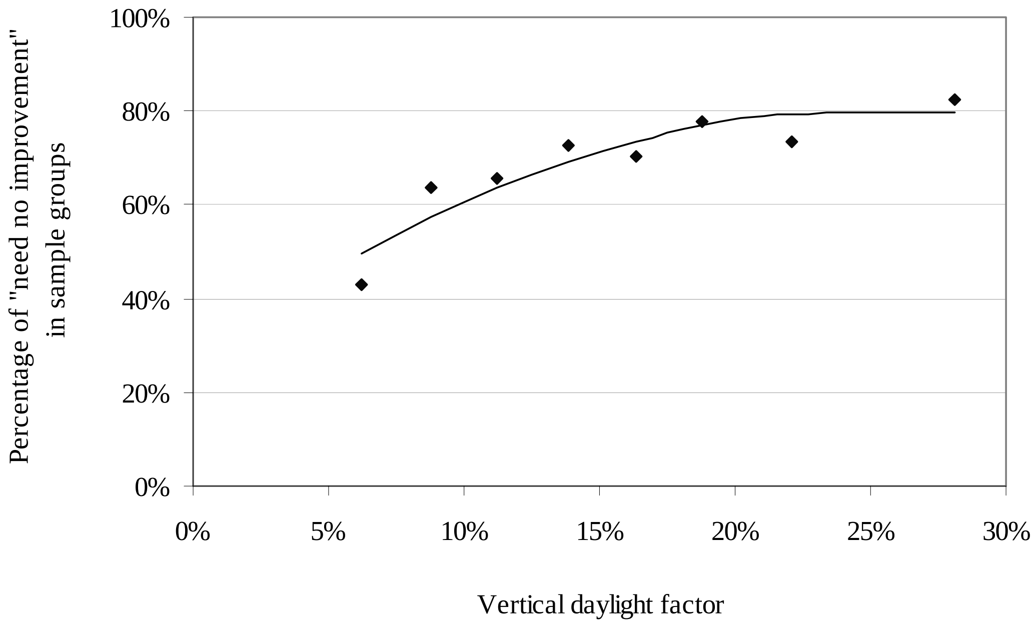


Figure 6.30 Percentage of “need no improvement” plotted against *VDF*

Table 6.14 *VDF* criteria based on percentage of “need no improvement”

Percentage of "need no improvement"	Daylight performance criteria (VDF)
80%	23.5%
70%	14.2%
60%	9.8%

For the same value of *VDF*, the percentage of “need no improvement” is lower than the percentage of satisfaction. It suggests that a satisfactory daylight environment may also need improvements. The percentage of “need no improvement” increases steadily as *VDF* increases, while the percentage of satisfaction stays at around 95% for *VDF* larger than about 16%. It means that further increase of *VDF* will not result in significant improvement of satisfaction. With reference to Table 6.13, the *VDF* criterion is equal to 7.7% when the percentage of satisfaction is 80%. A *VDF* criterion of 7.7% is in fact rather lax when its corresponding daylight factor value is compared with the criterion suggested by the standards and design guides. In chapter

5, the average daylight factor on the working plane can be expressed by the following equation:

$$\overline{DF}_{wp} = \frac{2tA_{win}VDF}{A(1-\rho^2)} \qquad (6.1)$$

For the living rooms in these two estates, window area (A_{win}) is about 3.5 m^2 and total area of interior surfaces (A) is about 71.7 m^2. The window transmittance (t) and the average reflectance of all interior surfaces (ρ) are assumed to be 0.85 and 0.5 respectively. If the *VDF* criterion is set to be 7.7%, then an average daylight factor of 0.85% is resulted. According to BS8206 (BSI, 1992), the minimum values of average daylight factor in residential buildings should be at least 1% in bedrooms, 1.5% in living rooms and 2% in kitchen. Therefore, a *VDF* of 7.7% is nearly half of the minimum requirement set up by the British Standard. For a percentage of satisfaction of 90%, the *VDF* criterion is evaluated to be 13.1%. The corresponding average daylight factor is calculated to be 1.5% which just complies with the minimum daylight factor requirement according to BS8206. As mentioned before, when *VDF* is larger than about 16%, the percentage of satisfaction remains fairly constant. A *VDF* of 16% corresponds to an average daylight factor value of 1.8% for the cases of these two estates. As for the percentage of "need no improvement", when the percentage is aimed at 80%, the *VDF* criterion is calculated to be 23.5%. Its corresponding average daylight factor value is calculated to be 2.6%. In the densely-packed building environment, only flats at higher floor can meet the *VDF* requirement of 23.5%.

Table 6.15 *ASDF* criteria based on percentage of satisfaction

Percentage of satisfaction	Daylight performance criteria (ASDF)
90%	10.8%

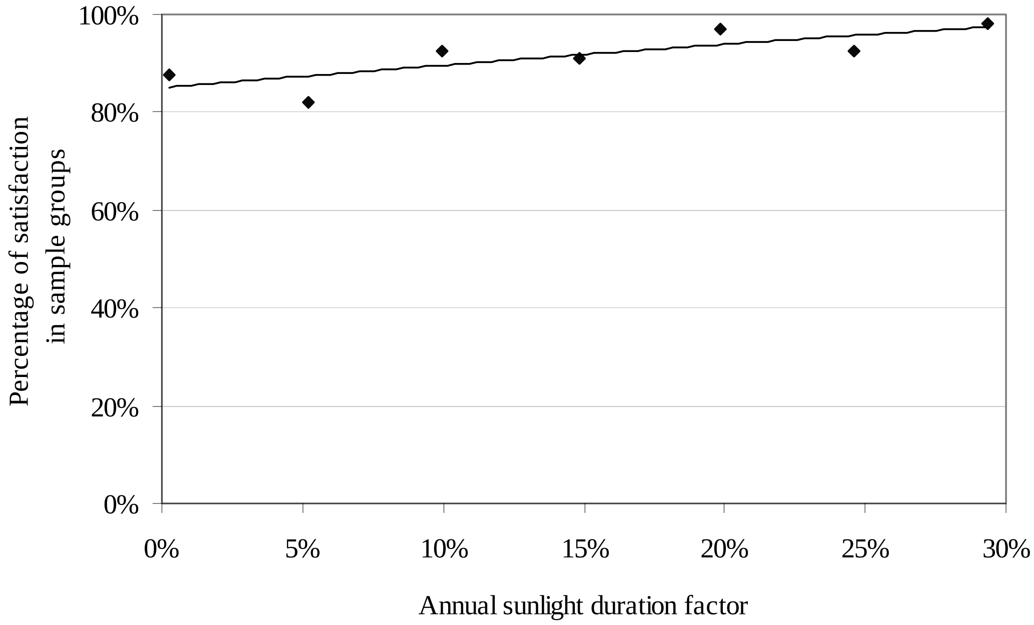


Figure 6.31 Percentage of satisfaction plotted against *ASDF*

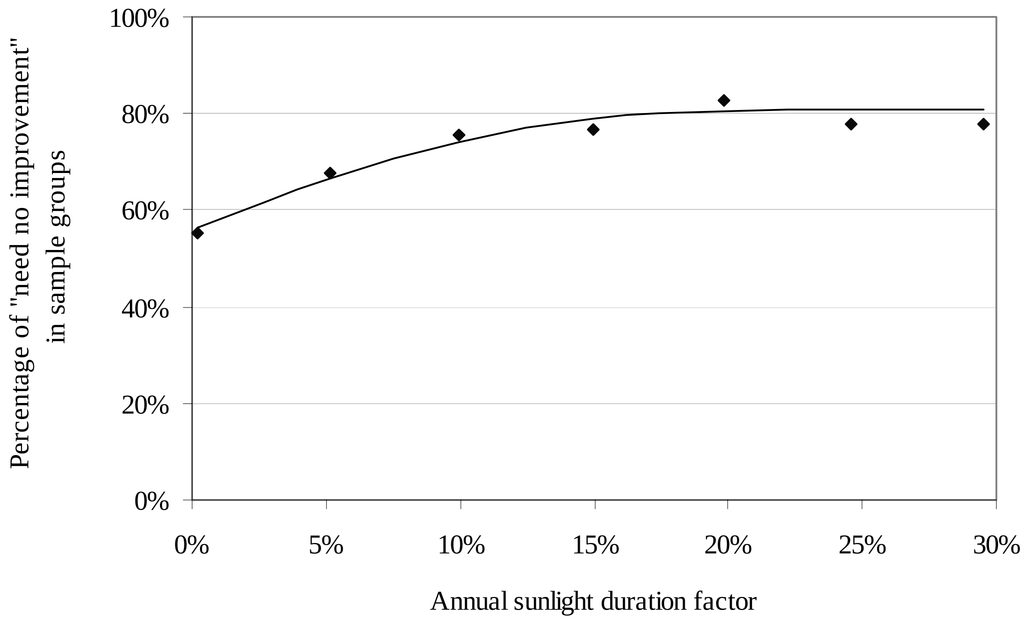


Figure 6.32 Percentage of “need no improvement” plotted against *ASDF*

Table 6.16 *ASDF* criteria based on percentage of "need no improvement"

Percentage of "need no improvement"	Daylight performance criteria (ASDF)
80%	17.0%
70%	7.2%
60%	1.9%

The daylight design criteria based on *ASDF* were also evaluated according to different degrees of occupants' satisfaction. The data were first divided into groups based on the *ASDF* values. Percentage of "need no improvement" and percentage of satisfaction were calculated for each group of data according to the questionnaire results of Q9 and Q10 respectively. A mean value of *ASDF* was calculated for every group. Figure 6.31 shows the graph of percentage of satisfaction versus mean value of *ASDF*. Figure 6.32 shows the graph of percentage of "need no improvement" versus mean value of *ASDF*. It is observed that the percentages of satisfaction for all the groups are above 80%. No *ASDF* criterion is recommended for a satisfaction level of 80%. If a satisfaction level of 90% is going to be achieved, then the value of *ASDF* should be higher than 10.8%. As for the percentage of "need no improvement", if the percentage is aimed at 80%, the *ASDF* criterion is calculated to be 17.0%. According to BS8206, the *ASDF* value of an interior in which the occupants have a reasonable expectation of direct sunlight should be at least 25% and *WSDF* should be at least 5%. If the *ASDF* criterion is increased to 25%, the percentage of satisfaction will be higher than 95% while the percentage of "need no improvement" will still stay at around 80%. It suggests that an *ASDF* criterion of 25% will increase the percentage of satisfaction, but it will not improve the percentage of "need no improvement".

6.2.4 Summary of questionnaire survey findings

A questionnaire survey had been conducted to study the occupants' attitude towards the daylighting performance of their households. Most of the occupants were satisfied with the daylight environment of their living rooms. Among the flats with low values of *VDF* and *ASDF*, there was still a portion of respondents who claimed the daylight environment to be very comfortable and even very bright. It could be explained by a possibility that they did not have a high expectation on the daylight performance of an interior in such a densely-packed housing estate. Therefore, nearly all of the respondents agreed that the daylight environment of their living rooms was satisfactory. The interpretation of the word "satisfactory" could be that the performance was already acceptable in such a compact building environment. So when the occupants were asked whether the daylight environment needed to be improved, a smaller portion of them answered positively. It suggests a possibility that they have some complaints about the daylight performance, but they accept the dissatisfaction as one of the conditions to live in a densely-packed residential estate in Hong Kong. If they could change the living environment, they would like the daylight environment to be improved.

A correlation analysis was carried out for the questionnaire survey results. It is found that a comfortable daylight environment is usually coupled with a brightly lit interior. The sensation to the amount of daylight strongly correlates with the brightness sensation. It is concluded that the comfort sensation, brightness sensation and the amount of daylight are the critical parameters determining the overall evaluation of a daylight environment, while the overall evaluation is affected most significantly by the brightness sensation. Another correlation analysis was carried out between the questionnaire results and the quantitative assessment parameters: *SSDF*, *WSDF*, *ASDF* and *VDF*. It is found that the frequency of the glare and heat problems due to the sunlight entering the space increase with the value of *SSDF*. Incoming sunlight in the morning is more acceptable. The brightness sensation of a daylight environment is highly correlated with *ASDF* and *VDF*, but the correlation is poor when the sunlight availability is very low. The sensation to the amount of daylight is generally dependent on *ASDF*. No significant correlation is found between comfort sensation and the four quantitative parameters or between overall evaluation and the parameters. The subjective sensation to comfort and overall performance of a daylight environment may depend on other subjective sensations. As brightness sensation, which is concluded to be the critical factor to the overall evaluation of the daylight environment, is highly correlated with *ASDF* and *VDF*, *ASDF* together with *VDF* should generally perform satisfactorily in the assessment of the daylighting performance of a window.

In order to set out a guideline for daylighting design, a set of daylighting design criteria was recommended. For a percentage of satisfaction equal to 80%, the *VDF* criterion is 7.7%. If the percentage of satisfaction is set to be 90%, the *VDF* criterion is 13.1% and the *ASDF* criterion is 10.8%. The percentage of satisfaction stays at around 95% for *VDF* larger than about 16%. For a percentage of “need no improvement” of 80%, the *VDF* criterion is 23.5% and the *ASDF* criterion is 17.0%.

6.3 Development of daylighting performance assessment method for residential buildings

In this section, the daylighting performance assessment methods for residential and commercial buildings are studied. The development of the assessment method for residential buildings is based on the questionnaire survey which was conducted in two housing estates in Hong Kong. The questionnaire survey had been discussed in the previous section. In the assessment method for residential buildings, daylighting requirements are recommended for daylighting performance assessment of habitable rooms. Credits are awarded when a building design satisfies the daylighting requirements. As Hong Kong is a typical dense urban region, the assessment method should be applicable to other densely packed cities.

It was concluded in chapter 3 that average daylight factor, *VDF* and sunlight duration factors are suitable assessment parameters for general evaluation of daylighting performance. In the context of a dense urban environment, the external obstruction is probably the most important factor affecting the daylight availability at a window which determines the daylighting performance of an interior. The site layout design stage is therefore considered to be the most critical process determining the potential interior daylight performance of a building development. The calculation of average daylight factor requires detailed information of the room which may be not confirmed yet at the early building design stage. As a result, it may be inconvenient to use average daylight factor as the daylighting design parameter at the site layout design stage. As for *VDF* and sunlight duration factors, they can be used to evaluate the skylight and sunlight availability at a window. *VDF* is also adopted as the performance-based assessment criteria of daylighting by the Buildings Department of the Hong Kong government. They are dependent on the external obstructing environment of the window, but not on the interior room details. From the results of the questionnaire survey discussed in the previous section, the annual sunlight duration factor (*ASDF*) and *VDF* highly correlated with the brightness sensation which was concluded to be the critical factor to the overall evaluation of a daylight environment. Therefore, *VDF* and *ASDF* are both considered to be useful and effective for daylighting performance assessment of a densely packed building development. Based on the questionnaire survey findings, a daylighting assessment method is recommended for habitable rooms in dense urban areas. The assessment method can be used for individual daylighting assessment or it can be used for the voluntary daylighting assessment scheme for the overall performance of a building in a high-rise building environment, like the HK-BEAM which had been introduced in chapter 3.

According to the findings of the questionnaire survey, for a percentage of satisfaction equal to 80%, the value of *VDF* is 7.7%. If the percentage of satisfaction is 90%, the values of *VDF* and *ASDF* are 13.1% and 10.8% respectively. The percentage of satisfaction stays at around 95% for *VDF* larger than about 16%. For a percentage of "need no improvement" equal to 80%, the values of *VDF* and *ASDF* are 23.5% and 17.0% respectively. The *VDF* requirements of the performance-based approach suggested by Buildings Department of the Hong Kong Government are 8% for habitable rooms and 4% for kitchens. With reference to the questionnaire survey results, for a satisfaction rate of 80% the value of *VDF* is 7.7% which is lower than 8%. It implies that such a low value (8%) of *VDF* of the performance-based approach is already good enough to obtain a satisfaction rate higher than 80% in the questionnaire survey. In order to promote a better than acceptable daylight environment, the assessment method should impose a set of daylighting requirements which are stricter than the building regulations. In order to quantify the daylight availability received at a window, the daylighting requirement is divided into two sections. One is the skylight provision which is assessed by the *VDF* and the other is the sunlight provision which is assessed by the *ASDF*. Credits are awarded where the window complies with requirements of skylight provision or sunlight provision. The maximum number of credits attainable for each provision is suggested to be two. Then a window which satisfies all the requirements will be awarded four credits.

For the skylight provision, one credit is awarded where the *VDF* calculated at the centre of the window is higher than 13% (which is the minimum value to achieve a 90% satisfaction level) and two credits are awarded where the *VDF* is higher than 16% (which is the minimum value to achieve a 95% satisfaction level). For the sunlight provision, one credit is awarded where the *ASDF* calculated at the centre of the window is higher than 11% (which is the minimum value to achieve a 90% satisfaction level) and two credits are awarded where the *ASDF* calculated is higher than 17% (which is minimum value to achieve a 80% of "need no improvement"). The daylighting requirements are summarized in Table 6.17. The values of *VDF* and *ASDF* can be calculated using the calculation procedures explained in chapter 5. Although sunlight is generally welcomed by the occupants, it should be excluded from critical task areas in order to control daylight glare. Besides, summer sunlight should be controlled to reduce the thermal load of the building. The author suggests that a summer sunlight control section should be incorporated in the daylight assessment scheme, in addition to the skylight and sunlight provision sections. The aim of the summer sunlight control section is to enhance the thermal comfort and reduce the energy consumption due to the solar heat gain. It is less related to the visual comfort of the daylight environment. At least one credit should be deducted from the total number of credits awarded where the summer sunlight duration factor (*SSDF*) exceed a certain value. However, the maximum value of *SSDF* is not studied in this thesis. Its value should be evaluated through a detailed study on the effect of

SSDF to the thermal impact of the window and the resultant energy consumption, which is not the main focus of this research study. Further study should be carried out in this aspect to find out the appropriate requirement of *SSDF*.

Table 6.17 Daylighting requirements for skylight and sunlight provision

Skylight provision:

Number of credits awarded	VDF
1	> 13%
2	> 16%

Sunlight provision:

Number of credits awarded	ASDF
1	> 11%
2	> 17%

The value of *ASDF* is dependent on the window orientation, while *VDF* is independent of window orientation. *VDF* quantifies the skylight availability under the CIE standard overcast sky, whose sky luminance is azimuthally uniform. *ASDF*, which quantifies the sunlight availability, is evaluated by finding the portion of visible sunpath from the point under concern. Two windows whose *VDF* values are calculated to be the same may not result in similar values of *ASDF*. Even when two windows face the same orientation and their *VDF* values are the same, their *ASDF* values can still be different. By using the calculation methods described in chapter 5, the maximum and minimum *ASDF* values received by windows of the same *VDF* value and orientation can be found. The maximum *ASDF* value is evaluated by spacing the external buildings so that the maximum *ASDF* value is found out from all possible configurations which result in the same value of *VDF*. The minimum

ASDF values are evaluated by similar procedures. Then any window, which faces the same direction, is bounded by the curves of maximum *ASDF* and minimum *ASDF* versus *VDF*.

Figure 6.33 illustrates the boundaries of maximum and minimum *ASDF* for windows facing south, north, east and west. The sky hemisphere division method is adopted for the calculation of *ASDF*. The curves will be much smoother when the angular width of the segments is smaller. The windows are assumed to have no external shading. The value of *VDF* indicates the degree of external obstruction. Small value of *VDF* indicates serious obstruction, and large value of *VDF* indicates light obstruction. For any window facing south, the calculated values of *VDF* and *ASDF* can be plotted inside the boundary for south direction. Similarly, the calculated values of *VDF* and *ASDF* for any window facing east, west and north can be plotted inside the boundary for east, west and north directions respectively. The numbers of credits awarded to windows with different values of *VDF* and *ASDF* are indicated in Figure 6.34. It is noticed that a window facing south has the highest potential to be awarded with four credits, followed by windows facing west and east. A window facing north, which is not installed with any external shading, can receive a high value of *ASDF* (about 26.5%) when its *VDF* value is higher than 5%. However, a large portion of sunlight received will be blocked if external shadings are installed, because sunlight usually shines on the north façade at high angles. It is mentioned previously that a summer sunlight control section should be incorporated to the daylight assessment scheme in order to reduce the thermal load of the building. It should be emphasized that all sunlight shinning on a window facing north is summer sunlight. Nevertheless, although windows facing east and west have high potential to satisfy the requirements of sunlight provision, at the same time their credits awarded under the sunlight provision are likely to be deducted because of the high exposure to summer sunlight.

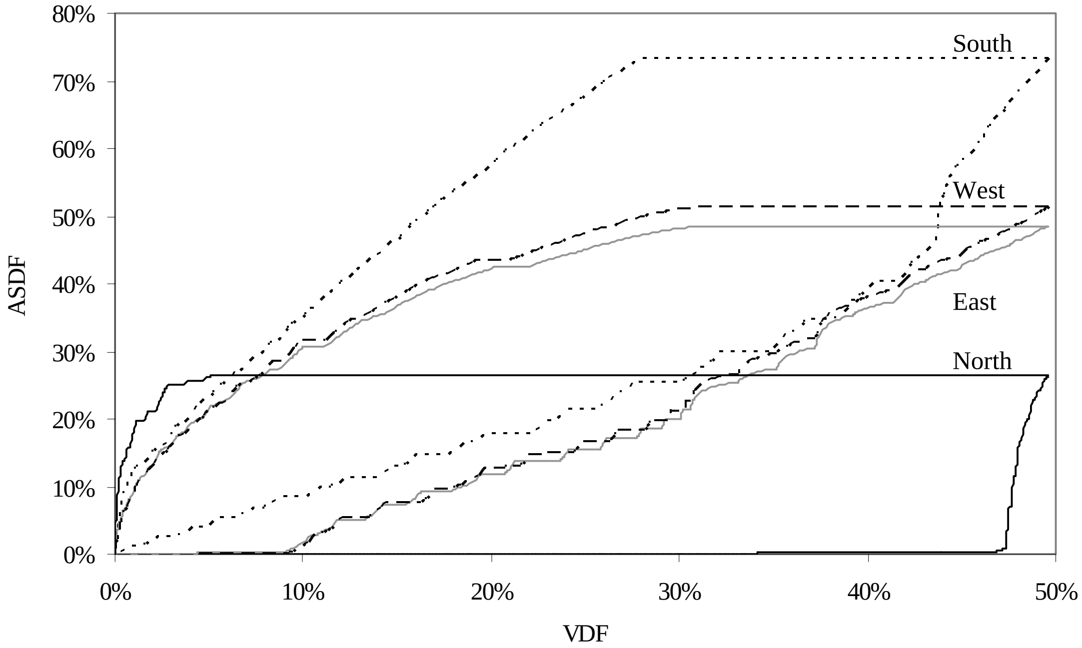


Figure 6.33 Ranges of all possible values of *VDF* and *ASDF*

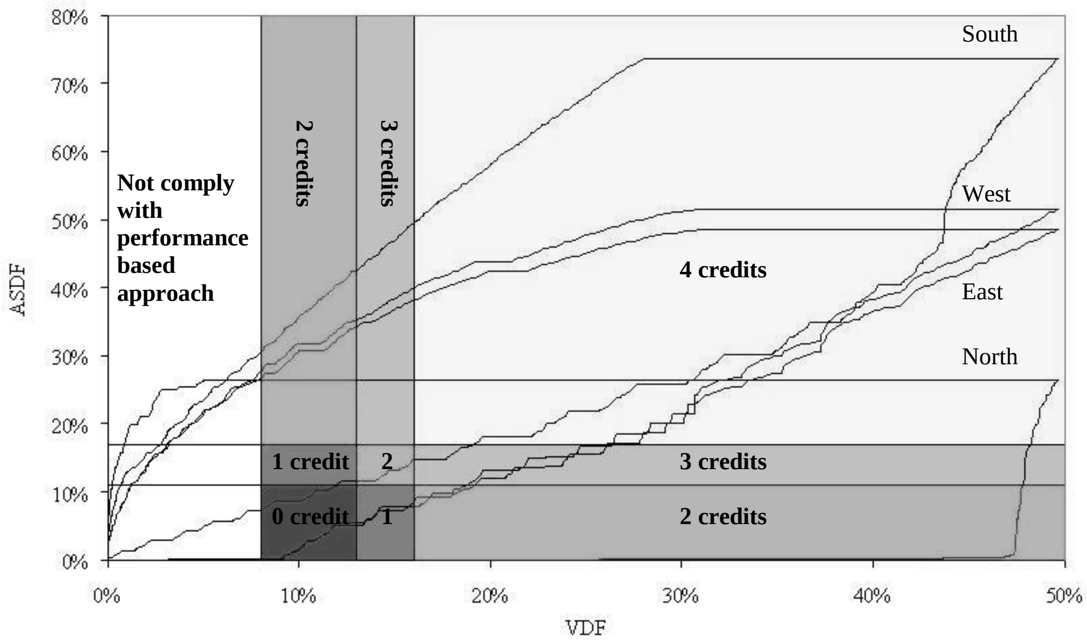


Figure 6.34 Number of credits awarded

In order for windows to achieve more credits from the skylight and sunlight provision and at the same time avoid credits being deducted due to excessive summer sunlight exposure, they should face south whenever it is possible. Windows should be installed with external shading to block the summer sunlight. The design of appropriate external shading was studied in chapter 5. Besides, the amount of summer sunlight received by a window can be reduced by careful self-shadowing. Site layout design should allow maximum amount of winter sunlight to enter the windows. It can be done by studying the sunpath diagram and the sky map of annual cumulative probable sunlight duration explained in chapter 5.

6.4 Conclusion

Based on the questionnaire survey conducted in two housing estates in Hong Kong, a set of daylighting design criteria was proposed for habitable rooms of residential buildings in a densely packed building environment. A daylighting assessment method for habitable rooms in residential buildings was also recommended. It can be used for individual daylight assessment or it can be used for the voluntary daylighting assessment scheme for the overall performance of a building in a high-rise building environment, like the HK-BEAM. The proposed daylighting requirements are divided into two sections. One is the skylight provision which is assessed by the *VDF* and the other is the sunlight provision which is assessed by the *ASDF*. For the skylight provision, one credit is awarded where the *VDF* calculated at the centre of the window is higher than 13% and two credits are awarded where the *VDF* calculated is higher than 16%. For the sunlight provision, one credit is awarded where the *ASDF* calculated at the centre of the window is higher than 11% and two credits are awarded where the *ASDF* calculated is higher than 17%. It is suggested that a summer sunlight control section should be incorporated in the daylight assessment scheme in order to control the solar heat gain. At least one credit should be deducted from the total number of credits awarded where *SSDF* exceeds a certain value.

CHAPTER 7
DEVELOPMENT OF DETAILED EVALUATION METHODS OF DAYLIGHTING PERFORMANCE

7.1 Introduction

Calculation methods of exterior vertical illuminance and annual daylight exposure due to skylight and sunlight received at a window were developed. They are recommended to be used for detailed evaluation of daylighting performance of buildings in dense urban environment. The exterior vertical illuminance calculates the daylight level at the external surface of a window under variable sky. It can be used to evaluate a set of time varying daylight illuminances for an entire year at a predetermined time step, like an hour. Then, a year's profile of exterior vertical illuminances can be evaluated for a window. The frequency of occurrence of daylight levels within specified bands can also be evaluated. By applying the concept of useful daylight illuminance (Nabil & Mardaljevic, 2005), the number of hours in a year for which the exterior vertical daylight level falls into a predefined range of "useful daylight" can be found. It provides useful information for visual comfort and energy saving analysis. Another parameter is the annual daylight exposure. It calculates the total cumulative daylight (skylight and sunlight) energy density of a window in a year term. The unit of this parameter is lm·hr/m^2. The calculation of this parameter makes use of an annual cumulative sky and an annual cumulative sun. They are used to evaluate the skylight and sunlight availability of a point. They were constructed using the TRY data of Hong Kong (Wong & Ngan, 1993). The two parameters give a realistic measure of the true daylighting performance of a window.

The calculation of exterior vertical illuminance is divided into two sections. One is the calculation of exterior vertical illuminance due to skylight and the other is the calculation of exterior vertical illuminance due to sunlight. Then the total value of vertical illuminance will be equal to the additions of these two parameters. This calculation method is applicable to any sky type of known luminance distribution. Its accuracy was tested by computer simulation using RADIANCE and measurement under real skies. In the following section, the calculation of exterior vertical illuminance due to skylight will be explained.

7.2 Calculation of exterior vertical illuminance due to skylight

The calculation of vertical daylight factor (*VDF*) in a high-rise building environment was discussed and explained in chapter 5. The *VDF* was selected to be the design and assessment parameter for general evaluation of daylighting performance. The calculation of *VDF* is based on several assumptions which are listed below:

1. The illuminance on the obstructing building (above the point of calculation) is uniform with the value same as the illuminance at the point of calculation.

2. The illuminance contribution from the obstructing building (below the point of calculation) and the ground is due to a horizontal plane whose illuminance is uniform and equal to half of the horizontal illuminance under an unobstructed sky.

3. The sky luminance distribution is the same as the CIE standard overcast sky.

The first and the second assumptions concern about the illuminances on the obstruction and the ground. The first assumption could be less valid if the window is expected to receive a higher direct skylight illuminance than the obstruction. This would happen when the obstruction height is much lower than the building at which the point of calculation situates or when this building is much larger than the obstructions so that it blocks much skylight from reaching the obstructions. Similarly, the assumptions may be less valid if the window is expected to receive a much lower direct skylight illuminance than the obstructions. Besides, in a densely packed building environment, the assumption that the illuminance of the ground plane is half of the horizontal illuminance under an unobstructed sky may overestimate the *VDF* for the lower floors of a building block. Nevertheless, *VDF* predicts only the daylight availability under the CIE standard overcast sky. For most of the cities in the sub-tropical area, like Hong Kong, overcast sky is not the major sky type in a year term. Although the assumptions mentioned above are acceptable for general evaluation of daylighting performance, when a detailed analysis is required, a more accurate yet simple method should be developed.

In this section, a calculation method of the exterior vertical illuminance due to skylight is explained. Its approach is similar to the daylight coefficient method which was developed by Tregenza and Waters(1983). It is applicable under any sky types of known sky luminance distributions. It depends on the concept that the external view of the window is divided azimuthally and altitudinally into many patches. The illuminance contribution from every patch is estimated from its luminance value and its orthographically projected area at the base of the unit hemisphere at the point of calculation. The centre of the window is treated as the reference point of calculation.

7.2.1 Vertical skylight coefficients method

The calculation of exterior vertical illuminance due to skylight is based on the daylight coefficient approach developed by Tregenza and Waters (1983). The concept of daylight coefficient depends on the idea of dividing up the sky into a large number of small elements, and analyzing separately their contributions to the internal illuminance. In this thesis, a new parameter, which is called the vertical skylight coefficient, is defined for the calculation of exterior vertical illuminance. It is similar to the daylight coefficient at a vertical external surface. The calculation procedure is independent of the sky luminance distribution. It depends on the geometry and reflectances of the external obstructions only. The vertical skylight coefficients method can calculate the vertical illuminances under a large number of skies without the need to repeat the light reflection process between the external building cavities. It saves the computation efforts of the light reflection process. Unlike daylight factor or *VDF*, vertical skylight coefficient is applicable to any sky luminance distributions. It takes into account direct light coming from the sky and reflected light from surrounding buildings both above and below the horizontal plane as well as the reflected light from the ground. The vertical skylight coefficients method should be more accurate and flexible than the vertical daylight factor approach, however with the sacrifice of simplicity. Therefore, it is recommended to be used for detailed evaluation of daylighting performance at the detailed design stage or for the estimation of electrical lighting energy saving.

The vertical skylight coefficients method depends on the concept that the sky hemisphere is divided azimuthally and altitudinally into many sky patches whose luminance values can be calculated from the equation of sky luminance distribution.

It uses a set of vertical skylight coefficients, which correspond to different sky patches, to calculate the illuminance at the reference point. The number of vertical skylight coefficients is equal to the number of sky patches divided from the sky hemisphere. The symbol $vsc^{sky(\phi,\gamma)}$ is used to represent the vertical skylight coefficient due to the sky patch $sky(\phi,\gamma)$. The quantity of $vsc^{sky(\phi,\gamma)}$ is equal to the ratio of the total vertical illuminance ($TVI_{ref}^{sky(\phi,\gamma)}$) at the reference point due to $sky(\phi,\gamma)$ to its luminance value ($L_{sky(\phi,\gamma)}$). The illuminance $TVI_{ref}^{sky(\phi,\gamma)}$ is composed of three components. The first component is the direct skylight from $sky(\phi,\gamma)$. The second component is the reflected skylight from $sky(\phi,\gamma)$ striking visible obstructions and back to the reference point. The last component is the reflected skylight from $sky(\phi,\gamma)$ striking the portion of visible ground and back to the reference point. The total skylight illuminance (including direct and reflected skylight) at the reference point is equal to the sum of all products of $vsc^{sky(\phi,\gamma)}$ and $L_{sky(\phi,\gamma)}$. In the following sub-sections, the calculation procedures of the vertical skylight coefficients will be explained step by step.

7.2.2 Sky hemisphere and external view divisions

The vertical skylight coefficients method depends on the concept that the sky hemisphere is divided azimuthally and altitudinally into many sky patches. In order to define the surrounding environment of a window, the external view of the window is treated as a vertical hemisphere and it is also divided azimuthally and altitudinally into many small patches, so that the external environment can be defined by groups of sky patches, obstruction patches and ground patches. The sky hemisphere and external view division methods were discussed in section 4.5. For a 5° division, the sky hemisphere is divided into 1,296 sky patches. The symbol $sky(\phi,\gamma)$ represents a sky patch whose centre subtends an azimuth angle ϕ from the south direction and an altitude angle γ above the horizon. The azimuth angle ϕ ranges from -177.5° to 177.5°, while the altitude angle γ ranges from 2.5° to 87.5°. As for the external hemispherical view from the window, it is also divided azimuthally and altitudinally into many small patches. The angular width and height of every patch is set to be 5°. Then the vertical hemispherical view is also divided into 1296 patches. Any point visible to the window can be defined by an azimuth angle δ and an altitude angle λ. The azimuth angle δ is measured from the normal to the window and the altitude angle λ is measured from the horizontal. Both δ and λ range from -87.5° to 87.5°. For any object visible to the reference point, a particular set of patches will be projected onto it. If the centre point of a patch (defined by the middle of altitude and azimuth ranges of the patch) is projected onto this object, then the whole patch is considered to be belonged to that object. As a result, the obstruction and ground can be described by a set of patches. The area of obstruction projected by a patch is called obstruction patch, while that on the ground is called ground patch. The patches are named by the locations of their centre point which is described by their azimuth angle δ and altitude angle λ. The symbols $obs(\delta,\lambda)$ and $gd(\delta,\lambda)$ represent obstruction patch and ground patch respectively. Figure 7.1 shows the definitions of sky patch, obstruction patch and ground patch.

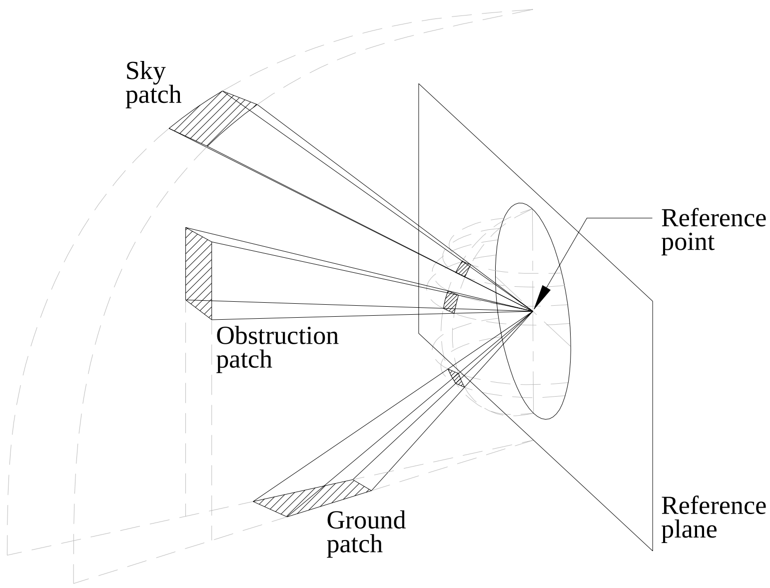


Figure 7.1 Definitions of sky, obstruction and ground patches

In order to determine whether a patch is an obstruction patch or a ground patch, the obstructing environment in every segment, which is represented by the azimuth angle δ, is studied. The altitude angles of the lower and upper limits of the external obstruction along the middle plane of every segment are found. The lower and upper limits are represented by altitude angles $\theta_L^{obs(\delta)}$ and $\theta_H^{obs(\delta)}$ respectively. They are measured from the horizontal to the lower and upper extents of the obstruction along the middle plane of that segment. The former is always negative while the latter is always positive. As a result, 36 pairs of $\theta_L^{obs(\delta)}$ and $\theta_H^{obs(\delta)}$ can be found to define the obstructing environment. They are used to determine whether a patch is an obstruction patch or ground patch according to the following rules.

1. The patch (δ, λ) is an obstruction patch if: $\theta_L^{obs(\delta)} < \lambda \le \theta_H^{obs(\delta)}$

2. The patch (δ, λ) is a ground patch if: $\lambda \le \theta_L^{obs(\delta)}$

The above procedures are used to define the obstruction and ground patches. As for the sky patch, it is defined by the sky division method which is explained previously using the angles ϕ and γ.

7.2.3 Vertical skylight coefficients

It is mentioned previously that $vsc^{sky(\phi,\gamma)}$ is evaluated by dividing $TVI_{ref}^{sky(\phi,\gamma)}$ by $L_{sky(\phi,\gamma)}$. As $TVI_{ref}^{sky(\phi,\gamma)}$ is composed of three components, $vsc^{sky(\phi,\gamma)}$ can be treated as a parameter which is composed of three components which include the direct skylight contribution from $sky(\phi,\gamma)$ and the reflected skylight contribution from visible obstruction and ground patches due to this sky patch. The components are named as: the direct skylight coefficient ($dsc^{sky(\phi,\gamma)}$), obstruction reflected coefficient ($orc^{sky(\phi,\gamma)}$) and the ground reflected coefficient ($grc^{sky(\phi,\gamma)}$).

$$vsc^{sky(\phi,\gamma)} = dsc^{sky(\phi,\gamma)} + orc^{sky(\phi,\gamma)} + grc^{sky(\phi,\gamma)} \tag{7.1}$$

The parameter $dsc^{sky(\phi,\gamma)}$ is defined as the ratio of the direct illuminance contribution due to $sky(\phi,\gamma)$ to its luminance value ($L_{sky(\phi,\gamma)}$). The obstruction reflected coefficient $orc^{sky(\phi,\gamma)}$ is defined as the reflected illuminance from all obstruction patches due to $sky(\phi,\gamma)$ divided by $L_{sky(\phi,\gamma)}$. The ground reflected coefficient $grc^{sky(\phi,\gamma)}$ is defined as the reflected illuminance from all the ground patches due to $sky(\phi,\gamma)$ divided by $L_{sky(\phi,\gamma)}$. They can be calculated as follows:

$$dsc^{sky(\phi,\gamma)} = \frac{DSI_{ref}^{sky(\phi,\gamma)}}{L_{sky(\phi,\gamma)}} \tag{7.2}$$

$$orc^{sky(\phi,\gamma)} = \frac{ORI_{ref}^{sky(\phi,\gamma)}}{L_{sky(\phi,\gamma)}} \tag{7.3}$$

$$grc^{sky(\phi,\gamma)} = \frac{GRI_{ref}^{sky(\phi,\gamma)}}{L_{sky(\phi,\gamma)}} \tag{7.4}$$

Then the total vertical daylight illuminance TVI_{ref}^{sky} at the window due to the whole sky hemisphere can be evaluated by the following expression:

$$\begin{aligned} TVI_{ref}^{sky} &= \sum_{\substack{\phi=-177.5 \\ (Step=5)}}^{177.5} \sum_{\substack{\gamma=2.5 \\ (Step=5)}}^{87.5} L_{sky(\phi,\gamma)} vsc^{sky(\phi,\gamma)} \\ &= \sum_{\substack{\phi=-177.5 \\ (Step=5)}}^{177.5} \sum_{\substack{\gamma=2.5 \\ (Step=5)}}^{87.5} L_{sky(\phi,\gamma)} \left(dsc^{sky(\phi,\gamma)} + orc^{sky(\phi,\gamma)} + grc^{sky(\phi,\gamma)} \right) \end{aligned} \tag{7.5}$$

The calculation procedures of $dsc^{sky(\phi,\gamma)}$ are simple and straightforward. If $sky(\phi,\gamma)$ is visible to the reference point, the value of $dsc^{sky(\phi,\gamma)}$ will be equal to the ratio of direct skylight illuminance due to this sky patch to its luminance value $L_{sky(\phi,\gamma)}$. In the calculation of $orc^{sky(\phi,\gamma)}$, the reflected illuminance from one obstruction patch is calculated first. Every obstruction patch is assumed to be perfectly diffusing with uniform luminance, so the luminance of an obstruction patch can be evaluated from its direct skylight illuminance. Then the reflected illuminance from an obstruction patch due to $sky(\phi,\gamma)$ can be found. The total value of $orc^{sky(\phi,\gamma)}$ is then calculated by summing up the reflected illuminance from all the obstruction patches and dividing it by $L_{sky(\phi,\gamma)}$. The value of $grc^{sky(\phi,\gamma)}$ is calculated by similar method. Then $vsc^{sky(\phi,\gamma)}$ is computed by summing up the three coefficients: $dsc^{sky(\phi,\gamma)}$, $orc^{sky(\phi,\gamma)}$

and $grc^{sky(\phi,\gamma)}$. The calculations of these three coefficients are based on the unit hemisphere method which has been introduced and explained in chapter 4.

7.2.4 Direct skylight coefficient

The direct skylight coefficient ($dsc^{sky(\phi,\gamma)}$) is defined as the ratio of the direct illuminance contribution due to a sky patch ($DSI_{ref}^{sky(\phi,\gamma)}$) to its luminance value ($L_{sky(\phi,\gamma)}$). It is expressed by the equation below:

$$dsc^{sky(\phi,\gamma)} = \frac{DSI_{ref}^{sky(\phi,\gamma)}}{L_{sky(\phi,\gamma)}} \tag{7.6}$$

According to the unit hemisphere method, if the sky patch is assumed to be perfectly diffusing with a uniform luminance, then $DSI_{ref}^{sky(\phi,\gamma)}$ is calculated by multiplying $L_{sky(\phi,\gamma)}$ and the orthographically projected area of the sky patch at the reference point ($OPAV_{ref}^{sky(\phi,\gamma)}$). The luminance of a sky patch can be represented by the luminance value at its centre and it can be calculated from equation of sky luminance distribution. Then $DSI_{ref}^{sky(\phi,\gamma)}$ can be evaluated by the following expression:

$$DSI_{ref}^{sky(\phi,\gamma)} = L_{sky(\phi,\gamma)} OPAV_{ref}^{sky(\phi,\gamma)} V_{ref}^{sky(\phi,\gamma)} \tag{7.7}$$

The parameter $V_{ref}^{sky(\phi,\gamma)}$ represents the visibility of the sky at azimuth angle ϕ and altitude angle γ to the reference point. It would be equal to 1 if $sky(\phi,\gamma)$ is visible to the reference point. On the contrary, if $sky(\phi,\gamma)$ is not visible to the reference point, $V_{ref}^{sky(\phi,\gamma)}$ would be equal to 0. In order to determine the visibility of a sky patch, we have to first find out the relative location of the sky patch to the reference point. The centre of a sky patch can be quantified by the azimuth angle δ and altitude angle λ which are also used to define the obstruction and ground patches. The angles δ, which represents the azimuthal location of the centre of a sky patch, can be evaluated by the following equations.

$$\delta = \begin{cases} \phi - \phi_{win} + 360 & \text{if } (\phi - \phi_{win}) < -180 \\ \phi - \phi_{win} & \text{if } -180 < (\phi - \phi_{\mathrm{win}}) < 180 \\ \phi - \phi_{win} - 360 & \text{if } (\phi - \phi_{\mathrm{win}}) > 180 \end{cases} \tag{7.8}$$

where ϕ_{win} is the azimuth angle of the window. It is measured from the south. It is positive when the normal of the window is measured in clockwise direction and it is negative when the normal is measured in anti-clockwise direction. The angle λ, which represents the altitudinal location of a sky patch relative to the reference point, is equal to γ. Then $sky(\phi, \gamma)$ can also be named as $sky(\delta, \lambda)$ which specifies its location relative to the reference plane. The visibility $V_{ref}^{sky(\phi,\gamma)}$ can be evaluated by the expression below.

$$V_{ref}^{sky(\phi,\gamma)} = V_{ref}^{sky(\delta,\lambda)} = \begin{cases} 1 & \text{if } \lambda > \theta_H^{obs(\delta)} \text{ and } |\delta| < 90^\circ \\ 0 & \text{otherwise} \end{cases} \tag{7.9}$$

In this way, $dsc^{sky(\phi,\gamma)}$ can be evaluated by the following expression:

$$dsc^{sky(\phi,\gamma)} = OPAV_{ref}^{sky(\phi,\gamma)} V_{ref}^{sky(\phi,\gamma)} \tag{7.10}$$

7.2.5 Obstruction reflected coefficient

The obstruction reflected coefficient $orc^{sky(\phi,\gamma)}$ is defined as the reflected illuminance from all obstruction patches due to $sky(\phi,\gamma)$ divided by $L_{sky(\phi,\gamma)}$. It is the reflected skylight from $sky(\phi,\gamma)$ striking visible obstructions and back to the reference point. It is expressed by the equation below:

$$orc^{sky(\phi,\gamma)} = \frac{ORI_{ref}^{sky(\phi,\gamma)}}{L_{sky(\phi,\gamma)}} \tag{7.11}$$

In order to calculate $ORI^{sky(\phi,\gamma)}$, the reflected illuminance from one of the obstruction patches is calculated first. As the obstruction patches are assumed to be perfectly diffusing with uniform luminance, the luminance of the obstruction patch can be evaluated from its direct skylight illuminance. Using similar method for the calculation of direct skylight illuminance at the reference point, the direct skylight illuminance at an obstruction patch $obs(\delta,\lambda)$ due to $sky(\phi,\gamma)$ is equal to:

$$DSI_{obs(\delta,\lambda)}^{sky(\phi,\gamma)} = L_{sky(\phi,\gamma)} OPAV_{obs(\delta,\lambda)}^{sky(\phi,\gamma)} V_{obs(\delta,\lambda)}^{sky(\phi,\gamma)} \tag{7.12}$$

The parameter $OPAV_{obs(\delta,\lambda)}^{sky(\phi,\gamma)}$ is the orthographically projected area of $sky(\phi,\gamma)$ on the base of the unit hemisphere at the centre point of $obs(\delta,\lambda)$. The parameter $V_{obs(\delta,\lambda)}^{sky(\phi,\gamma)}$ represents the visibility of $sky(\phi,\gamma)$ to the centre point of $obs(\delta,\lambda)$. It can be calculated by similar method for finding $V_{ref}^{sky(\phi,\gamma)}$. Then the reflected illuminance from this obstruction patch at the reference point due to $sky(\phi,\gamma)$ is expressed as:

$$ORI_{ref}^{obs(\delta,\lambda)sky(\phi,\gamma)} = \left(L_{sky(\phi,\gamma)} OPAV_{obs(\delta,\lambda)}^{sky(\phi,\gamma)} V_{obs(\delta,\lambda)}^{sky(\phi,\gamma)}\right) \frac{\rho_b OPAV_{ref}^{obs(\delta,\lambda)}}{\pi} \tag{7.13}$$

The parameter $OPAV_{ref}^{obs(\delta,\lambda)}$ is the orthographically projected area of $obs(\delta,\lambda)$ on base of the unit hemisphere at the reference point. By summing up the reflected skylight illuminance from all obstruction patches, the obstruction reflected coefficient due to $sky(\phi,\gamma)$ can be calculated by dividing the sum by $L_{sky(\phi,\gamma)}$.

$$orc^{sky(\phi,\gamma)} = \sum_{\substack{\delta=-87.5 \\ (Step=5)}}^{87.5} \sum_{\substack{\lambda=-87.5 \\ (Step=5)}}^{87.5} \frac{OPAV_{obs(\delta,\lambda)}^{sky(\phi,\gamma)} V_{obs(\delta,\lambda)}^{sky(\phi,\gamma)} \rho_b OPAV_{ref}^{obs(\delta,\lambda)} V_{ref}^{obs(\delta,\lambda)}}{\pi} \tag{7.14}$$

The parameter $V_{ref}^{obs(\delta,\lambda)}$ represents the visibility of $obs(\delta,\lambda)$ to the reference point. It can be calculated by similar method for finding $V_{ref}^{sky(\phi,\gamma)}$.

7.2.6 Ground reflected coefficient

The ground reflected coefficient $grc^{sky(\phi,\gamma)}$ is defined as the reflected illuminance from all ground patches due to the sky patch $sky(\phi,\gamma)$ divided by $L_{sky(\phi,\gamma)}$. It is the reflected skylight from $sky(\phi,\gamma)$ striking the portion of visible ground and back to the reference point. It is expressed by the equation below:

$$grc^{sky(\phi,\gamma)} = \frac{GRI_{ref}^{sky(\phi,\gamma)}}{L_{sky(\phi,\gamma)}} \tag{7.15}$$

In order to calculate $GRI^{sky(\phi,\gamma)}$, the reflected illuminance from one of the ground patches is calculated first. As the ground patches are assumed to be perfectly diffusing with uniform luminance, the luminance of the ground patch can be evaluated from its direct skylight illuminance. Using similar method for the calculation of direct skylight illuminance at the reference point, the direct skylight illuminance at a ground patch $gd(\delta,\lambda)$ due to the sky patch $sky(\phi,\gamma)$ is equal to:

$$DSI_{gd(\delta,\lambda)}^{sky(\phi,\gamma)} = L_{sky(\phi,\gamma)} OPAH_{gd(\delta,\lambda)}^{sky(\phi,\gamma)} V_{gd(\delta,\lambda)}^{sky(\phi,\gamma)} \tag{7.16}$$

The parameter $OPAH_{gd(\delta,\lambda)}^{sky(\phi,\gamma)}$ is the orthographically projected area of $sky(\phi,\gamma)$ on the base of the unit hemisphere at the centre point of $gd(\delta,\lambda)$. The parameter $V_{gd(\delta,\lambda)}^{sky(\phi,\gamma)}$ represents the visibility of $sky(\phi,\gamma)$ to the centre point of $gd(\delta,\lambda)$. It can be calculated by similar method for finding $V_{ref}^{sky(\phi,\gamma)}$. Then the reflected illuminance from this ground patch at the reference point due to $sky(\phi,\gamma)$ is expressed as:

$$GRI_{ref}^{gd(\delta,\lambda)sky(\phi,\gamma)} = \left(L_{sky(\phi,\gamma)} OPAH_{gd(\delta,\lambda)}^{sky(\phi,\gamma)} V_{gd(\delta,\lambda)}^{sky(\phi,\gamma)}\right) \frac{\rho_g OPAV_{ref}^{gd(\delta,\lambda)}}{\pi} \tag{7.17}$$

The parameter $OPAV_{ref}^{gd(\delta,\lambda)}$ is the orthographically projected area of $gd(\delta,\lambda)$ on base of the unit hemisphere at the reference point. By summing up the reflected skylight illuminance from all ground patches, the ground reflected coefficient due to the sky patch $sky(\phi,\gamma)$ can be calculated by dividing the sum by $L_{sky(\phi,\gamma)}$.

$$grc^{sky(\phi,\gamma)} = \sum_{\substack{\delta=-87.5 \\ (Step=5)}}^{87.5} \sum_{\substack{\lambda=-87.5 \\ (Step=5)}}^{87.5} \frac{OPAH_{gd(\delta,\lambda)}^{sky(\phi,\gamma)} V_{gd(\delta,\lambda)}^{sky(\phi,\gamma)} \rho_g OPAV_{ref}^{gd(\delta,\lambda)} V_{ref}^{gd(\delta,\lambda)}}{\pi} \tag{7.18}$$

The parameter $V_{ref}^{gd(\delta,\lambda)}$ represents the visibility of $gd(\delta,\lambda)$ to the reference point. It can be calculated by similar method for finding $V_{ref}^{sky(\phi,\gamma)}$.

7.2.7 Vertical illuminance

After calculating the three components of vertical skylight coefficients, the total vertical daylight illuminance TVI_{ref}^{sky} at the window due to the whole sky hemisphere can be evaluated by the following expression:

$$TVI_{ref}^{sky} = \sum_{\substack{\phi=-177.5 \\ (Step=5)}}^{177.5} \sum_{\substack{\gamma=2.5 \\ (Step=5)}}^{87.5} L_{sky(\phi,\gamma)} \left(dsc^{sky(\phi,\gamma)} + orc^{sky(\phi,\gamma)} + grc^{sky(\phi,\gamma)} \right) \qquad (7.19)$$

7.2.8 Calculation spreadsheet

The evaluation of $vsc^{sky(\phi,\gamma)}$ requires a lot of repetitious illuminance calculation. Computation effort can be saved if all the equations are input to a calculation spreadsheet, so that the results of $vsc^{sky(\phi,\gamma)}$ can be evaluated automatically. The obstructing buildings in the layout plan can be defined by coordinates system. Then the obstruction and ground patches can be identified by simple geometric equations. A calculation spreadsheet was developed for the computation of $vsc^{sky(\phi,\gamma)}$. A façade of a building on the layout plan is defined by the coordinates of its two end points and the wall azimuth angle. All facades are defined and numbered in the calculation spreadsheet. The spreadsheet starts the calculation by identifying the obstruction and ground patches of the reference point. For an azimuth angle (smaller than 90°) from the normal to the reference point, a radial line from the reference point should meet at least one obstruction wall or no obstruction. Then the altitude angles subtended to the upper and lower limits of the obstruction at this meeting point on plan are found out. If no obstruction is encountered at this azimuth angle, the two altitude angles would both equal to 0°. The patches between these two elevation angles are defined as obstruction patches, while those below the lower altitude angle are defined as ground patches. The locations of the obstruction and ground patches can be found out and represented by coordinates in the coordinates system. The locations of the sky patches can also be identified. The value of $dsc^{sky(\phi,\gamma)}$ is equal to the orthographically projected area of the sky patch if it is visible to the reference point, otherwise $dsc^{sky(\phi,\gamma)}$ is equal to 0.

As the buildings in the layout are identified in the coordinates system, the reference point of calculation can be changed to any point in the coordinate system. For example, the point of calculation can be changed to the centre point of an obstruction patch. In this way the visibility of a sky patch relative to this obstruction patch can be identified also. The direct skylight illuminance at this obstruction patch due to this sky patch is calculated, and the illuminance contribution due to the reflected light from this obstruction patch can also be calculated. Then $orc^{sky(\phi,\gamma)}$ is evaluated by summing up the reflected light contributions from all the obstruction patches due to this sky patch and dividing the sum by the luminance of this sky patch. Similarly, the visibility of a sky patch to a ground patch can be evaluated by changing the point of calculation to the horizontal centre point of the ground patch. The direct skylight illuminance at the ground patch and its reflected illuminance contribution to the reference point are calculated. The value of $grc^{sky(\phi,\gamma)}$ can be evaluated by summing up the reflected illuminances from all the ground patches due to this sky patch and dividing the sum by the luminance of this sky patch. The value of $vsc^{sky(\phi,\gamma)}$ is equal to the sum of $dsc^{sky(\phi,\gamma)}$, $orc^{sky(\phi,\gamma)}$ and $grc^{sky(\phi,\gamma)}$. The vertical skylight coefficients due to all the sky patches in the sky hemisphere can be computed by the same procedures. A flow chart showing the general procedures of the calculation spreadsheet is shown in Figure 7.2. For the detailed computation logic of the spreadsheet, please refer to the flow chart diagrams in Appendix F1.

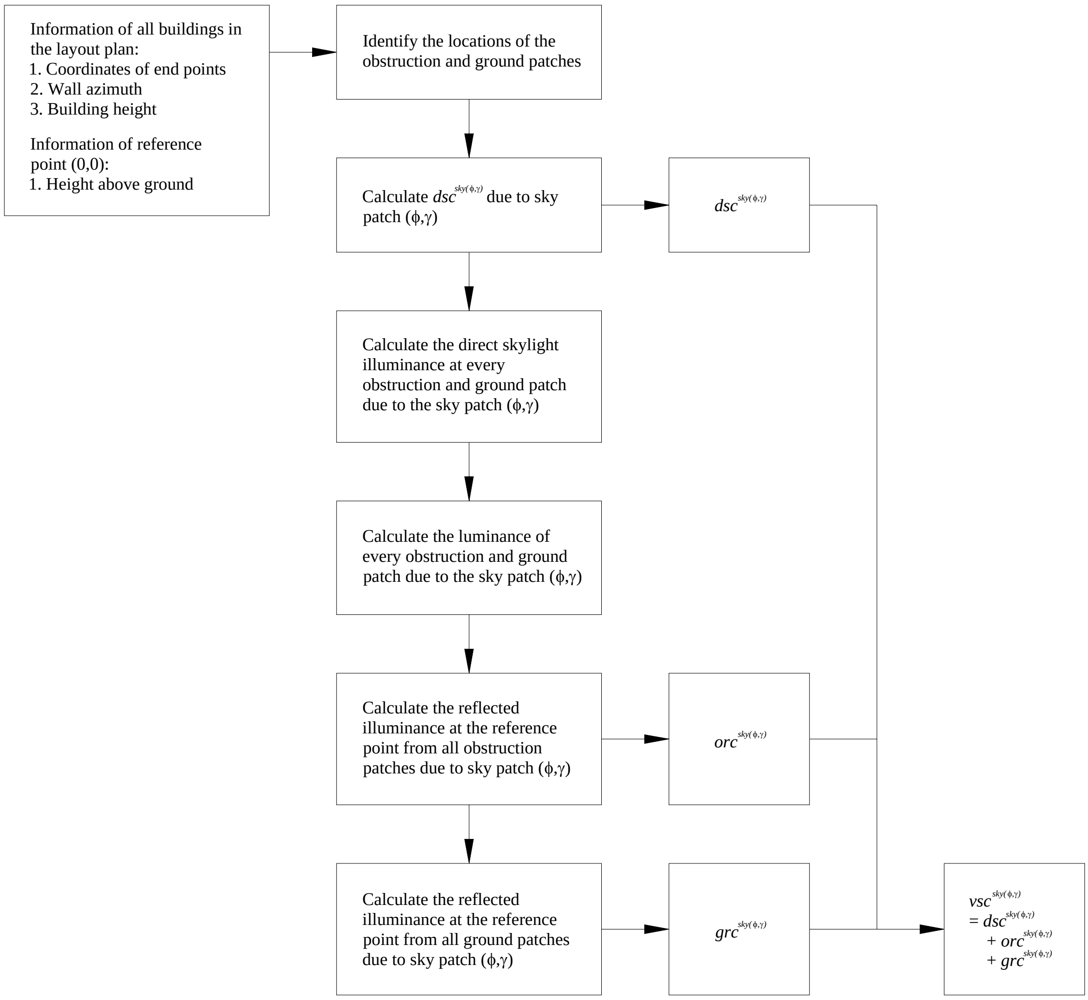


Figure 7.2 General procedures of the calculation spreadsheet

For an angular width of 5°, the sky hemisphere is divided into 1,296 sky divisions. The total illuminance contribution at the reference point due to one sky patch is represented by one vertical skylight coefficient. For 1,296 sky patches, there should be 1,296 vertical skylight coefficients. With the aid of the calculation spreadsheet, the 1,296 vertical skylight coefficients for a vertical point in a building layout can be evaluated in minutes. For a point on a vertical wall without any obstruction, its illuminance value is highly dependent on the luminance of the sky patches in front of the wall. The set of vertical skylight coefficients for a point on a vertical wall facing an unobstructed sky is illustrated graphically in Figure 7.3. The azimuth angles of the sky patches in front of the wall range from -90° to 90°, while the altitude angles range from 0° to 90°. It is observed that the sky patches near the horizon and in front of the wall have the highest values of $vsc^{sky(\phi,\gamma)}$. The values decrease as the locations of the sky patches are moving away from the point directly opposite to the vertical point on the wall. As there is no external obstruction, $vsc^{sky(\phi,\gamma)}$ is a sum of $dsc^{sky(\phi,\gamma)}$ and $grc^{sky(\phi,\gamma)}$ only. The reflectance of the ground is assumed to be 0.2 in this example. Due to the low ground reflectance, $dsc^{sky(\phi,\gamma)}$ dominates the quantity of $vsc^{sky(\phi,\gamma)}$. It results in the high values and low values of $vsc^{sky(\phi,\gamma)}$ for the sky patches in front of and behind the wall respectively. It also explains that the maximum values of $vsc^{sky(\phi,\gamma)}$ occur in the sky patches near the horizon and in front of the wall because of their high orthographically projected areas resulting in high values of $dsc^{sky(\phi,\gamma)}$.

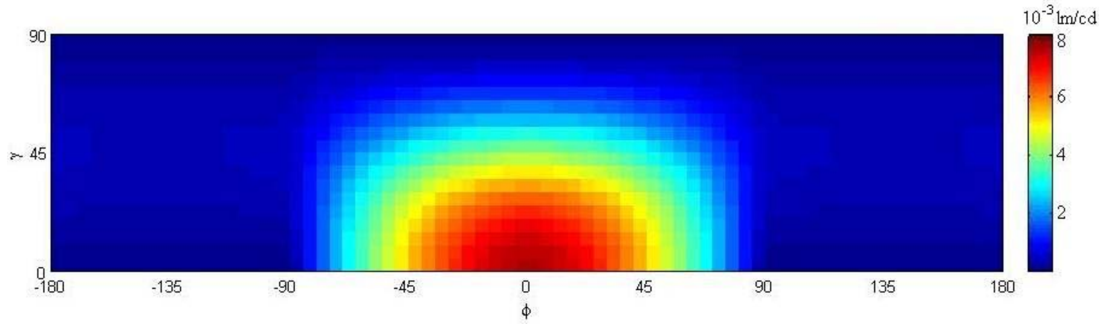
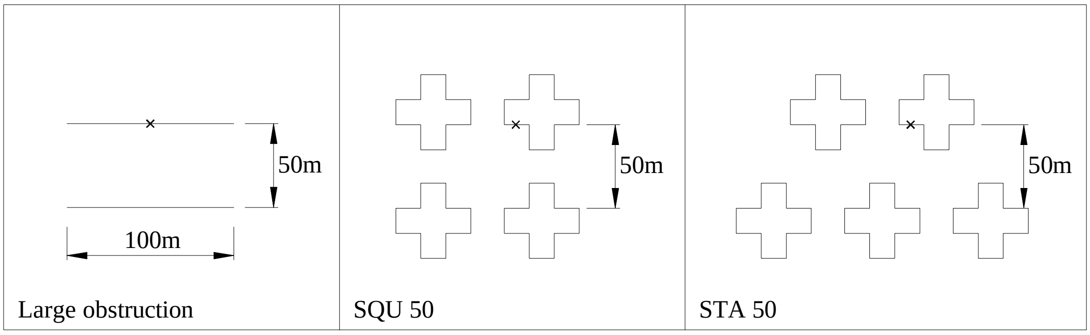


Figure 7.3 Vertical skylight coefficients for a vertical point without external obstruction



Notes:
1. " × " represents the point of calculation.
2. The height of building is equal to 100m. The point of calculation is 50m above the ground.

Figure 7.4 Site layouts for the examples of vertical skylight coefficients

Three site layouts as shown in Figure 7.4 were studied to demonstrate the results of vertical skylight coefficients. The results for the reference points (marked with a cross) in the three site layouts are evaluated as examples. For a vertical wall with large obstruction of reflectance value equal to 0.2, the vertical skylight coefficients are illustrated graphically in Figure 7.5. The sky patches being blocked by the obstruction and the sky patches behind the wall have low values of $vsc^{sky(\phi,\gamma)}$. It is because of the low reflectance values of the ground and the obstruction. Figure 7.6 shows another graph of $vsc^{sky(\phi,\gamma)}$ for the same building layout. In this case, the obstruction reflectance and the ground reflectance are both increased to 0.7. It is observed that the sky patches behind the reference wall have much higher values of $vsc^{sky(\phi,\gamma)}$ than the previous case. For the sky patch which is invisible to the reference point, the value of $vsc^{sky(\phi,\gamma)}$ is equal to the sum of $orc^{sky(\phi,\gamma)}$ and $grc^{sky(\phi,\gamma)}$ only. As the reflectances of the obstruction and ground increase, the values of obstruction and ground reflected components ($orc^{sky(\phi,\gamma)}$ and $grc^{sky(\phi,\gamma)}$) increase, therefore $vsc^{sky(\phi,\gamma)}$ also increase significantly. Figure 7.7 to Figure 7.10 illustrate graphically the vertical skylight coefficient results for the two other building layouts as shown in Figure 7.4.

The values of vertical skylight coefficients are evaluated for obstruction and ground reflectance equal to both 0.2 and 0.7. It is observed that the values of $vsc^{sky(\phi,\gamma)}$ of the sky patches behind the reference wall will also increase with the obstruction and ground reflectances. The numerical values of $vsc^{sky(\phi,\gamma)}$ for all examples are shown in Appendix F2. With the set of vertical skylight coefficients calculated for a reference point, the total vertical illuminance at this point under a certain sky condition can be calculated by summing up the products of $vsc^{sky(\phi,\gamma)}$ and $L_{sky(\phi,\gamma)}$ for all the sky patches.

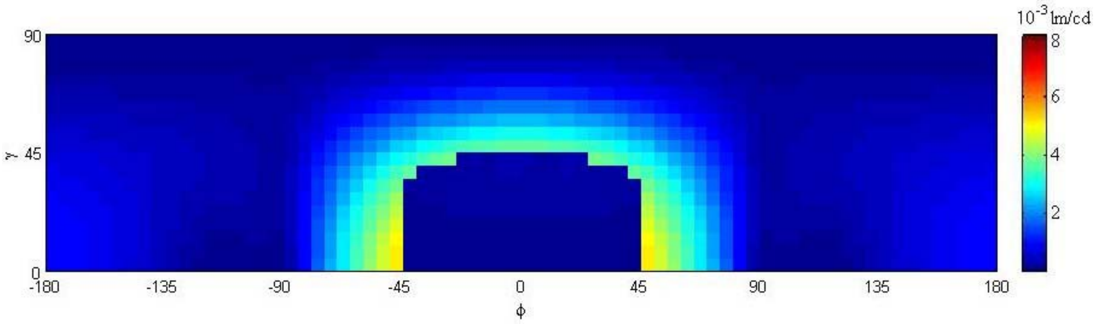


Figure 7.5 Vertical skylight coefficients for a vertical point with large obstruction ($\rho_b = \rho_g = 0.2$)

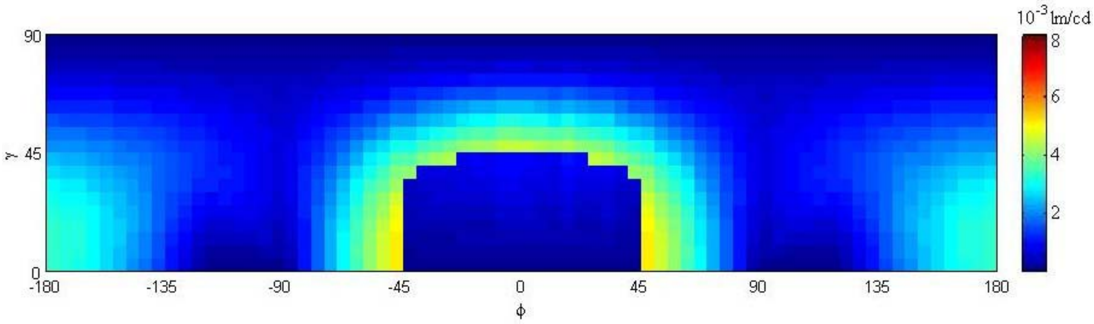


Figure 7.6 Vertical skylight coefficients for a vertical point with large obstruction ($\rho_b = \rho_g = 0.7$)

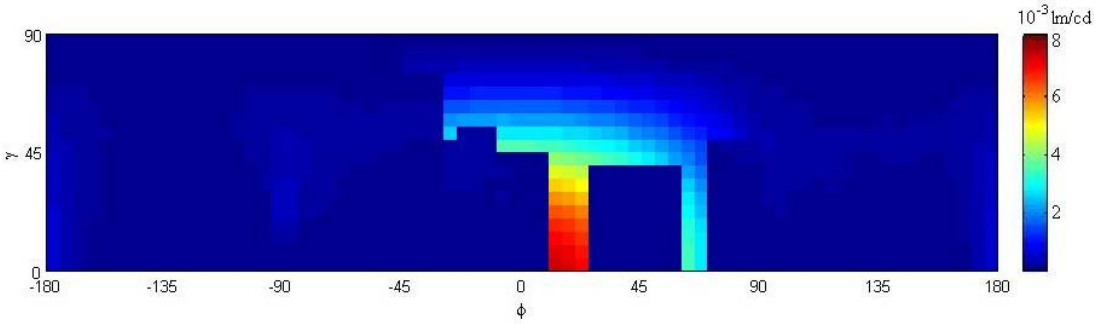


Figure 7.7 Vertical skylight coefficients for SQU50 ($\rho_b = \rho_g = 0.2$)

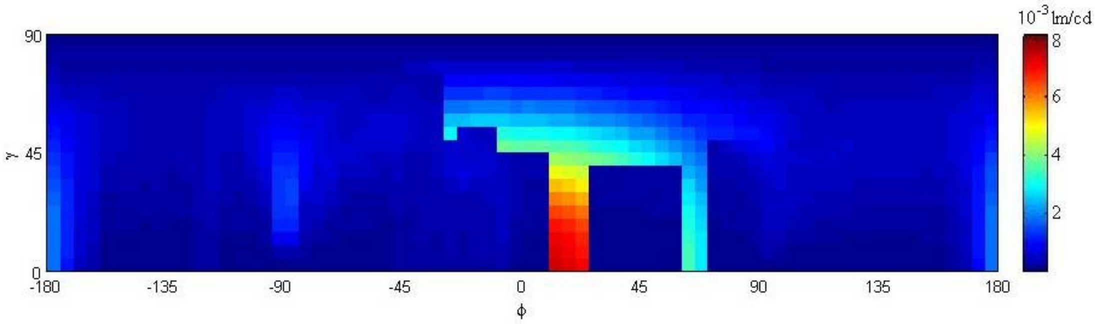


Figure 7.8 Vertical skylight coefficients for SQU50 ($\rho_b = \rho_g = 0.7$)

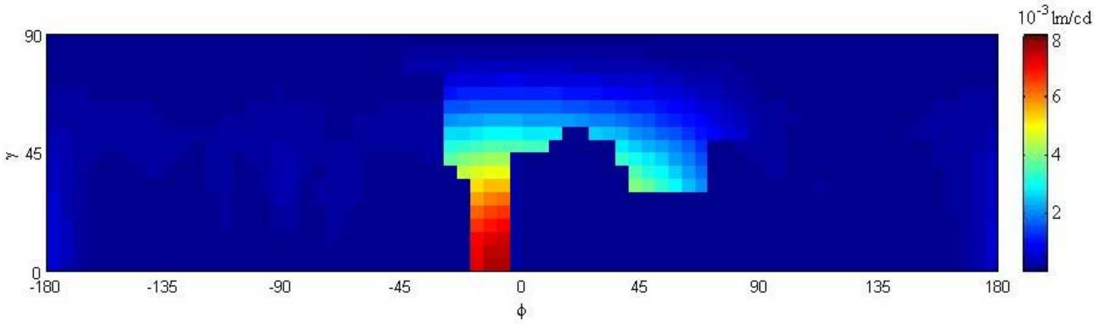


Figure 7.9 Vertical skylight coefficients for STA50 ($\rho_b = \rho_g = 0.2$)

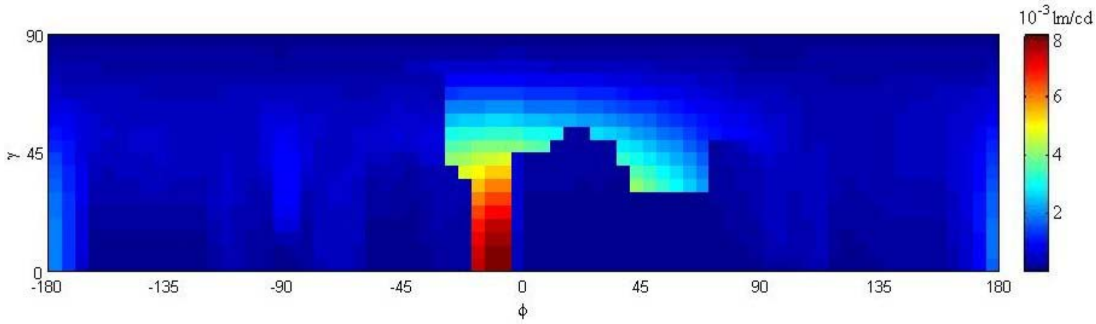


Figure 7.10 Vertical skylight coefficients for STA50 ($\rho_b = \rho_g = 0.7$)

7.3 Calculation of exterior vertical illuminance due to sunlight

The total vertical illuminance due to sunlight (TVI_{ref}^{sun}) is composed of the direct sunlight illuminance DSI_{ref}^{sun}, the obstruction reflected sunlight illuminance ORI_{ref}^{sun} and ground reflected sunlight illuminance GRI_{ref}^{sun}. The direct sunlight illuminance at a point is dependent on the solar normal illuminance, which is equal to $\frac{(E_g - E_d)}{\sin \gamma_s}$, and the angle of incidence of sunlight to the plane at which this point is located. The direct sunlight illuminance will be equal to 0 if the sun is invisible to this point. The visibility of sunlight at the reference point is represented by the parameter V_{ref}^{sun}. Then, the direct sunlight illuminance at the reference point can be calculated by the following equation:

$$DSI_{ref}^{sun} = \frac{(E_g - E_d)\cos \phi_{ref}^{sun} V_{ref}^{sun}}{\tan \gamma_s} \tag{7.20}$$

The symbol ϕ_{ref}^{sun} represents the solar azimuth angle relative to the reference point. It is measured from the normal to the reference plane. It is negative when the solar azimuth is measured in anti-clockwise direction and positive when it is measured in clockwise direction. The direct sunlight illuminances of all the obstruction and ground patches can be calculated by similar method. The direct sunlight illuminance ($DSI^{sun}_{obs(\delta,\lambda)}$) at the obstruction patch $obs(\delta,\lambda)$ can be calculated by the following equation:

$$DSI^{sun}_{obs(\delta,\lambda)} = \frac{(E_g - E_d)\cos\phi^{sun}_{obs(\delta,\lambda)} V^{sun}_{obs(\delta,\lambda)}}{\tan\gamma_s} \tag{7.21}$$

The symbol $\phi^{sun}_{obs(\delta,\lambda)}$ represents the solar azimuth angle to the obstruction plane. It is measured from the normal to the obstruction plane. It is negative when the solar azimuth is measured in anti-clockwise direction and positive when it is measured in clockwise direction. The parameter $V^{sun}_{obs(\delta,\lambda)}$ denotes the visibility of the sun to the obstruction patch. Then the luminance value of $obs(\delta,\lambda)$ can be calculated from its reflectances. The obstruction reflected sunlight illuminance from $obs(\delta,\lambda)$ can be calculated from its luminance values and the orthographically projected areas of the obstruction patch to the reference point ($OPAV^{obs(\delta,\lambda)}_{ref}$). As a result, the obstruction reflected sunlight illuminance at the reference point due to all obstruction patches (ORI^{sun}_{ref}) is calculated to be:

$$ORI^{sun}_{ref} = \sum_{\substack{\delta=-87.5 \\ (Step=5)}}^{87.5} \sum_{\substack{\lambda=-87.5 \\ (Step=5)}}^{87.5} \left\{ \left[\frac{(E_g - E_d)\cos\phi^{sun}_{obs(\delta,\lambda)} V^{sun}_{obs(\delta,\lambda)}}{\tan\gamma_s} \right] \frac{\rho_b OPAV^{obs(\delta,\lambda)}_{ref} V^{obs(\delta,\lambda)}_{ref}}{\pi} \right\} \tag{7.22}$$

As for the direct sunlight illuminance at the ground patch $gd(\delta,\lambda)$ ($DSI^{sun}_{gd(\delta,\lambda)}$), it is found by the following equation:

$$DSI_{gd(\delta,\lambda)}^{sun} = \left(E_g - E_d\right)V_{gd(\delta,\lambda)}^{sun} \tag{7.23}$$

The parameter $V_{gd(\delta,\lambda)}^{sun}$ denotes the visibility of the sun to the ground patch. The luminance value of $gd(\delta,\lambda)$ can be calculated from its reflectances. The ground reflected sunlight illuminance from $gd(\delta,\lambda)$ can be calculated from its luminance values and the orthographically projected areas of the ground patch to the reference point ($OPAV_{ref}^{gd(\delta,\lambda)}$). Then, the ground reflected sunlight illuminance at the reference point due to all ground patches (GRI_{ref}^{sun}) is evaluated by the following expression:

$$GRI_{ref}^{sun} = \sum_{\substack{\delta=-87.5 \\ (Step=5)}}^{87.5} \sum_{\substack{\lambda=-87.5 \\ (Step=5)}}^{87.5} \left\{ \left[\left(E_g - E_d\right)V_{gd(\delta,\lambda)}^{sun}\right] \frac{\rho_g OPAV_{ref}^{gd(\delta,\lambda)} V_{ref}^{gd(\delta,\lambda)}}{\pi} \right\} \tag{7.24}$$

Finally, the total vertical illuminance due to the direct and reflected sunlight to the reference point (TVI_{ref}^{sun}) is evaluated by adding up the three components.

$$TVI_{ref}^{sun} = DSI_{ref}^{sun} + ORI_{ref}^{sun} + GRI_{ref}^{sun} \tag{7.25}$$

The calculation procedures of TVI_{ref}^{sun} can also be input to the calculation spreadsheet which was developed for the evaluation of the vertical skylight coefficients $vdc^{sky(\phi,\gamma)}$. So that the total vertical illuminances due to skylight (TVI_{ref}^{sky}) and sunlight (TVI_{ref}^{sun}) can be calculated automatically by the calculation spreadsheet.

7.4 Comparison of calculation and RADIANCE simulation results

Case studies comparing the calculation results by the vertical skylight coefficients method and the simulation results by RADIANCE are presented in this section. The vertical skylight coefficients method is used to calculate the vertical skylight illuminance under a sky of known luminance distribution. It can also be used to evaluate *VDF* by dividing the vertical illuminance by the instantaneous horizontal illuminance under the unobstructed sky.

$$VDF = \frac{TVI_{ref}^{sky}}{E_d} \tag{7.26}$$

The values of *VDF* were calculated under the CIE standard overcast sky by the vertical skylight coefficients method. The *VDF* results were also simulated by RADIANCE for comparison. Simulation results with RADIANCE have been physically validated for a range of building geometries (Mardaljevic,1995).

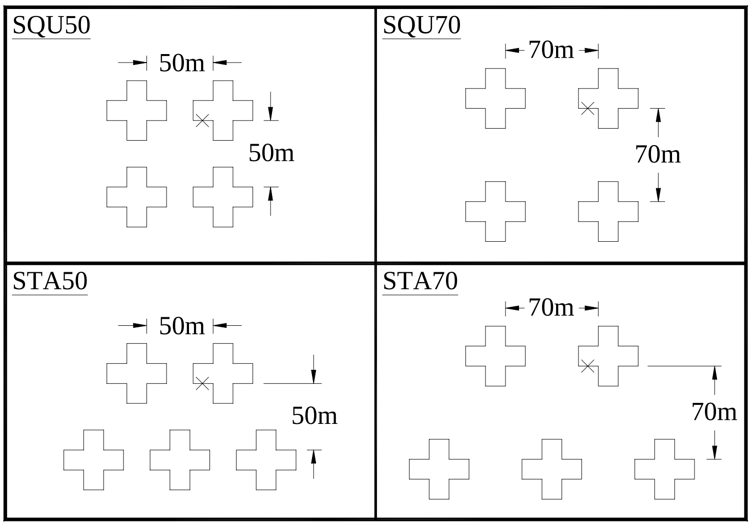


Figure 7.11 Site layouts for *VDF* calculation

For the purpose of comparison, four building estate layouts (two square layouts with four cross-shaped blocks and two staggered layouts with five cross-shaped blocks) were studied for the *VDF* calculation comparison. The four building layouts are shown in Figure 7.11. These configurations are selected to demonstrate a densely-packed building environment. All the building blocks are 100 m high. The reflectances of obstruction and ground surfaces are both 0.2. Reference point positions used for *VDF* calculation are indicated by crosses. Heights of the reference point above ground vary between 10 m and 90 m.

The vertical skylight coefficients for the reference points were first calculated. The luminance value of every sky patch was found. The total vertical illuminance could be calculated by summing up all the products of vertical skylight coefficient and the luminance of the corresponding sky patch. Then the value of *VDF* could be evaluated by dividing the sum by the horizontal illuminance under the unobstructed sky (E_d) which can be calculated by the expression below.

$$E_d = \sum_{\substack{\phi=-177.5 \\ (Step=5)}}^{177.5} \sum_{\substack{\gamma=2.5 \\ (Step=5)}}^{87.5} L_{sky(\phi,\gamma)} OPAH^{sky(\phi,\gamma)} \qquad (7.27)$$

For the CIE standard overcast sky, E_d can also be calculated directly by the expression: $\frac{7}{9}\pi L_Z$. The *VDF* results, which were calculated by the vertical skylight coefficients method, were compared with results simulated by RADIANCE, covering the four layouts and, for each layout, 9 positions of reference point at different heights above ground. The numerical results of *VDF* by both methods are shown in Appendix F3. The regression statistics are given in Figure 7.12, which also shows the best-fit line of the correlation of results between this method and RADIANCE. The root mean square error (RMSE), which was based on departures of the calculated *VDF* values from the RADIANCE simulation, was calculated to be 3.9%. The agreement is good between the calculation results by vertical skylight coefficients method and the simulation results by RADIANCE simulation. It shows that the presented method calculates the *VDF* to a satisfactory degree of accuracy.

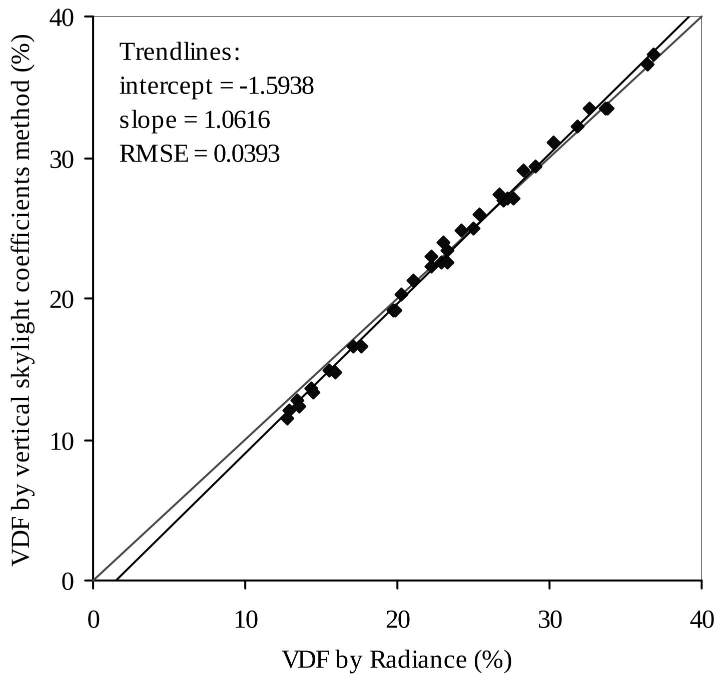


Figure 7.12 Comparison of *VDF* results

7.5 Comparison of calculation and measurement results

The calculation methods of exterior vertical illuminances due to skylight and sunlight (TVI_{ref}^{sky} and TVI_{ref}^{sun}) were described in sections 7.2 and 7.3. The total daylight illuminance at a window under variable sky can be found by adding up these two values together. In order to test the validity of the calculation methods, a simple model was constructed and measurements were carried out under real skies.

The site location was the roof of a primary school which was generally free from effective obstruction. The experiment model consisted of two vertical planes of 0.5 m high and 0.5 m wide facing each other. One should act as the obstruction plane of another. The two vertical planes were perpendicular to a horizontal ground plane between them. The ground plane was of 0.5 m wide and 0.5 m long. The reflectance of the vertical planes was measured to be 0.71 while that of the ground plane was measured to be 0.14. The rest of the ground was assumed to have a reflectance value of 0.2. The vertical surfaces of the experimental model were aligned with the north-south line, so that the two vertical planes faced east and west. The measurement was conducted on seven days which included clear, partly cloudy and overcast skies. The simultaneous global and diffuse horizontal illuminances, total vertical illuminances at the centres of the two vertical planes, as well as sky zenith luminance were recorded. The two centre points of the vertical planes were treated as the reference points. Measured illuminance values were compared with the illuminance values ($TVI_{ref}^{sky} + TVI_{ref}^{sun}$) calculated by the methods described in sections 7.2 and 7.3. The methodology of the measurement was discussed in section 4.8.

7.5.1 Measurement of total vertical illuminance under real skies

During the measurement under real skies, simultaneous global and diffuse horizontal illuminances, total vertical illuminances at the reference points, as well as sky zenith luminance were recorded. The sky types at the time of measurement included clear, partly cloudy and overcast sky. The global horizontal illuminance ranged from about 2 klx on the overcast day to as high as 150 klx at noon on clear day. The measured global and diffuse horizontal illuminances are plotted in Figure 7.13 and Figure 7.14. The vertical illuminances were measured at the reference points facing east and west.

For clear days, the vertical illuminance at the plane facing east peaked in the morning while that at the plane facing west peaked in the afternoon. The measured vertical illuminance spread in the range between around 1 klx and 85 klx. The measured vertical illuminances at reference points facing east and west are shown in Figure 7.15 and Figure 7.16 respectively.

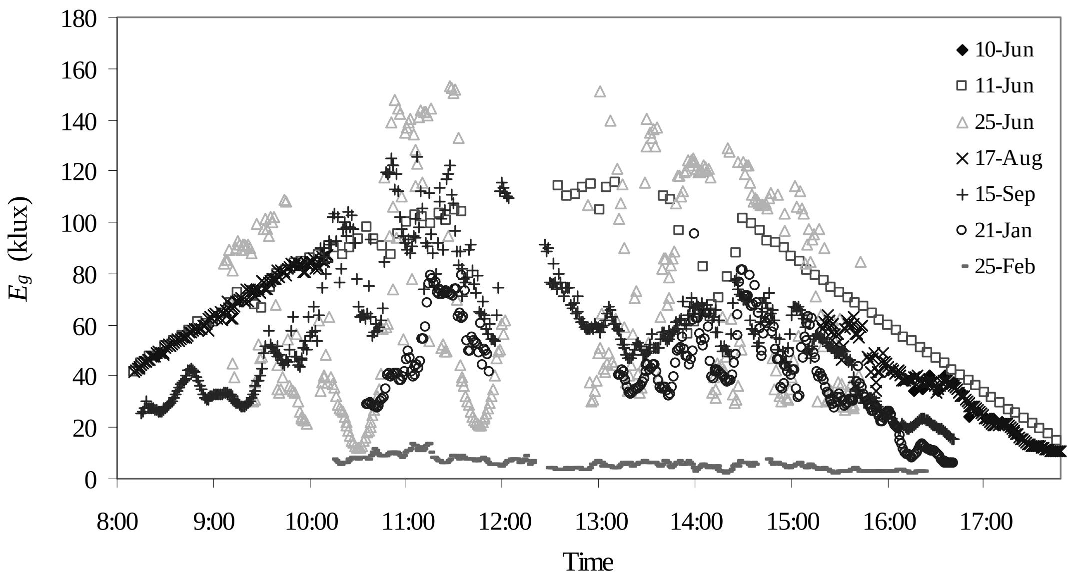


Figure 7.13 Measured global horizontal illuminances for various days of measurement

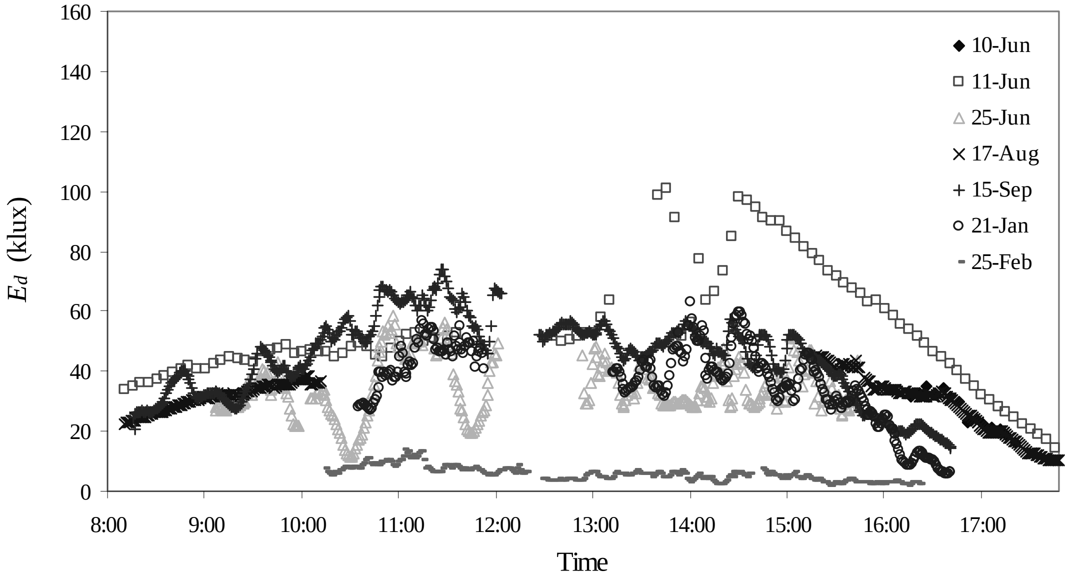


Figure 7.14 Measured diffuse horizontal illuminances for various days of measurement

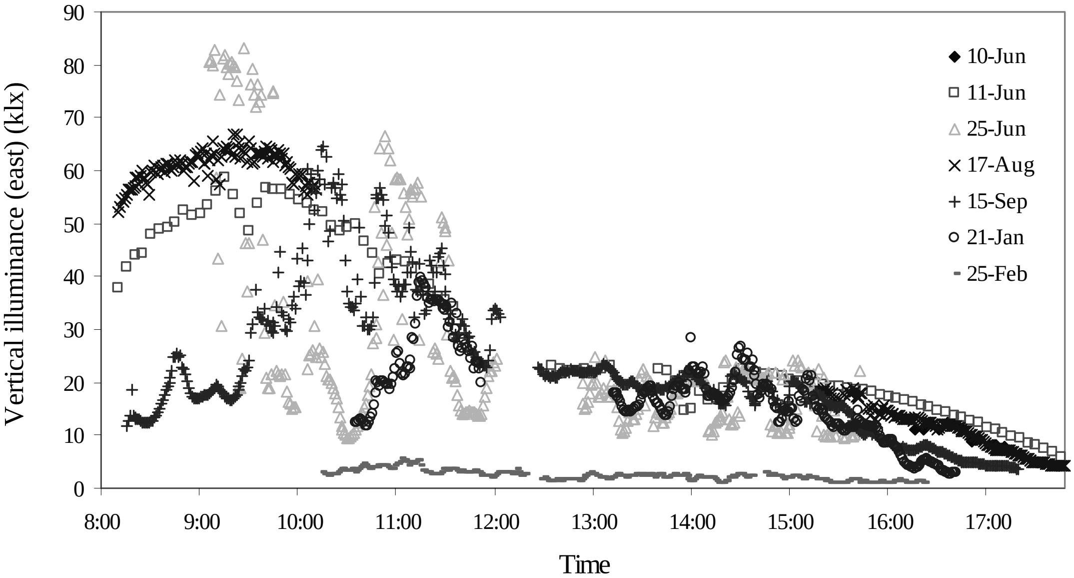


Figure 7.15 Measured vertical illuminances at reference point facing east for various days of measurement

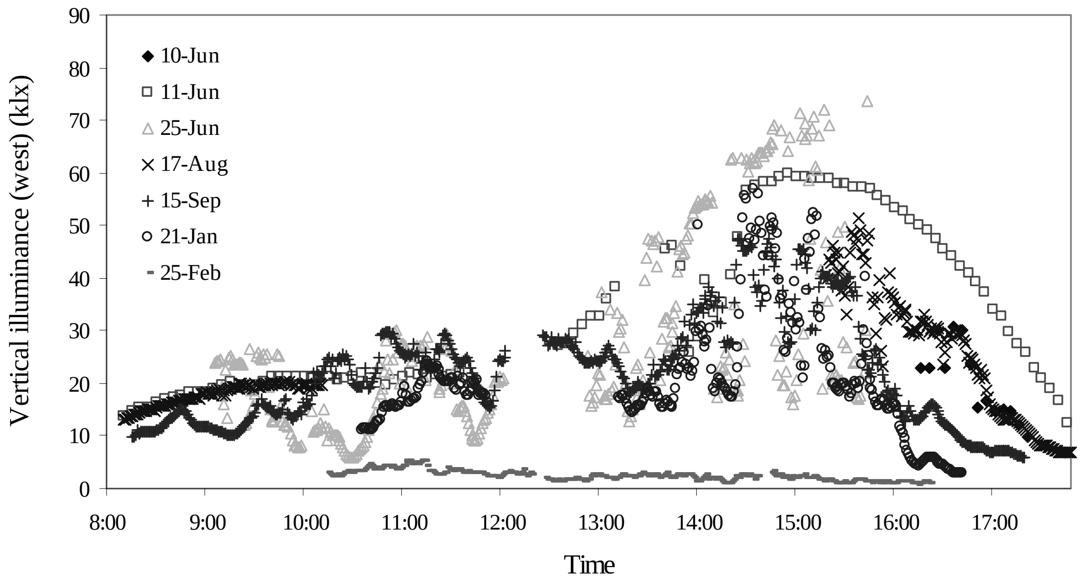


Figure 7.16 Measured vertical illuminances at reference point facing west for various days of measurement

7.5.2 Calculation of total vertical illuminance

The measurement result was compared with the calculation result ($TVI_{ref}^{sky} + TVI_{ref}^{sun}$) computed by the methods described in sections 7.2 and 7.3. The value of TVI_{ref}^{sky} was calculated using the vertical skylight coefficients method, which was explained in section 7.2, and the value of TVI_{ref}^{sun} was calculated using the method described in section 7.3. As the two reference points faced each other in a symmetrical layout, their sets of vertical skylight coefficients ($vsc^{sky(\phi,\gamma)}$) should be the same. Using the calculation spreadsheet developed in section 7.2, the set of $vsc^{sky(\phi,\gamma)}$ was found. It is illustrated graphically in Figure 7.17. The numerical values are shown in Appendix F4. For every set of measurement, the sky type of the real sky at the time of measurement was classified according to the CIE standard of general sky (CIE, 2003). Then the equation of sky luminance distribution was found and the luminance of every sky patch ($L_{sky(\phi,\gamma)}$) in the sky hemisphere can be calculated from the equation. As a result, the value of TVI_{ref}^{sky} at every time of measurement can be calculated by summing up the products of $vsc^{sky(\phi,\gamma)}$ and $L_{sky(\phi,\gamma)}$ for every sky patch.

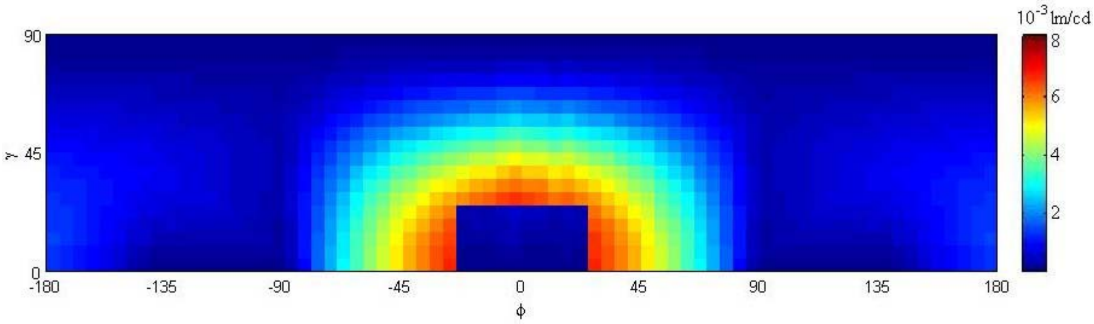


Figure 7.17 Vertical skylight coefficients for the reference points

As for the calculation of TVI_{ref}^{sun}, it is composed of the direct sunlight illuminance (DSI_{ref}^{sun}), obstruction reflected sunlight illuminance (ORI_{ref}^{sun}) and ground reflected sunlight illuminance (GRI_{ref}^{sun}). For every set of measurement, the solar altitude (γ_s) and solar azimuth angle relative to the reference plane (ϕ_{ref}^{sun}) were calculated by standard equations. The values of DSI_{ref}^{sun}, ORI_{ref}^{sun} and GRI_{ref}^{sun} were calculated by Equations (7.20), (7.22) and (7.24) respectively. Then the value of TVI_{ref}^{sun} at every time of measurement was evaluated by summing up DSI_{ref}^{sun}, ORI_{ref}^{sun} and GRI_{ref}^{sun}. A calculation spreadsheet was developed for the calculations of TVI_{ref}^{sky} and TVI_{ref}^{sun}, so that the total vertical illuminance due to skylight and sunlight ($TVI_{ref}^{sky} + TVI_{ref}^{sun}$) can be computed automatically.

7.5.3 Results comparison

The vertical illuminance values were measured at the reference points. The measurement results were compared with the calculation results which were estimated using the methods explained in sections 7.2 and 7.3. The scatter plots which compare the calculation and measurement results are shown in Figures 7.18 to 7.21. Figure 7.18 illustrates the overall performance of the calculation methods of TVI_{ref}^{sky} and TVI_{ref}^{sun} under all sky conditions. Figures 7.19 to 7.21 show the comparisons under clear, partly cloudy and overcast skies respectively. They show the result deviations with the best-fit line of the correlation between the calculation and measurement results. The mean bias error (MBE) and root mean square error (RMSE) were calculated to be 8.1% and 15.4% respectively for the data under all sky conditions. The errors for each surfaces under the three types of sky conditions are summarized in Table 7.1. The MBE and RMSE were both based on the departure of the calculated vertical illuminance from the measured values. The agreement is quite satisfactory and it shows that the calculation methods of TVI_{ref}^{sky} and TVI_{ref}^{sun} calculate the total vertical illuminance with big obstruction under real skies to a satisfactory degree of accuracy. The graphs comparing the measurement and calculation results against time for all the measurement days are shown in Appendix F5.

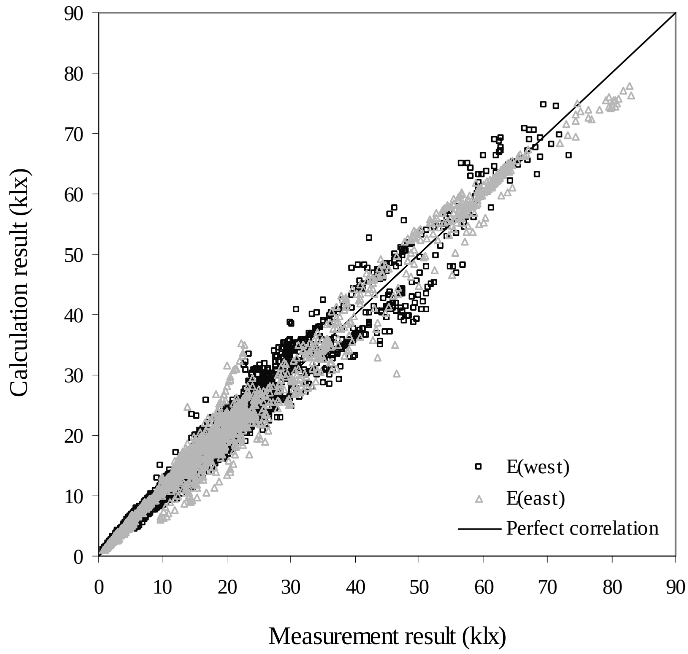


Figure 7.18 Calculation results plotted against measurement results for all sky conditions

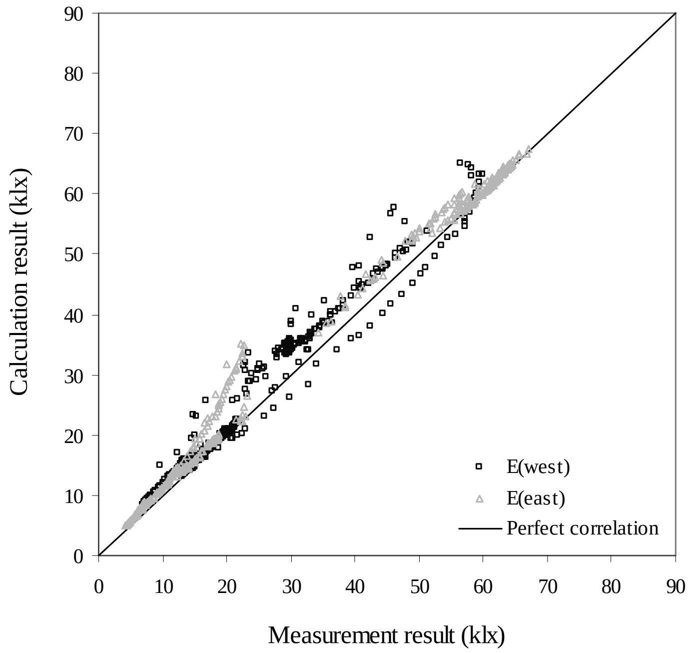


Figure 7.19 Calculation results plotted against measurement results for clear skies

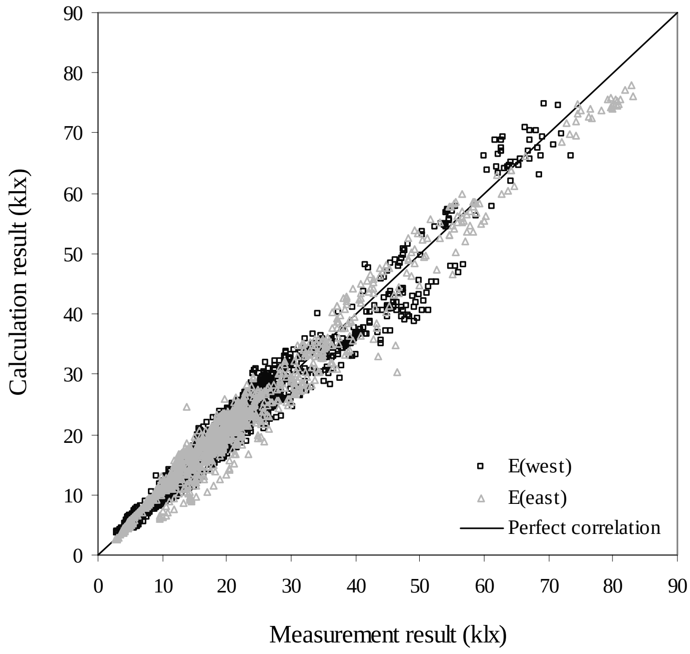


Figure 7.20 Calculation results plotted against measurement results for partly cloudy skies

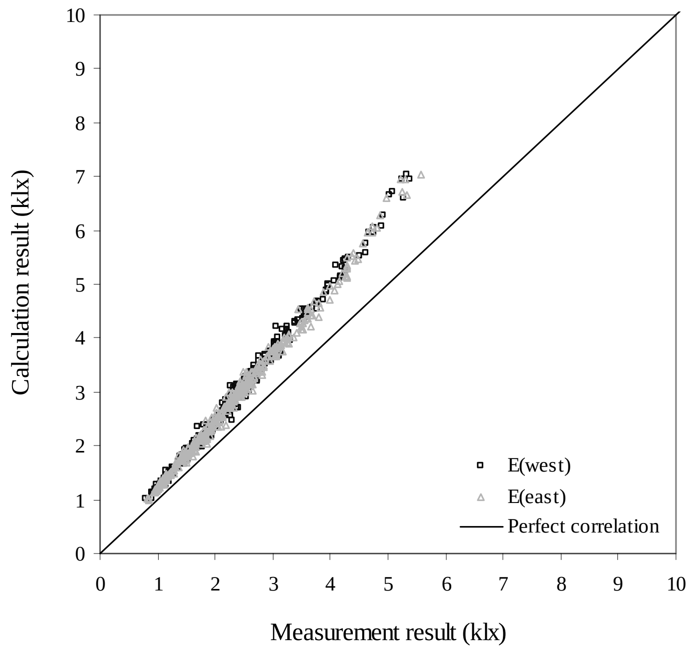


Figure 7.21 Calculation results plotted against measurement results for overcast skies

Table 7.1 Summary of MBE and RMSE for various sky conditions

	MBE (%)			RMSE (%)		
Sky condition	E_{west}	E_{east}	$E_{west} + E_{east}$	E_{west}	E_{east}	$E_{west} + E_{east}$
All	7.4	8.9	8.1	14.9	15.9	15.4
Clear	8.3	10.6	9.5	13.5	15.3	14.4
Partly cloudy	2.4	3.9	3.1	11.8	12.8	12.3
Overcast	22.6	23.2	22.9	23.1	23.6	23.3

7.5.4 Source of errors

The deviations of the calculated results from the measurement results can be explained by several reasons. One of the probable reasons is that errors existed in the process of measurement. The measurement errors could be due to equipment. The accuracy of a photocell is governed by its frequency response, linearity, response time, repeatability, noise level and compatibility. The photocells used in the experimental measurement were newly bought from the supplier. They had been tested under international standards with error of ±2%. Its degree of error was reduced to a minimum value. The measurement of sky zenith luminance by the tailor made tube would inevitably induce errors. However, this method enabled the simultaneous measurement of illuminance and sky zenith luminance. It then reduced the possible human error due to misread of data and deviations in marking the time of measurement. The set up errors were another source of errors. In the experiments, the models were aligned manually with a compass. Systematic error was arised from the difference between the true north and the magnetic north. The degrees of magnetic declination for the measurement days are summarized in Table 7.2. Besides, the set up of the horizontal and vertical receptor heads might induce other errors. In order to ensure that the receptor head was measuring the illuminance on a defined plane, every receptor head was inlaid securely to a plastic board first. Then the plastic board was installed to the model on the days of measurement. It enabled easy checking of correct measurement plane of a receptor head. The alignment of the shadow band for measurement of horizontal diffuse illuminance was another source of set up errors. All the measurement errors were minimized by the greatest effort in order to produce accurate measurement results.

Table 7.2 Magnetic declination on measurement days

Year	Month	Magnetic declination
2004	June	2° 8' W
2004	August	2° 9' W
2004	September	2° 9' W
2005	January	2° 10' W
2005	February	2° 10' W

Note: The values have been computed using the International model (IGRF).

As for the calculations of the total vertical illuminances (TVI_{ref}^{sky} and TVI_{ref}^{sun}), there were some limitations of the methods. Firstly, the accuracy of TVI_{ref}^{sky} was affected by the precision of the sky luminance equation which modeled the real sky conditions. Secondly, the sky division method was applied to the calculation of TVI_{ref}^{sky}. The unobstructed sky was assumed to be composed of sky patches whose angular width and angular height were both set to be 5°. The accuracy of the calculation method would then depend on the ability of the selected group of sky patches to imitate the actual portion of unobstructed sky. The luminances of the obstruction and ground patches would be similarly affected by the precision of the sky division method. The operation of multiplying the luminance of an obstruction or ground patch with its orthographically projected area at the reference point in order to find out the reflected illuminance from this patch would increase the calculation error due to the finite size of a patch. Similarly, the accuracy of estimating the reflected sunlight from obstruction and ground patches was affected similarly by the precision of the sky division method. Although the calculation methods have a number of limitations, they provide systematic procedures of estimating the daylight illuminance on a vertical surface under real sky conditions. The calculation methods are applicable to a densely packed and high-rise building environment.

7.6 Daylighting assessment method using exterior vertical illuminances

In the context of a dense urban environment, the instantaneous daylight availability of an interior can be assessed using the exterior vertical illuminance at the external surface of a window. Using the calculation methods explained in sections 7.2 and 7.3, the exterior vertical illuminance under variable sky can be estimated from the basic meteorological measurements, which include the global and diffuse horizontal illuminances as well as the sky zenith luminance. If the daylight availability of every hour in a year is of interest, the exterior vertical illuminances can be calculated for an entire year at a time step of an hour. It results in a year's profile of exterior vertical illuminance. It provides a realistic measure of the true daylighting performance for a window along the time line. It also provides useful information for visual comfort and energy saving analysis. Besides, the hourly data can be reorganized to evaluate the frequency of occurrence of exterior vertical illuminances within a range of useful daylight. By applying the concept of "useful daylight illuminances" (Nabil & Mardaljevic, 2005), the number of hours in a year for which the exterior vertical daylight level falls into a predefined range of "useful daylight" can be found. In this section, the concept of useful daylight illuminances is applied to the daylighting performance assessment of an interior. The range of “useful exterior vertical illuminances” is going to be calculated from the limits of useful daylight illuminances suggested by Nabil and Mardaljevic (2005), so that the total number of hours for which useful exterior vertical illuminance occurs can be calculated. The total duration of useful exterior vertical daylight in a year can be used as an assessment parameter for the daylighting performance of a window. The concept of useful daylight illuminances will be explained in the following section.

7.6.1 Useful daylight illuminances

Daylight illuminance which is too low may not contribute in any useful way to either the perception of the visual environment or in the carrying out of visual tasks. Conversely, if the daylight illuminance is too high, it may produce visual or thermal discomfort. According to the survey conducted by Nabil and Mardaljevic (2005), daylight illuminances less than 100 lx are generally considered insufficient. The working plane daylight illuminances in the range of 100 lx to 500 lx are considered effective either as the only source of illumination or in conjunction with artificial lighting. The illuminances in the range of 500 lx to 2,000 lx are often perceived as either desirable or at least tolerable. Besides, daylight illuminances higher than 2,000 lx are likely to produce visual or thermal discomfort. Therefore, Nabil and Mardaljevic (2005) suggest the bounds of minimum and maximum interior daylight illuminance to be 100 lx and 2,000 lx respectively. “Useful daylight illuminance” is said to occur whenever all the illuminances in the task area fall within the range of 100 lx to 2,000 lx. Although this range of useful daylight is applied to the interior horizontal illuminance at the working plane, the corresponding vertical illuminances at the external surface of a window can be estimated.

A side-lit room is assumed for the calculation of useful exterior vertical illuminances. The room has the dimensions shown in Figure 7.22. It aims to model the daylighting environment of a typical office in the perimeter zone. The window is located at the longer side of the room. The window-to-floor area ratio is equal to 0.15. The window transmittance is 0.8. The reflectances of the ceiling, walls and floor are equal to 0.7, 0.5 and 0.2 respectively. All interior surfaces are assumed to be perfectly diffusing and behave as if the room is an integrating sphere. Besides, it is assumed that the window is perfectly diffusing with same value of illuminance falling on every part of it, so that it can be treated as perfectly diffusing light source with uniform luminance value. The range of exterior vertical illuminances will be found out in order to achieve the target interior illuminances of 100 lx to 2,000 lx at all the calculation points. For a side-lit room, daylight enters the space from one side. The deeper part of the room should receive less daylight. The calculation points are proposed to lie on the working plane, along a straight line from the middle of the window to the back of the room. According to the IESNA Recommended practice of daylighting (IESNA, 1989), the distance of useful daylight penetration is usually not more than twice the window head height. It is assumed that the maximum distance for utilizing daylight is equal to twice the window head height (2.3 m). On the other hand, it is unlikely that the task area would start immediately from the window. Therefore, the distances from the window (d_p) to the first and last calculation points are equal to 1 m and 4.6 m respectively. The distance between consecutive calculation points is 0.2 m.

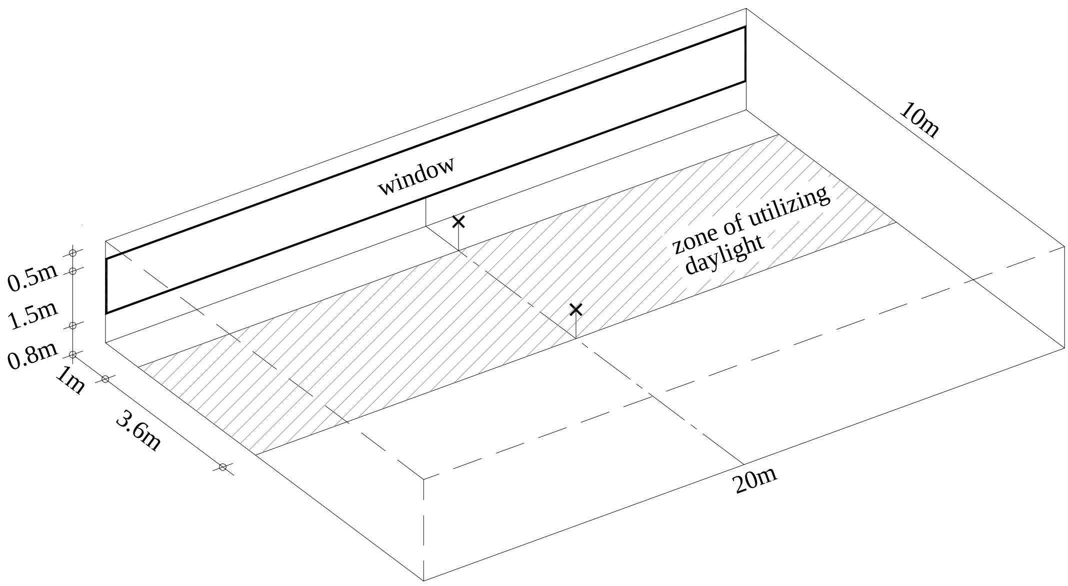


Figure 7.22 Room model for calculation of useful daylight illuminances

The direct illuminance at the calculation point due to the window can be calculated by the unit hemisphere method. Its value is equal to the product of orthographically projected area and luminance value of the window. The orthographically projected area ($OPAH$) of the window at the base of the unit hemisphere located at the calculation point can be calculated by the following expression. Please refer to Appendix B4 for details.

$$\begin{aligned} OPAH = \Big\{ & \frac{1}{4}\left[\sin 2\left(\sin^{-1} x_1\right) + 2\sin^{-1} x_1\right] - \frac{b}{4}\left[\sin 2\left(\sin^{-1} x_1\right) + 2\sin^{-1} x_1\right] \\ & + \frac{1}{4}\left[\sin 2\left(\sin^{-1} x_2\right) - \sin 2\left(\sin^{-1} x_1\right) + 2\sin^{-1} x_2 - 2\sin^{-1} x_1\right] \\ & - \frac{d_p}{W_{win}}\left(x_2^{\ 2} - x_1^{\ 2}\right)\Big\} \times 2 \end{aligned} \tag{7.28}$$

where

$$b = \cos\left(\tan^{-1}\frac{H_{win}}{d_p}\right) \tag{7.29}$$

$$x_1 = \sqrt{\frac{b^2}{b^2 + \frac{4d_p{}^2}{W_{win}{}^2}}} \tag{7.30}$$

$$x_2 = \sqrt{\frac{W_{win}{}^2}{W_{win}{}^2 + 4d_p{}^2}} \tag{7.31}$$

The relation between the interior horizontal illuminance (E_i) and the total exterior vertical illuminance due to skylight and sunlight at the window (TVI) can be illustrated by the equation below. It is composed of two parts. The former part is the direct illuminance and the latter part is the internally reflected illuminance.

$$E_i = \frac{TVI \times OPAH \times t}{\pi} + \frac{TVI \times t \times A_{win} \times \rho}{A(1-\rho)} \tag{7.32}$$

By using the above equation, the values of TVI can be calculated for E_i equal to 100 lx or 2,000 lx at the calculation points. In general office spaces, the recommended interior horizontal illuminance is 500 lx (CIBSE, 1994). Therefore, the values of TVI are also calculated for E_i equal to 500 lx. The results are shown in Figure 7.23. The numerical results for the first and last calculation points are summarized in Table 7.3. For a minimum horizontal illuminance of 100 lx, the exterior vertical illuminance should be larger than 470 lx and 2,000 lx for the first and last calculation points respectively. It is mentioned previously that useful daylight illuminance is said to occur only when all the illuminances fall within the range of useful daylight illuminance. If the interior illuminances of all the calculation points have to be above 100 lx, then the exterior vertical illuminance should be above 2,000 lx. For a maximum horizontal illuminance of 2,000 lx, the exterior vertical illuminance should be smaller than 9,500 lx and 41,000 lx for the first and last calculation points respectively.

Table 7.3 Results of exterior vertical illuminance for the first and last calculation points

	TVI (lx)	
E_i (lx)	First calculation point	Last calculation point
100	470	2,000
500	2,400	10,000
2,000	9,500	41,000

Note: The calculation results are rounded to two significant figures.

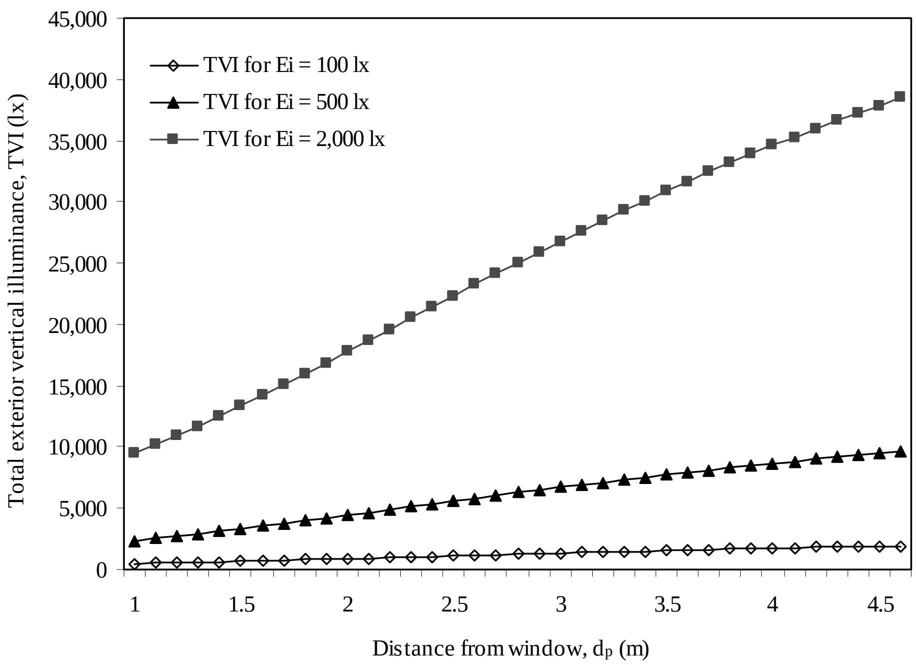


Figure 7.23 Results of exterior vertical illuminance for all the calculation points

As horizontal illuminances higher than 2,000 lx are likely to produce visual or thermal discomfort, it follows that the exterior vertical illuminance should be below 9,500 lx so that the interior illuminances of all the calculation points would be below 2,000 lx. However, this value of exterior illuminance is calculated for a window without any internal shading device. When internal shading is installed, it softens and redirects the daylight so that the interior horizontal illuminance may be below the upper bound of useful daylight illuminances (2,000 lx), even if the exterior vertical illuminance is above 9,500 lx. Therefore, it should be not suitable to set up an upper limit for the exterior vertical illuminance. Besides, in an urbanized region, the daylight falling on a window is usually heavily obstructed by the densely-packed external buildings. In order to promote the use of daylight, the daylight level on a window should not be restricted by an upper limit. (It is assumed that, at the early design stage, the summer sunlight exposure is already minimized by the methods introduced in chapter 5.) As a result, it is proposed that useful exterior vertical illuminance is said to occur when the exterior vertical illuminance at the window is above 2,000 lx. When the exterior vertical illuminance is above 9,500 lx, it is likely that the interior horizontal illuminance is higher than 2,000 lx, thus cauing visual and thermal discomfort. Then internal shading devices are recommended to be installed and activated. Although the calculation of useful exterior vertical illuminances is based on the model room in Figure 7.22, their values should work well for other large interior spaces with long continuous window.

7.6.2 Assessment method

By using the calculation methods described in previous sections, the exterior vertical illuminance at a window can be calculated for an entire year at a time step of an hour. Then the hourly data can be used to derive the cumulative availability of daylight illuminance as well as the number of hours in a year for which the exterior vertical illuminance at the window exceeds 2,000 lx and 9,500 lx. The number of hours for which the exterior vertical illuminance exceeds 2,000 lx is the duration of useful exterior vertical daylight. It can be used to assess the daylight availability of a window. It represents the probability that the interior daylight level is higher than 100 lx and it is effective either as the only source of illumination or in conjunction with artificial lighting. The number of hours for which the exterior vertical illuminance exceeds 9,500 lx represents the probability that the high daylight level may produce visual or thermal discomfort. If this number is high, internal shading devices are recommended to be installed. According to the research work carried out by Nabil and Mardaljevic (2005), Venetian blind can increase the duration of useful daylight illuminances for windows facing south, east and west. Internal shading device should be activated when the interior daylight illuminance is too high. However, it is important that the shading device should be retracted whenever the daylight illuminance falls back within the comfortable range. The calculation of the minimum value of useful exterior vertical illuminance (2,000 lx) is based on a window without internal shading and a window-to-floor area ratio of 15%. The relations between this value and different kinds of window system should be analysed by further study.

7.7 Calculation of annual daylight exposure

A method of calculating the total vertical daylight illuminance under any sky types has been introduced. The total vertical illuminance value is composed of two illuminance values. One is the vertical illuminance due to skylight (TVI_{ref}^{sky}) and the other is the vertical illuminance due to sunlight (TVI_{ref}^{sun}). The value of TVI_{ref}^{sky} is calculated by the vertical skylight coefficients approach, while the value of TVI_{ref}^{sun} is calculated from the solar normal illuminance. In this thesis, a new parameter is proposed to evaluate the annual daylight availability of a window. It is called the annual daylight exposure. It can be divided into two components: annual skylight exposure and annual sunlight exposure. They are the daylight "energy density" due to skylight and sunlight respectively. They account for the cumulative "skylight energy density" and "sunlight energy density" falling on a window in a year. The unit of this kind of "energy density" is lm·hr/m^2. Their calculation methods are similar to those of TVI_{ref}^{sky} and TVI_{ref}^{sun}. An annual cumulative sky and an annual cumulative sun were constructed for the calculation of annual daylight exposure. The annual skylight exposure is similar to the value of TVI_{ref}^{sky} under the annual cumulative sky and the annual sunlight exposure is similar to the value of TVI_{ref}^{sun} under the annual cumulative sun. The constructions of the annual cumulative sky and sun were based on the hourly basic data of the test reference year (TRY) in Hong Kong (Wong & Ngan, 1993) which included the global and diffuse horizontal irradiations. The hourly irradiation (unit = J/m^2) divided by 3,600 s is the hourly average irradiance (unit = W/m^2). Then the hourly average global and diffuse horizontal illuminance values (unit = lx) were evaluated using the luminous efficacy (unit = lm/W) suggested by Chung (1992) for daylight in Hong Kong. The values of direct solar, diffuse and global luminous efficacy for different sky types are summarized in Table 7.4.

Table 7.4 Luminous efficacy for different sky types

	Direct solar luminous efficacy	Diffuse luminous efficacy	Global luminous efficacy
Clear sky (S < 0.3)	K_s=48.5+1.67γ_s-0.0098γ_s^2	K_d=137	K_g=102.2-0.69γ_s-0.0059γ_s^2
Partly cloudy sky (0.3 < S < 0.8)	K_s=48.5+1.67γ_s-0.0098γ_s^2	K_d=135.3-25.7S	K_g=$K_d S$+K_s(1-S)
Overcast sky (S > 0.8)	K_{oc}=(102.2+0.67γ_s-0.0059γ_s^2)(1.18-0.00087Ω+9.3×10$^{-7}\Omega^2$)		

The parameter S is the sky ratio (IES Calculation Procedures Committee, 1984) which is calculated by the following expression:

$$S = \frac{\text{Diffuse horizontal irradiance}}{\text{Global horizontal irradiance}} \tag{7.33}$$

The parameter Ω is the ratio of horizontal irradiance to $\sin\gamma_s$. The constructions of the annual cumulative sky and sun as well as the calculations of annual skylight and sunlight exposure will be discussed in the following sub-sections.

7.7.1 Annual skylight exposure

An annual cumulative sky is constructed to calculate the annual skylight exposure (AIH_{ref}^{sky}), which accounts for the direct and reflected skylight falling on the reference point. It presents the annual cumulative "luminance" ($\sum_{\text{annual}} H_{sky(\phi,\gamma)}$) of all sky patches ($sky(\phi,\gamma)$) in the sky hemisphere. The unit of this cumulative luminance is lm·hr/m^2.sr. By using this annual cumulative sky, AIH_{ref}^{sky} can be calculated by the vertical skylight coefficients approach.

$$AIH_{ref}^{sky} = \sum_{\substack{\phi=-177.5 \\ (Step=5)}}^{177.5} \sum_{\substack{\gamma=2.5 \\ (Step=5)}}^{87.5} \left(\sum_{\text{annual}} H_{sky(\phi,\gamma)} \right) vsc^{sky(\phi,\gamma)} \tag{7.34}$$

The values of $\sum_{\text{annual}} H_{sky(\phi,\gamma)}$ were calculated based on the averaged hourly diffuse horizontal illuminance values (E_d) which were converted from the basic data of TRY. Totally, about 4,000 set of hourly data were recorded in the TRY. Then, the same number of E_d was converted as basic data for the calculation of $\sum_{\text{annual}} H_{sky(\phi,\gamma)}$.

For every hourly value of E_d, a blended sky luminance distribution was assumed so that the luminance value of every sky patch ($L_{sky(\phi,\gamma)}^{\text{blended}}$) could be calculated. Then the cumulative luminance value of every sky patch ($H_{sky(\phi,\gamma)}$) was calculated by multiplying $L_{sky(\phi,\gamma)}^{\text{blended}}$ and the time-step of TRY record which was equal to 1 hour. In this way, the annual cumulative luminance value was evaluated by adding up all the hourly luminance values (about 4,000 numbers) in a year.

$$\begin{aligned}\sum_{\text{annual}} H_{sky(\phi,\gamma)} &= \sum_{\text{annual}} \left(L_{sky(\phi,\gamma)}^{\text{blended}} \times 1 \right) \\ &= \sum_{\text{annual}} L_{sky(\phi,\gamma)}^{\text{blended}}\end{aligned} \tag{7.35}$$

In the calculation of $L_{sky(\phi,\gamma)}^{\text{blended}}$ for every sky patch, a blended sky was assumed for every hourly value of E_d. The blended sky was produced by mixing the CIE standard overcast and partly cloudy skies. The mixing factors (f_o and f_p) of overcast and partly cloudy skies determined the relative proportions of overcast and partly cloudy skies used to mix the blended sky. Based on the sky ratio, these two factors were calculated for all data (about 4,000 numbers) of TRY.

The sky conditions were classified using the sky ratio (S) method recommended by the US National Bureau of Standards (NBS). The sky type was classified to be overcast when S was larger than 0.8 and it was classified to be clear when S was smaller than 0.3. The skies of S between 0.3 and 0.8 were classified to be partly cloudy. As the blended sky was normalized to E_d, the sum of the fractional contribution from each sky model was equal to one, that was $f_o + f_p = 1$. By assuming a linear relationship between f_o and S when S was between 0.3 and 0.8, the two mixing factors were evaluated by the expressions below:

$$f_o = \begin{cases} 1 & \text{if } S < 0.3 \\ \dfrac{S - 0.3}{0.8 - 0.3} & \text{if } 0.3 < S < 0.8 \\ 0 & \text{if } S > 0.8 \end{cases} \tag{7.36}$$

$$f_p = 1 - f_o \tag{7.37}$$

The technique of mixing two sky models to produce a blended sky can be referred to the research work by Mardaljevic and Rylatt (2003). After calculating f_o and f_p, the contribution of diffuse horizontal illuminance from each sky model was calculated by the following equations:

$$E_d^{\text{overcast}} = f_o \times E_d \tag{7.38}$$

$$E_d^{\text{partly cloudy}} = f_p \times E_d \tag{7.39}$$

The zenith luminance of the overcast sky model L_z^{overcast} can be calculated by the following expression:

$$\begin{aligned} L_z^{\text{overcast}} &= \frac{9}{7\pi} E_d^{\text{overcast}} \\ &= \frac{9}{7\pi}\left(f_o \times E_d\right) \end{aligned} \tag{7.40}$$

With reference to the unit hemisphere method, the illuminance due to a sky patch is equal to the product of its luminance and its orthographically projected area on the base of the unit hemisphere at the reference point. Then the contribution of diffuse horizontal illuminance from the partly cloudy sky model could be expressed by the equation below:

$$E_d^{\text{partly cloudy}} = \sum_{\substack{\phi=-177.5 \\ (Step=5)}}^{177.5} \sum_{\substack{\gamma=2.5 \\ (Step=5)}}^{87.5} L_{sky(\phi,\gamma)}^{\text{partly cloudy}} OPAH^{sky(\phi,\gamma)} \tag{7.41}$$

where $L_{sky(\phi,\gamma)}^{\text{partly cloudy}}$ is the luminance of the sky patch $sky(\phi,\gamma)$ of the partly cloudy sky model. According to the standard of the CIE standard general skies (CIE, 2003), the luminance distribution of a partly cloudy sky is presented by the expression below:

$$\frac{L_{sky(\phi,\gamma)}^{\text{partly cloudy}}}{L_z^{\text{partly cloudy}}} = \frac{f(\chi)\varphi(Z)}{f(Z_s)\varphi(0)} \tag{7.42}$$

where $L_z^{\text{partly cloudy}}$ is the zenith luminance of the partly cloudy sky model. The meaning of the parameters $f(\chi)$, $f(Z_s)$, $\varphi(Z)$ and $\varphi(0)$ can be referred to chapter 3. Sky type 6 of the CIE general skies (CIE, 2003) was assumed to be the partly cloudy sky model for the evaluation of the blended sky. In order to produce a diffuse horizontal illuminance equal to $E_d^{\text{partly cloudy}}$, $L_z^{\text{partly cloudy}}$ can be calculated by the following expression:

$$L_z^{\text{partly cloudy}} = \frac{E_d^{\text{partly cloudy}}}{\sum\limits_{\substack{\phi=-177.5 \\ (Step=5)}}^{177.5} \sum\limits_{\substack{\gamma=2.5 \\ (Step=5)}}^{87.5} \frac{L_{sky(\phi,\gamma)}^{\text{partly cloudy}}}{L_z^{\text{partly cloudy}}} OPAH^{sky(\phi,\gamma)}}$$
$$= \frac{f_p \times E_d}{\sum\limits_{\substack{\phi=-177.5 \\ (Step=5)}}^{177.5} \sum\limits_{\substack{\gamma=2.5 \\ (Step=5)}}^{87.5} \left(\frac{f(\chi)\varphi(Z)}{f(Z_s)\varphi(0)} \right) OPAH^{sky(\phi,\gamma)}} \tag{7.43}$$

As a result, the luminance value of every sky patch of the blended sky ($L_{sky(\phi,\gamma)}^{\text{blended}}$) was evaluated by adding together the corresponding luminance values of the overcast and partly cloudy sky models.

$$L_{sky(\phi,\gamma)}^{\text{blended}} = L_{sky(\phi,\gamma)}^{\text{overcast}} + L_{sky(\phi,\gamma)}^{\text{partly cloudy}}$$
$$= \frac{L_z^{\text{overcast}}}{3}(1 + 2\sin\gamma) + \frac{L_z^{\text{partly cloudy}} f(\chi)\varphi(Z)}{f(Z_s)\varphi(0)} \tag{7.44}$$

where $L_{sky(\phi,\gamma)}^{\text{overcast}}$ is the luminance of the sky patch $sky(\phi,\gamma)$ of the overcast sky model. An example of a blended sky of half overcast and half partly cloudy sky models is shown in Figure 7.24. The solar altitude and azimuth are 68° and 98° respectively. Each sky model produces half of the relative luminance of the blended sky luminance distribution. By repeating the above procedures for all the data of TRY, an annual cumulative luminance ($\sum\limits_{\text{annual}} H_{sky(\phi,\gamma)}$) was computed for every sky patch and the annual skylight exposure received at a reference point (AIH_{ref}^{sky}) can be calculated by the vertical skylight coefficients approach. The result of annual cumulative sky of Hong Kong is illustrated graphically in Figure 7.25. The numerical values are tabulated in Appendix F6.

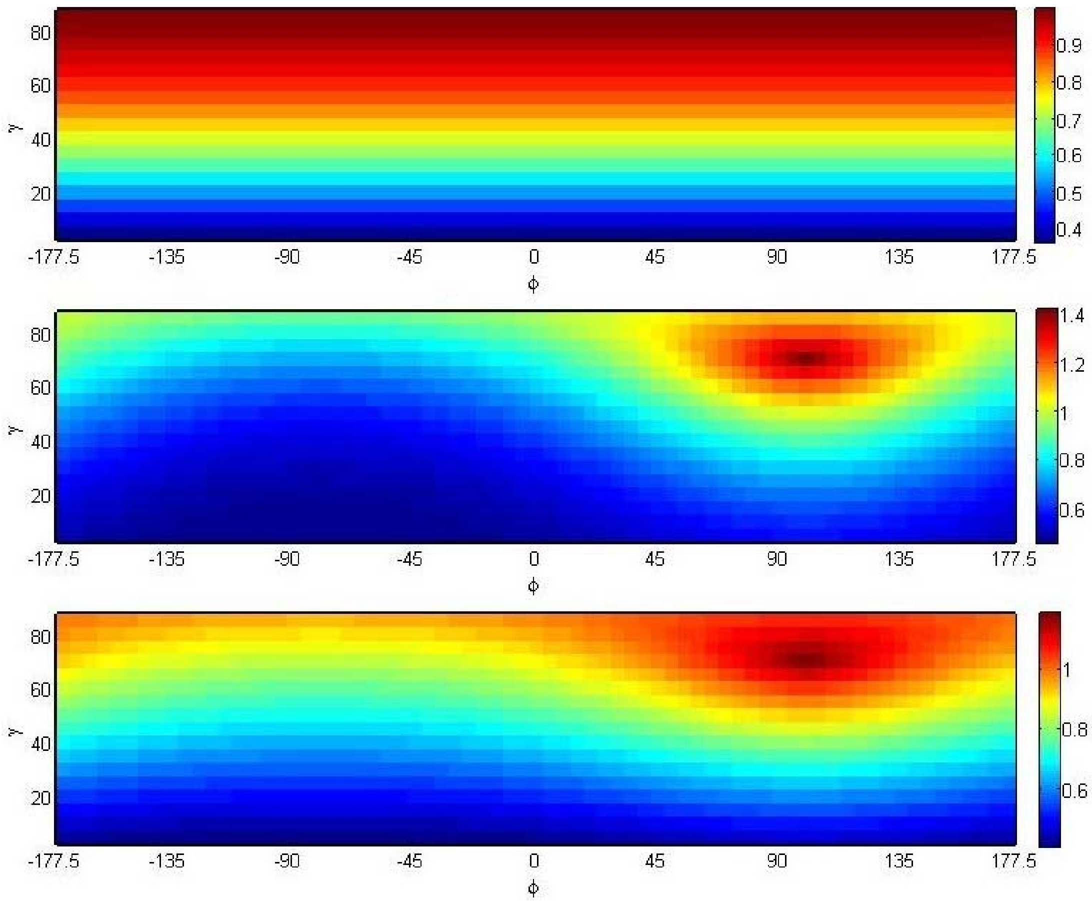


Figure 7.24 Relative luminance of a blended sky (lowest graph) of half overcast (top graph) and half partly cloudy sky (middle graph) models

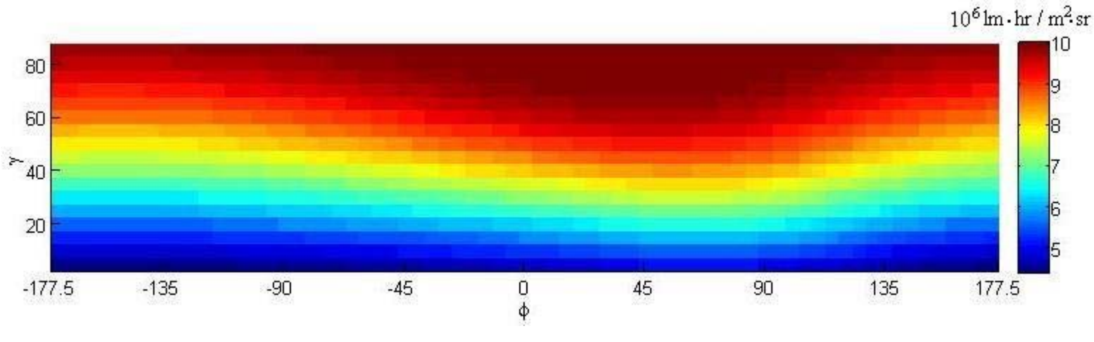


Figure 7.25 Annual cumulative sky of Hong Kong

7.7.2 Annual sunlight exposure

An annual cumulative sun was used to calculate the annual sunlight exposure (AIH_{ref}^{sun}), which accounts for the cumulative direct and reflected sunlight falling on the reference point in a year. It is composed of all the hourly “suns” in a year. According to the hourly basic data of TRY in Hong Kong, there were about 4,000 occurring sun positions recorded annually. The average solar illuminance on a surface normal to sun’s rays (solar normal illuminance E_n) for each sun position was calculated from the global and diffuse radiation data. In order to simplify the calculation procedures, the problem was transformed from the time-series domain to the sun position domain. With reference to the procedures recommended by Mardaljevic and Rylatt (2003), the sun positions (ϕ_s and γ_s) and the corresponding solar normal illuminances (E_n) were first calculated in a time-step of 15 min in order to ensure a smooth distribution. For every sun position, the solar illumination energy density on a normal surface (solar normal illumination energy density G, in lm·hr/m^2) was calculated by multiplying E_n and the time-step of the data which is equal to 15 min (0.25 hr), that is $G = 0.25 \times E_n$. All the G data were allocated to the sky patches according to the values of ϕ_s and γ_s. A total of 594 sky patches that contained one or more sun positions was resulted for the TRY data in Hong Kong. The 594 sky patches are named by a symbol p equal to 1 to 594. Then the solar normal illumination energy density for the pth sky patch is represented by G_p. For example, the solar normal illumination energy density for the first and the last sky patches of the 594 sky patches are represented by G_1 and G_{594} respectively. In this way, the annual cumulative solar normal illumination energy density for the pth sky patch ($\sum_{\text{annual}} G_p$) was evaluated by adding up all the G_p values in a year which were allocated to the pth sky patch. The azimuth and altitude angles of the averaged sun position in the pth sky patch were evaluated and represented by $\overline{\phi_{s,p}}$ and $\overline{\gamma_{s,p}}$. The values $\sum_{\text{annual}} G_p$, $\overline{\phi_{s,p}}$ and $\overline{\gamma_{s,p}}$ were used to calculate the annual sunlight exposure of a reference point (AIH_{ref}^{sun}). The annual cumulative sun presents the value of $\sum_{\text{annual}} G_p$, $\overline{\phi_{s,p}}$ and $\overline{\gamma_{s,p}}$ for every sky patch in the sky hemisphere. It is illustrated graphically in Figure 7.26. The average sun position ($\overline{\phi_{s,p}}$ and $\overline{\gamma_{s,p}}$) in each sky patch is marked by a cross (+). The numerical values of $\sum_{\text{annual}} G_p$, $\overline{\phi_{s,p}}$ and $\overline{\gamma_{s,p}}$ are tabulated in Appendix F7. Then AIH_{ref}^{sun} can be evaluated by the calculation method of TVI_{ref}^{sun} , which was introduced in section 7.3. In the calculation of TVI_{ref}^{sun} , there is only one direct sunlight source (the sun) in the sky. However, for the annual cumulative sky for sunlight availability, there are 594 "suns" in the sky hemisphere. The values of AIH_{ref}^{sun} can be calculated by repeating the procedures and adding up the energy density values due to all the 594 "suns". The parameter AIH_{ref}^{sun} consists of three components. These components are the direct sunlight illumination energy density ($DSIH_{ref}^{sun}$), obstruction reflected sunlight illumination energy density ($ORIH_{ref}^{sun}$) and ground reflected sunlight illumination energy density ($GRIH_{ref}^{sun}$) received annually at the reference point. The value of AIH_{ref}^{sun} is computed by adding the three components together.

$$AIH_{ref}^{sun} = DSIH_{ref}^{sun} + ORIH_{ref}^{sun} + GRIH_{ref}^{sun} \tag{7.45}$$

According to the calculation procedures explained in section 7.3, the three components can be calculated by repeating the procedures and adding up the illumination energy density values due to the 594 “suns”. The calculations of the three components are expressed by the equations below.

$$DSIH_{ref}^{sun}=\sum_{p=1}^{594}\left[\left(\sum_{annual}G_p\right)\cos\phi_{ref}^{sun(\overline{\phi_{s,p}},\overline{\gamma_{s,p}})}\cos\overline{\gamma_{s,p}}V_{ref}^{sun(\overline{\phi_{s,p}},\overline{\gamma_{s,p}})}\right] \tag{7.46}$$

$$\begin{aligned}ORIH_{ref}^{sun}=&\sum_{\substack{\delta=-87.5\\(Step=5)}}^{87.5}\sum_{\substack{\lambda=-87.5\\(Step=5)}}^{87.5}\left\{\sum_{p=1}^{594}\left[\left(\sum_{annual}G_p\right)\cos\phi_{obs(\delta,\lambda)}^{sun(\overline{\phi_{s,p}},\overline{\gamma_{s,p}})}\cos\overline{\gamma_{s,p}}V_{obs(\delta,\lambda)}^{sun(\overline{\phi_{s,p}},\overline{\gamma_{s,p}})}\right]\right.\\&\left.\times\frac{\rho_b OPAV_{ref}^{obs(\delta,\lambda)}V_{ref}^{obs(\delta,\lambda)}}{\pi}\right\}\end{aligned} \tag{7.47}$$

$$\begin{aligned}GRIH_{ref}^{sun}=&\sum_{\substack{\delta=-87.5\\(Step=5)}}^{87.5}\sum_{\substack{\lambda=-87.5\\(Step=5)}}^{87.5}\left\{\sum_{p=1}^{594}\left[\left(\sum_{annual}G_p\right)\sin\overline{\gamma_{s,p}}V_{gd(\delta,\lambda)}^{sun(\overline{\phi_{s,p}},\overline{\gamma_{s,p}})}\right]\right.\\&\left.\times\frac{\rho_g OPAV_{ref}^{gd(\delta,\lambda)}V_{ref}^{gd(\delta,\lambda)}}{\pi}\right\}\end{aligned} \tag{7.48}$$

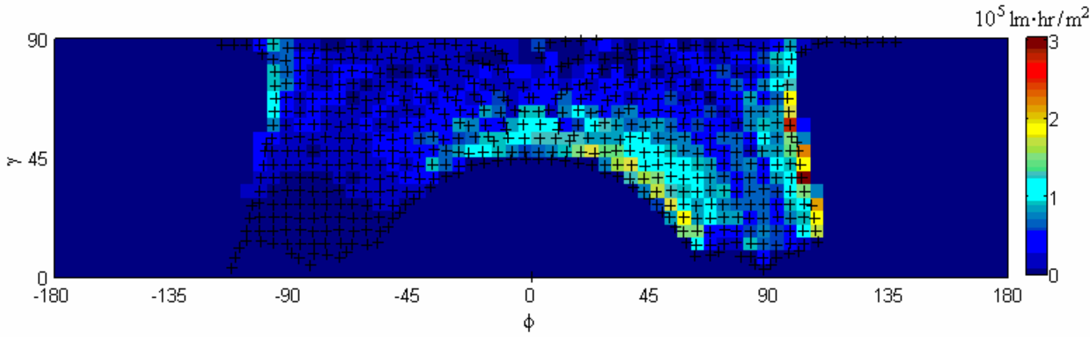


Figure 7.26 Annual cumulative sun of Hong Kong

7.7.3 Application to photovoltaic power system

The annual daylight exposure quantifies the annual daylight availability of a window. It can be used to determine the effectiveness of using photovoltaic (PV) power system on a vertical surface over the course of a year. Photovoltaic solar cells, which directly convert daylight into electricity, are made of semi-conducting materials. The simplest photovoltaic cells power watches and calculators and the like, while more complex systems can light houses and provide power to the electrical grid. Photovoltaic systems are not cost effective by themselves. However if they are being integrated to buildings elements, they could be economically feasible. Production of electrical power combined with the benefits, such as insulation, shading, sound proofing, and construction and maintenance benefits, has made Building Integrated Photovoltaics (BIPV) economically attractive. Moreover, it is interesting to note that the building electrical load profile generally matches with the availability of solar radiation. For example, typical energy use for office buildings peaks near midday and during the summer time when there is the greatest solar potential. One potential of integrating PV systems into the buildings is by curtain walling. The electrical potential of a BIPV system depends on the daylight availability, building surface geometry and PV system efficiency. With the methods described previously, the annual radiation available at a vertical surface can be evaluated from the annual daylight exposure. Then the system designers can analyze the performance of the BIPV system and determine the financial feasibility of installing the PV facades. The possible amount of energy generated by the system and its payback period may also be evaluated.

7.8 Conclusion

The calculation method of exterior vertical illuminance under variable sky was explained. The calculation of the exterior vertical illuminance due to skylight depends on the vertical skylight coefficients approach. It is applicable to any sky type whose sky luminance distribution is known. As for the calculation of exterior vertical illuminance due to sunlight, it is dependent on the solar normal illuminance value. The methods can be used to predict the hourly vertical daylight illuminance at a window, so that a year's profile of exterior vertical illuminance can be resulted. Besides, the hourly data can be reorganized to evaluate the number of hours in a year for which the exterior vertical daylight level falls into a predefined range of "useful daylight". Apart from the exterior vertical illuminance, the calculation method of annual daylight exposure at a window was also explained. An annual cumulative sky and an annual cumulative sun were constructed to predict the annual daylight exposure. It quantifies the total daylight availability at a window in the whole year. Both parameters are recommended to be used for detailed evaluation of daylighting performance of buildings in dense urban environment.

CHAPTER 8
STUDY OF THE PERFORMANCE-BASED APPROACH OF BUILDING REGULATIONS IN HONG KONG

8.1 Introduction

In order to allow flexible building design, the Buildings Department of the Hong Kong government issued a Practice Note PNAP278 (Buildings Department, 2003) on the performance-based approach in lighting and ventilation requirements in 2003. On the natural lighting part, the performance-based approach uses the vertical daylight factor (*VDF*) at the centre of the window in the specification of the performance standards. The Practice Note requires the minimum *VDF* to be 8% for habitable rooms and 4% for kitchens. It is stated that demonstration of compliance to the performance standards can be by any suitably verified and scientifically validated methods. However, the calculation of *VDF* is not a simple task and may require computer simulation using detailed data of the geometry and surface properties of the building itself and surrounding buildings. In many cases, detailed data are not available and designers may want to compare several design options with just rough sketches. Therefore, a simplified assessment method called the unobstructed vision area (UVA) method is recommended by the Buildings Department as a reliable way to demonstrate compliance with the *VDF* requirements. In this chapter, a review of the performance of the UVA method in predicting *VDF* is given. A new method based on orthographically projected area (*OPA*) was developed for fast evaluation of *VDF* at the window centre. Independent test comparing the performance of UVA and OPA methods was carried out. Calculation results by the two methods were compared with the simulation results using RADIANCE.

8.2 Review on the unobstructed vision area (UVA) method

In 2003, a researcher in Hong Kong (Ng, 2003a, 2003b) developed a new calculation method called the unobstructed vision area (UVA) method for daylighting assessment of buildings in Hong Kong. This method is used to estimate the value of *VDF* at the lowermost window in a building as an alternative method of assessment for regulatory control of daylighting in Hong Kong (Buildings Department, 2003). The *UVA* requirement is given for habitable room (8% *VDF*) and domestic kitchen (4% *VDF*) with glazing area equal to 10%, 15% and 20% of usable floor area. The UVA method is similar in nature with the Daylight Indicator adopted in the UK in 1968 (Ministry of Housing and Local Government, 1968). The system of the Daylight Indicator was based on the principle that the patch of sky seen at a particular point should be large enough to give the standard of direct daylight which was assessed by the sky factor. It used the unobstructed area enclosed in a sector to quantify the open area outside window.

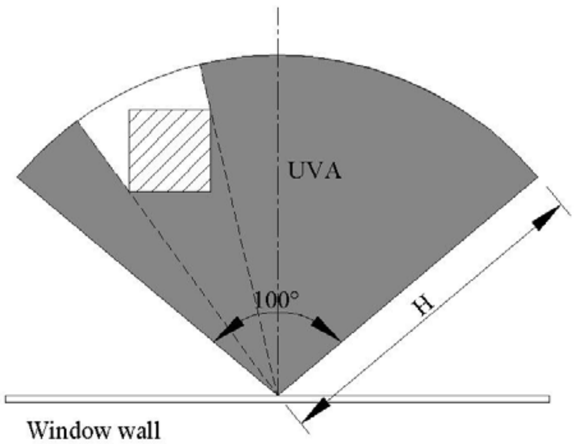


Figure 8.1 Measurement of *UVA*

The UVA method is based on a two-dimensional ‘visible area / volume in front of the window’. The UVA method considers an area in the shape of a cone that is 100°

wide. The so-called “cone” is actually a sector (of a circle), or a fan-shaped area, on the plan. The sector is symmetrical and perpendicular to the window. The length of the sector is equal to the height of the building above the window head. Figure 8.1 shows the measurement of *UVA*. H is the height of the building above the window head. The UVA method assumes that the value of *VDF* at the lowermost window is directly proportional to the two-dimensional *UVA* in front of the window. The UVA method is simple and straightforward. It relates the daylighting performance of a window to the horizontal area in a sector visible to it. In other words, it connects the photometric properties of the window to the geometric dimensions of its visible view. It allows easy adoption of the method for site planners and architects who are not familiar with the daylighting calculations.

The correlation results between *UVA* and *VDF* were based on computational studies of 40 theoretical configurations (Ng, 2003a). 25 blocks of 1 unit × 1 unit on plan were randomly laid out on a 5 unit × 5 unit grid. The grid was duplicated 8 times to form a surrounding. The reflectances of building and ground surfaces were assumed to 0.2. Relationships between *VDF* and *UVA* were deduced for different height of building to width of street ratios (*H/W*). The *H/W* ratios under testing included 2, 3 and 4. According to the research by Ng (2003a), a regression line which predicts *VDF* using *UVA* was drawn for each ratio.

For *H/W* = 2: $VDF = 0.0518UVA + 0.0057$ (8.1)

For *H/W* = 3: $VDF = 0.0163UVA + 0.0077$ (8.2)

For *H/W* = 4: $VDF = 0.0058UVA + 0.0215$ (8.3)

The coefficients of determination (R^2) were reported to be 0.7358, 0.7956 and 0.6810 respectively for the *H/W* ratios of 2, 3 and 4. Furthermore, Ng (2003a) presented three lines representing the lower quartile of the data relating *VDF* and *UVA* but without giving the expressions for these lower quartile lines. Instead, the coefficient *K* relating the required *UVA* for a *VDF* of 8% according to the following equation was given for each *H/W* ratio.

$$UVA = KH^2 \tag{8.4}$$

The coefficients *K* were given to be 0.40, 0.58 and 0.75 for *H/W* ratios of 2, 3 and 4 respectively. However, the coefficients are very different from the actual coefficients used in the minimum *UVA* values given in PNAP278. As the UVA method considers only the 100° segment of length equal to the height of the building above the window, two extreme cases can result in the same maximum *UVA* value of $\pi H^2 \times \frac{100}{360}$, which is the total area of the 100° segment. One of the extreme cases is that there is no external obstruction outside the window under concern. It is shown in the left drawing of Figure 8.2. Then the *VDF* value should be equal to nearly 50%, depending on the ground reflectance value. The other case is that the area outside the 100° cone is full of buildings. It is shown in the right drawing of Figure 8.2. The obstruction is illustrated by the shaded area. Then daylight can only reach the window from the “top opening” of the 100° cone. By using the calculation method of *VDF* described in the chapter 5, the *VDF* values at the window surface can be calculated for different obstruction environments. The *VDF* value of a window with this external view should be about 11%. The difference between these two extreme cases is about 39%. Although the latter case is not practical and unrealistic, it demonstrates the possible variations in *VDF* values which are resulted from layouts of the same *UVA*. The maximum and minimum *VDF* which result in the same value of *UVA* can be evaluated by the calculation method described in chapter 5.

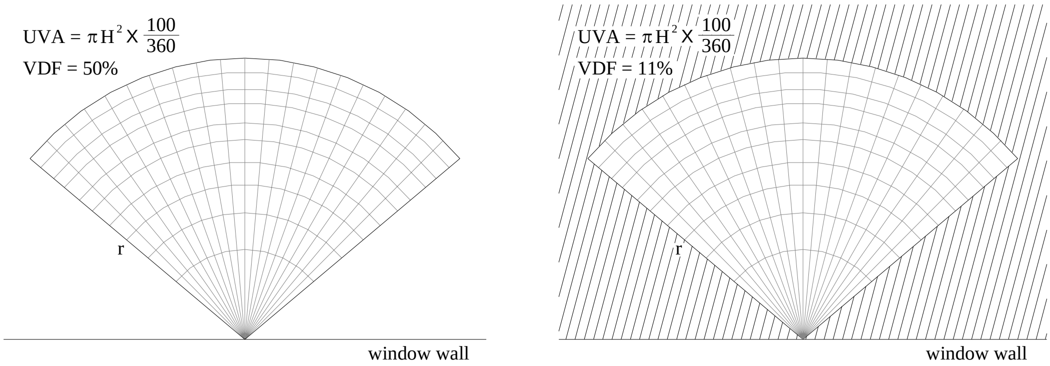


Figure 8.2 The two extreme cases which result in *UVA* value of $\pi H^2 \times \frac{100}{360}$

8.2.1 Maximum and minimum vertical daylight factors

It is understood that two obstruction layouts resulting in the same *UVA* value at a window may not produce the same *VDF* result. In order to study the possible variation in *VDF* values, external obstructions can be so arranged that two layouts, which produce two extreme values of *VDF*, would result in the same value of *UVA*. The area outside the 100° cone may be clear or obstructed. If the maximum *VDF* is going to be found for a particular *UVA* value, the area outside the cone should be assumed to be clear, and vice versa. Based on the external view division method described in section 4.2, the view of the window is divided azimuthally into segments of angular width of 5°. Then for a 100° cone, it is divided into 20 segments of 5° angular width. Each segment is further divided into subdivisions. If the cone is divided into n subdivisions of equal area, then the area of each subdivision is calculated by the following equation:

$$\Delta UVA = \pi H^2 \times \frac{100}{360} \times \frac{1}{n} = \frac{5\pi H^2}{18n} \qquad (8.1)$$

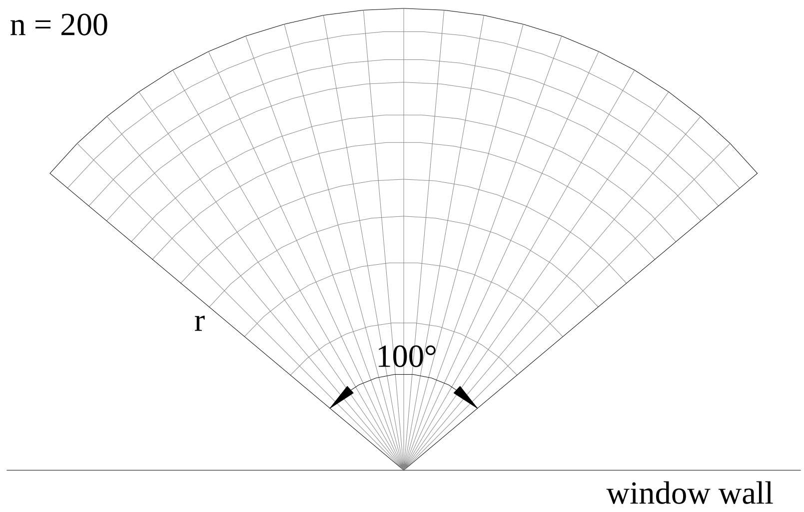


Figure 8.3 The shapes of the 200 subdivisions whose area are equal to ΔUVA

In this study, *n* is set to be 200. Then the cone is divided into 200 subdivisions. After the cone has been divided azimuthally into 20 equal segments, every segment is further divided into 10 subdivisions whose areas are all equal to ΔUVA. Figure 8.3 shows the shapes of the 200 subdivisions (n = 200) of area equal to $\frac{5\pi r^2}{18 \times 200} = \frac{\pi r^2}{720}$.

For a cone without any obstruction, the *UVA* is equal to $\Delta UVA \times n$. If some of the subdivisions of the cone are occupied by obstruction whose height is equal to *H* (Let's say the number of subdivisions which are occupied by building is equal to *m*, where *m* is smaller than *n*), then the *UVA* of this cone will be equal to $\Delta UVA \times (n - m)$. For a cone which is fully occupied by obstruction (*m* = *n*), the UVA is equal to $\Delta UVA \times (n - n) = 0$. For the case without any obstruction, m is equal to 0. When m is increased by 1, the *UVA* will be decreased by one unit of ΔUVA.

The calculations of maximum and minimum *VDF* start with an obstruction which results in a *UVA* value equal to one unit of ΔUVA. The obstruction is allocated symmetrically in the cone so that the *VDF* result is the largest (for the maximum *VDF* calculation) or smallest (for the minimum *VDF* calculation) among all the possible locations. The procedure repeats as the unit of ΔUVA is added to the cone one by one until up to its total area. In the calculation of maximum *VDF*, obstruction is allocated to the outer most subdivisions of the segments on the two sides, followed by the nearer subdivisions of the same segments on the two sides. When all of the subdivisions in the segments are being occupied by obstruction, then the outer subdivisions of the second segments on the two sides are selected. It should be noted that the obstructed subdivision should start with the outmost one, because when a subdivision is being obstructed, those behind it will be obstructed also. Figure 8.4 shows several examples of the obstruction layouts for the calculation of maximum *VDF*. In the calculation of minimum *VDF*, obstruction is allocated to the outer most subdivisions of the segments at the centre, followed by the nearer subdivisions of the same segments. When all of the subdivisions in the segments are being occupied by obstruction, then the outer subdivisions of the segments next to the centre segments are selected. Figure 8.5 shows several examples of the obstruction layouts for the calculation of minimum *VDF*.

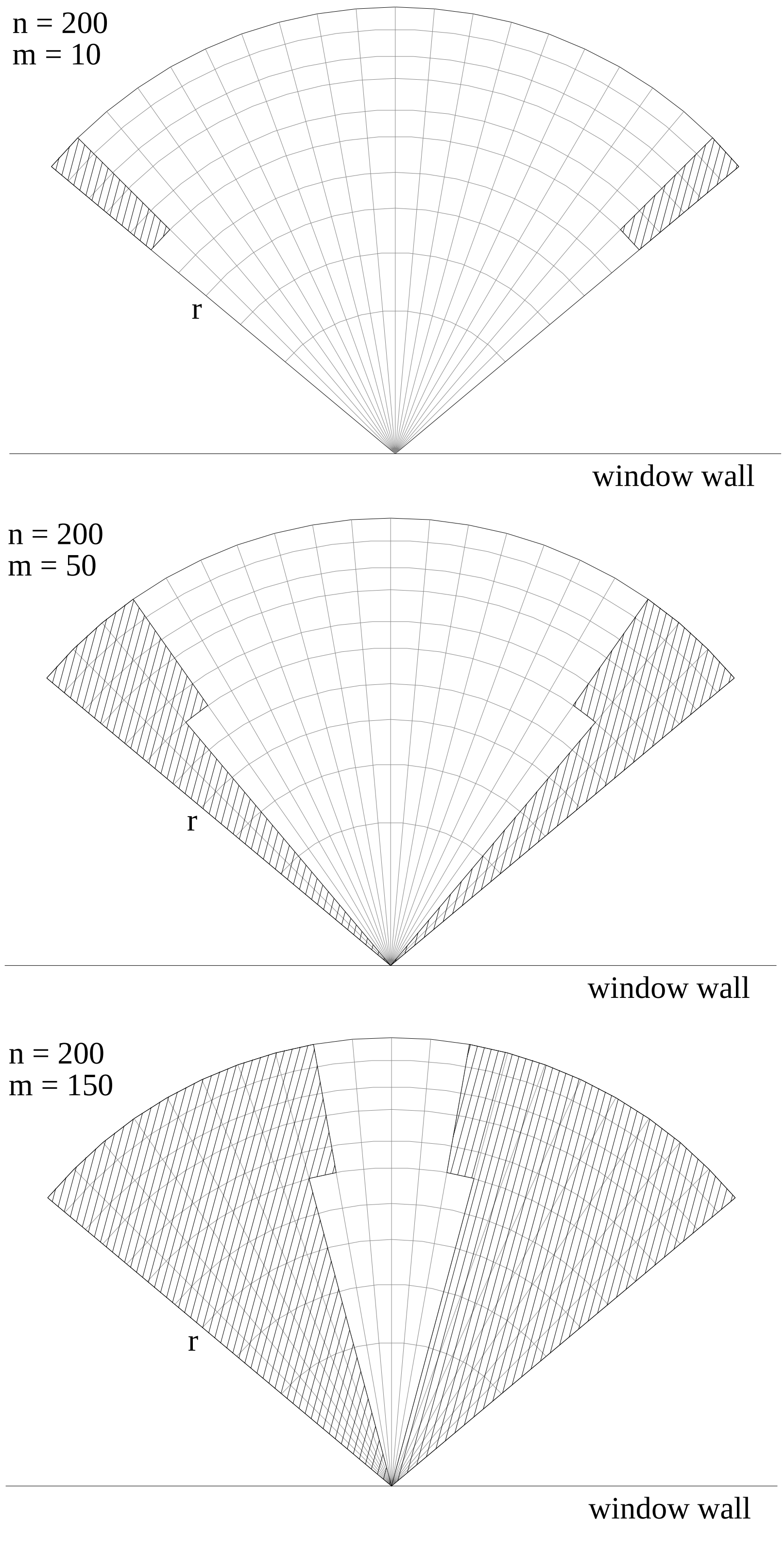


Figure 8.4 Examples of obstruction layout (shaded area) for the calculation of maximum *VDF*

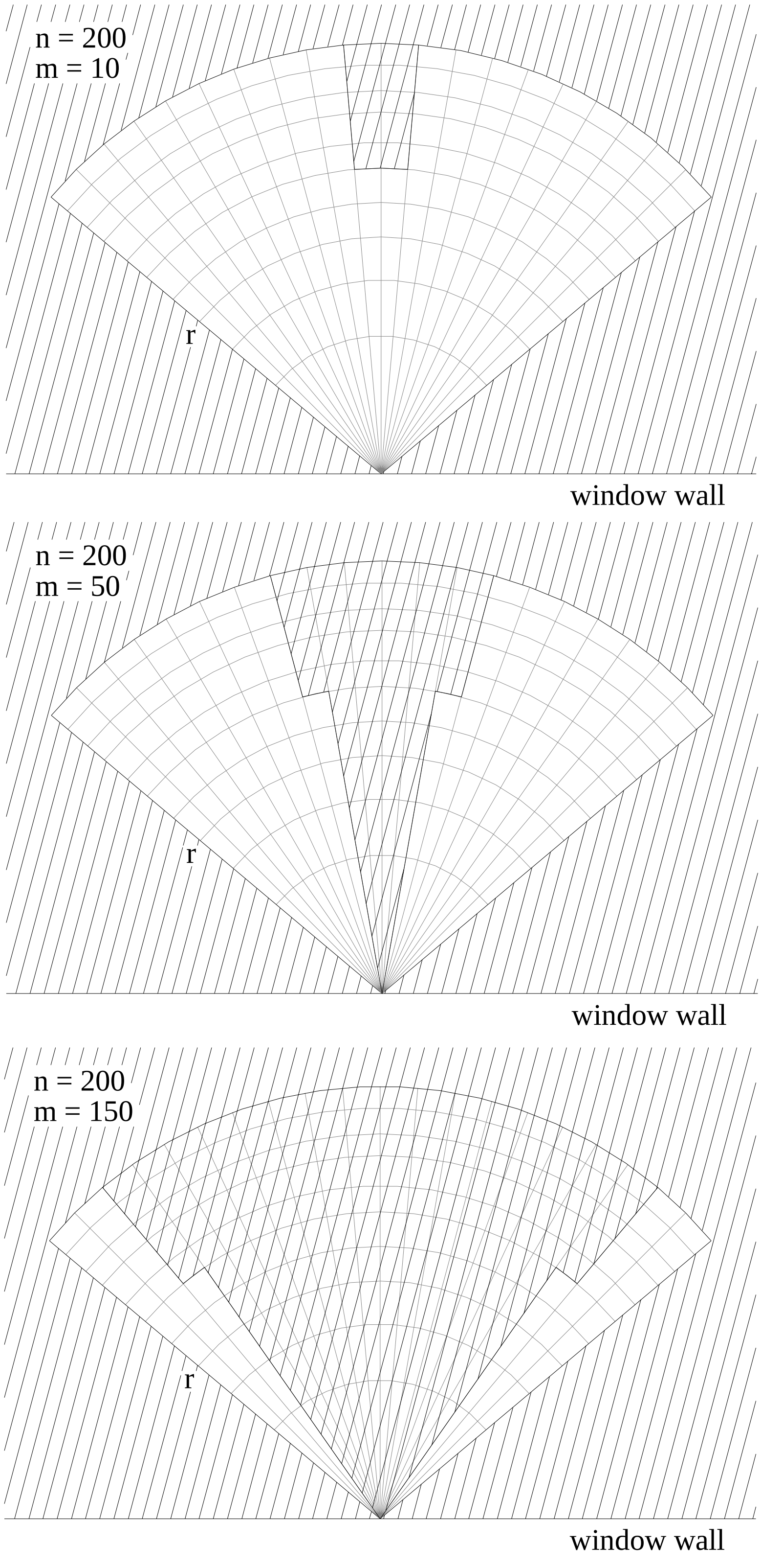


Figure 8.5 Examples of obstruction layout (shaded area) for the calculation of minimum *VDF*

The *UVA* for every value of m can be calculated by the equation: $\Delta UVA \times (n - m)$. As for the *VDF*, it can be found from the obstruction angles ($\theta_L^{sky(\phi)}$) of all the 20 segments in the 100° cone. The obstruction angle in every segment can be calculated by solving the following equation:

$$\pi \left(\frac{H}{\tan \theta_L^{sky(\phi)}} \right)^2 \times \frac{5}{360} = \pi H^2 \times \frac{5}{360} - \Delta UVA \times m' \qquad (8.6)$$

The parameter m' is the number of obstructed subdivisions in one segment. Then the obstruction angle is calculated to be:

$$\therefore \theta_L^{sky(\phi)} = \begin{cases} \tan^{-1} \sqrt{\dfrac{n}{n - 20m'}} & \text{if } m' \neq \dfrac{n}{20} \text{ and } m' \neq 0 \\ 90 & \text{if } m' = \dfrac{n}{20} \\ 0 & \text{if } m' = 0 \text{ (for maximum VDF)} \\ 45 & \text{if } m' = 0 \text{ (for minimum VDF)} \end{cases} \qquad (8.7)$$

The obstruction angles of the segments outside the 100° segment are equal to 0° and 90° for the calculation of maximum and minimum *VDF* respectively. Then a set of 20 obstruction angles can be calculated for every value of m. The *VDF* values can then be calculated by the calculation method described in chapter 5. The illuminance on the obstruction is assumed to be the same as the illuminance on the window. However, the assumption that the ground illuminance is equal to half of the horizontal illuminance under unobstructed sky would result in a non-zero value of minimum *UVA* when the *UVA* approaches zero. Therefore, the illuminance ratio $D \times \rho_g$ in the calculation of maximum and minimum *VDF* is estimated by assuming a linear relationship between $D \times \rho_g$ and DSC in order to produce a minimum *VDF* curve which goes through (0,0). For an unobstructed vertical plane, the maximum DSC and $D \times \rho_g$ are about 39.6% and $\frac{\rho_g}{2} \times 100\%$ respectively. By linear proportion calculation, the $D \times \rho_g$ value can be estimated by the following expression:

$$D \times \rho_g = \frac{DSC}{0.396} \times \frac{\rho_g}{2} \times 100\% \qquad (8.8)$$

The illuminance ratios C and $D \times \rho_g$ can be calculated from the 20 obstruction angles and the *VDF* values can also be evaluated. The results of the maximum and minimum *VDF* are plotted against $\frac{UVA}{H^2}$ as shown in Figure 8.6. The calculated maximum *VDF* is shown in a zigzag hidden line. In the calculation, the UVA "cone" is divided azimuthally into 20 segments. If the number of azimuthal divisions increases, the line will become smoother. When the number of divisions approaches infinity, the maximum *VDF* curve will be like the curve in solid line shown in Figure 8.6.

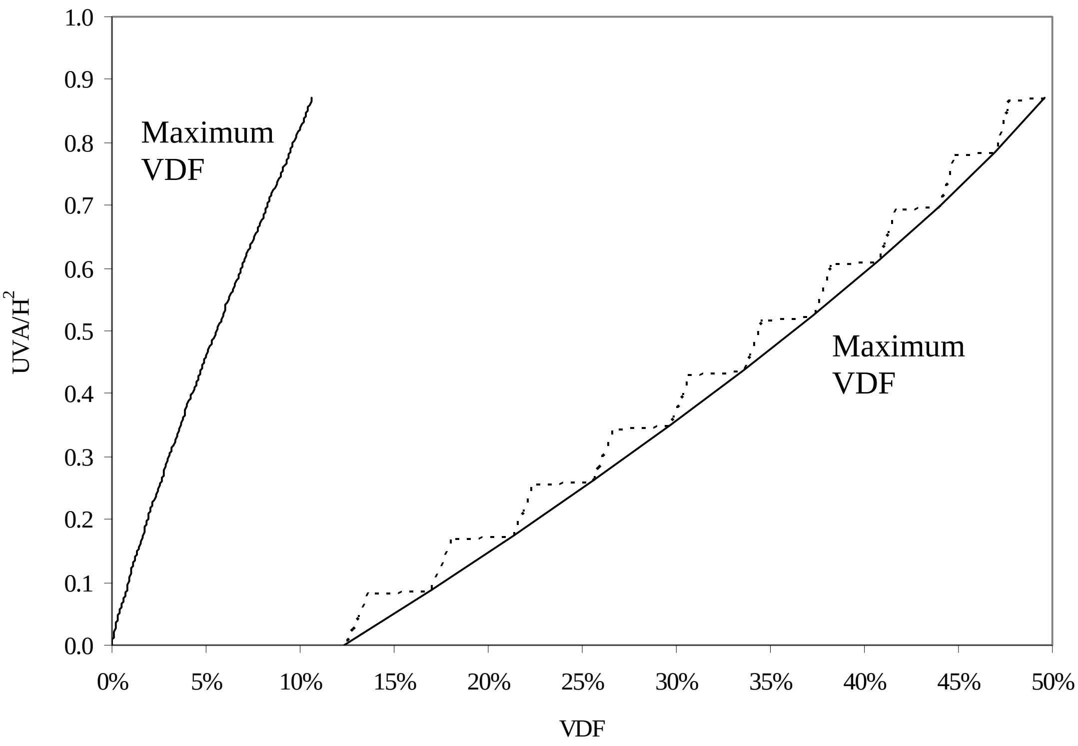


Figure 8.6 Graph of the maximum and minimum *VDF*

8.2.2 Estimation of vertical daylight factor using UVA method

The maximum and minimum *VDF* values show the potential error of direct conversion of *UVA* into *VDF*. From Figure 8.6, it is observed that the error tends to increase with the $\frac{UVA}{H^2}$ value. The *UVA* calculation does not consider the daylight sensitivity at the window to different parts of the sky. The whole portion of visible sky from the 100° cone is treated equally in the *UVA* calculation. It results in the poor correlation of $\frac{UVA}{H^2}$ with *VDF*. Besides, the area outside the cone is not considered in the *UVA* calculation, thus leading to more deviations. Although $\frac{UVA}{H^2}$ has poor correlation with *VDF*, it may be used as a parameter to safeguard the minimum *VDF* for a site layout design. The UVA method is easy and clear. By developing a relationship between $\frac{UVA}{H^2}$ and minimum *VDF*, $\frac{UVA}{H^2}$ is reasonable to be treated as a regulating parameter to protect the daylight provision on the window. In the report of consultancy study on the daylight provision led by Ng (Buildings Department, 2004), a table of *UVA* requirement for various *VDF* performances and heights of building is given. Please refer to Appendix A2 for the table of *UVA* requirements. The *UVA* values can be transformed into $\frac{UVA}{H^2}$. Then the *UVA* requirements for various *VDF* performances are plotted onto the graph of maximum and minimum *VDF* as shown in Figure 8.7.

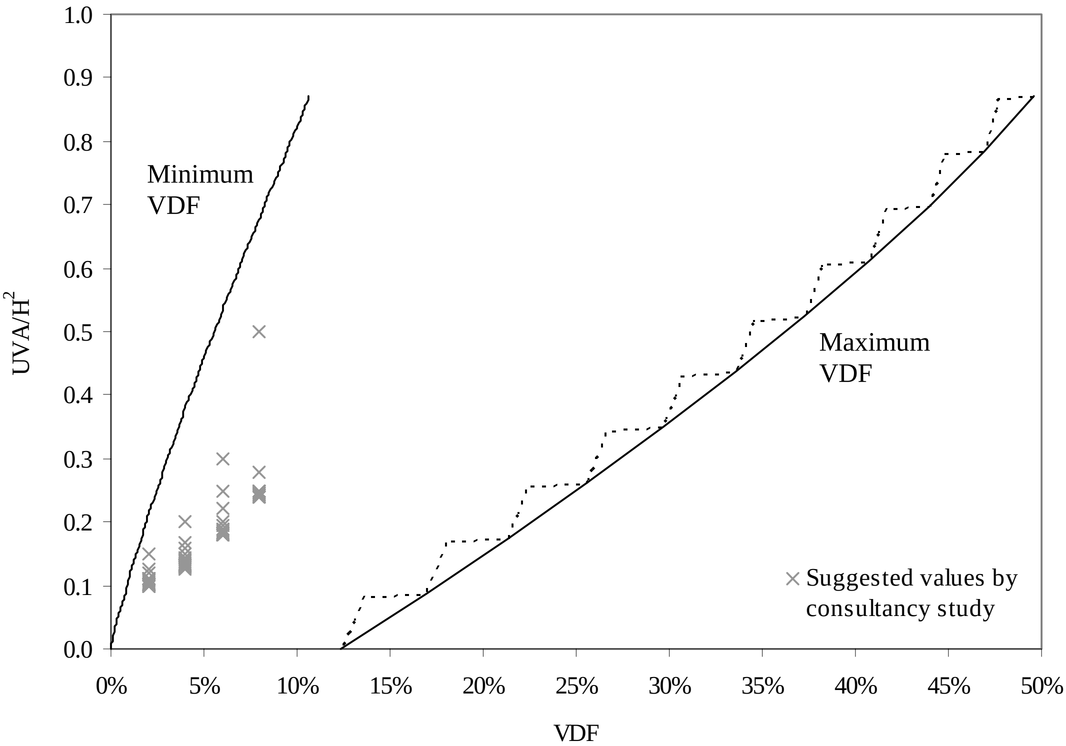


Figure 8.7 Suggested values of UVA/H^2 by the consultancy study

If UVA is used as a parameter to safeguard the minimum *VDF* received at the window, the minimum *VDF* curve can be used to find the UVA value which will probably result in a *VDF* value larger than a particular requirement. According to the minimum *VDF* curve plotted on Figure 8.6, for a *VDF* requirement of 8%, the $\frac{UVA}{H^2}$ value is calculated to be about 0.685. Then the *UVA* requirement for various heights of building can be calculated. Table 8.1 compares the *UVA* requirements suggested by the consultancy report and the *UVA* requirements calculated from the minimum *VDF* curve. It is noticed that the *UVA* values calculated from the minimum *VDF* curve are much higher than that suggested by the consultancy report. It is because the former *UVA* values represent the largest *UVA* which will result in a *VDF* of 8%. These values safeguard the daylighting provision of a window by ensuring a *VDF* values larger than 8% for all possibilities.

Table 8.1 *UVA* requirements suggested by the Buildings Department and the requirements calculated from minimum *VDF* curve

Height of building (m)	Minimum UVA (m^2) for VDF = 8%	
	Suggested values by PNAP278	Calculated values from minimum VDF curve
10	50	69
20	100	274
30	250	617
40	400	1,096
50	600	1,713
60	900	2,466
70	1,200	3,357
80	1,600	4,384
90	2,000	5,549
100	2,400	6,850
110	2,900	8,289
120	3,500	9,864
130	4,100	11,577
140	4,800	13,426
150	5,400	15,413
160	6,200	17,536
170	7,000	19,797
180	7,800	22,194
190	8,700	24,729
200	9,600	27,400

8.3 Orthographically projected area (OPA) method

The OPA method is recommended for easy adoption in the general evaluation of daylighting performance, especially at the preliminary design stage. The spirit of this method is similar to another simple design method developed by Capeluto (2003). He proposed a method to be used during initial design stage to assess the daylighting potential of the building site by using the sky solid angle subtended from the centre of the window. In this section, the OPA method is introduced to estimate the value of *VDF* at the external surface of the window. It depends on the unit hemisphere method that the illuminance at a point due to a uniformly diffusing source is given by integrating, over the whole projected area, the product of the source luminance and the orthographically projected area of the source on the base of the unit hemisphere at the reference point. The unit hemisphere method had been introduced in chapter 4. If a uniformly diffusing source has a constant luminance, the illuminance due to this source will be equal to the product of its luminance and its orthographically projected area at the reference point. Anything visible to the reference point can be projected on the base of the unit hemisphere, and the orthographically projected area of this object can be calculated. The value of *OPA* is defined as the total orthographically projected area of all the external obstructions above the horizon at the reference point. Figure 8.8 compares the *UVA* and *OPA* at the reference point with the same external obstruction. The value of *OPA* is equal to the shaded area in this circle whose radius is equal to 1.

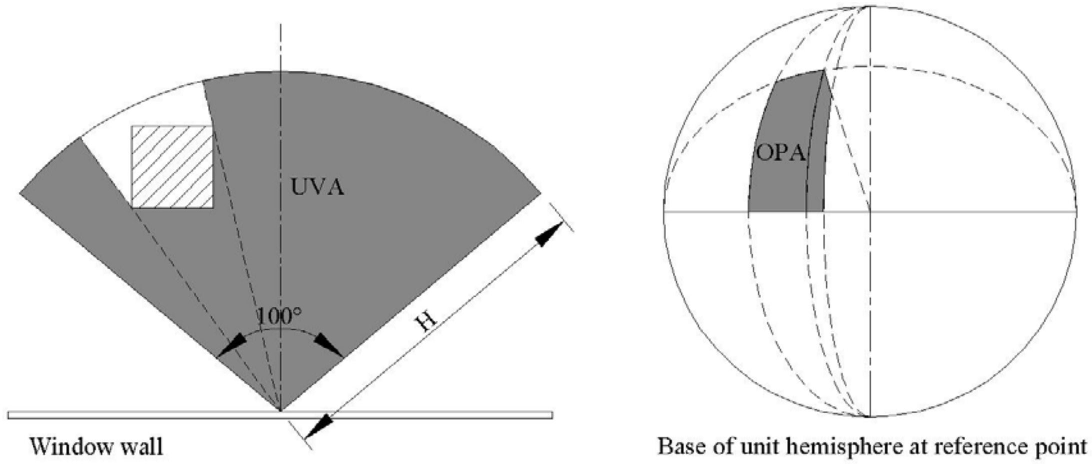


Figure 8.8 Measurement of *UVA* and *OPA*

In the context of densely-packed building environment, reflected light can be as important as direct skylight (Wa-Gichia, 1998). The daylighting potential of a building site depends not only on the portion of visible sky but also on the obstruction and ground reflectances. The direct skylight component is approximately the reverse proportion of *OPA*. Besides, as the value of *OPA* increases, the illuminance received by the obstructions due to the unobstructed portion of sky decreases, and hence also the luminance of the obstructions. It results in the obstruction reflected component decreases correspondingly. The possibility of using *OPA* for the estimation of *VDF* was studied by correlating *VDF* with *OPA* for various site layout and obstruction reflectances. *VDF* at the external surface of a window should approach a maximum value when there is no external obstruction. The value of *OPA* will become zero in this case. In the contrast, *VDF* should approach minimum when the external environment is so densely packed that no sky is visible to the window. Only external obstruction should be projected on the base of the unit hemisphere at the window. Then *OPA* will approach a value of $\frac{\pi}{2}$ which is equal to half of the area of a unit circle.

The orthographically projected area of a building can be found by projecting the outlines of the building and integrating the area bounded by these lines. It was proved that the projection of a line to the base of the unit hemisphere on a plane parallel to this line is in form of an ellipse. Besides, the projection of a perpendicular line to the base of a unit hemisphere is a radial line from the centre of the hemisphere. The calculations are shown in Appendix B1 and Appendix B2. Examples of orthographical projection to the base of a unit hemisphere on a vertical plane are also illustrated in Appendix B3. Although the orthographically projected area of individual obstruction can be evaluated by the calculation procedures explained in Appendix B1 and Appendix B2, it may be too complicated and troublesome to repeat the calculation for all external obstructions. In order to simplify the calculation procedures, the method of external view division adopted in section 5.2 was used to define the external obstruction. The method is based on the concept of dividing the external view of a window azimuthally into many segments. Then the obstructing environment is defined by the obstruction angle ($\theta_L^{sky(\phi)}$) subtended by the external building in every segment. A set of 36 obstruction angles: $\theta_L^{sky(-87.5)}$, $\theta_L^{sky(-82.5)}$, … , $\theta_L^{sky(82.5)}$, $\theta_L^{sky(87.5)}$ is used to define the external obstructing environment. In this section, the same set of obstruction angles ($\theta_L^{sky(\phi)}$) is used to evaluate the value of *OPA*. By the first principle, the illuminance due to a uniformly diffusing light source of luminance L, which is azimuthally bounded by angles ϕ_1 and ϕ_2 and altitudinally bounded by angles θ_1 and θ_2 can be evaluated by the following equation:

$$
\begin{aligned}
E &= \int_{\theta_2}^{\theta_1}\int_{\phi_2}^{\phi_1} L\cos^2\phi\cos\theta d\phi d\theta \\
&= L\times\left(\sin\phi_1-\sin\phi_2\right)\left(\frac{\theta_1-\theta_2}{2}\times\frac{\pi}{180}+\frac{\sin 2\theta_1-\sin 2\theta_2}{4}\right)
\end{aligned}
\tag{8.9}
$$

According to the unit hemisphere method, the illuminance at a point due to a uniformly diffusing source is given by integrating, over the whole projected area, the product of the source luminance and the orthographically projected area of the source on the base of the unit hemisphere at the point of interest. Then the orthographically projected area of this light source should be calculated by the following expression:

$$
\text{OPA of light source} = \left(\sin\phi_1-\sin\phi_2\right)\left(\frac{\theta_1-\theta_2}{2}\times\frac{\pi}{180}+\frac{\sin 2\theta_1-\sin 2\theta_2}{4}\right) \tag{8.10}
$$

Therefore, the total orthographically projected area of all the external obstructions above the horizon at the reference point can be evaluated by the expression below.

$$
OPA = \sum_{\substack{\phi=-87.5 \\ (Step=5)}}^{87.5} \left[\sin(\phi+2.5)-\sin(\phi-2.5)\right]\left(\frac{\theta_L^{sky(\phi)}\times\pi}{360}+\frac{\sin 2\theta_L^{sky(\phi)}}{4}\right) \tag{8.11}
$$

8.3.1 Estimation of vertical daylight factor using OPA method

In order to study the relations between *VDF* and *OPA*, a correlation analysis was carried out for five building layouts, which are shown in Figure 8.9. The height of all building blocks is equal to 145m. The points marked with a cross are selected to be the reference points. Heights of the reference points above ground vary between 5 m and 135 m. The *VDF* results at the reference points were simulated by RADIANCE which has been physically validated for a range of building geometries (Mardaljevic, 1995). The corresponding values of *OPA* were calculated by the equation explained above for correlation analysis. Results were also simulated with different building reflectances (ρ_b) of 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6, while the ground reflectance (ρ_g) is kept to be constant at 0.2. The *VDF* results are plotted against *OPA*, as shown in Figure 8.10. It shows the correlations between *VDF* and *OPA* for different values of obstruction reflectance. Please refer to Appendix G1 for the numerical values of *VDF* and *OPA*. The results show that the correlations are good. The coefficient of determination (R^2) ranges from 0.94 to 0.99. It suggests that the *OPA* method can be adopted as a fast evaluation method of *VDF* for daylighting performance assessment. The polynomial relation between *VDF* and *OPA* can be summarized by the following expression:

$$VDF = (2.21 - 38.06\rho_b)OPA^2 + (59.79\rho_b - 35.06)OPA + 49.6 \tag{8.12}$$

By using the above equation, the daylight availability at the external surface of a window can be estimated easily by a set of obstruction angles. The angles can be calculated by simple trigonometric equations. In this way, site planners and architects who are unfamiliar with the daylighting calculations can also estimate the daylighting performance of a window in the proposed site layout at the preliminary design stage.

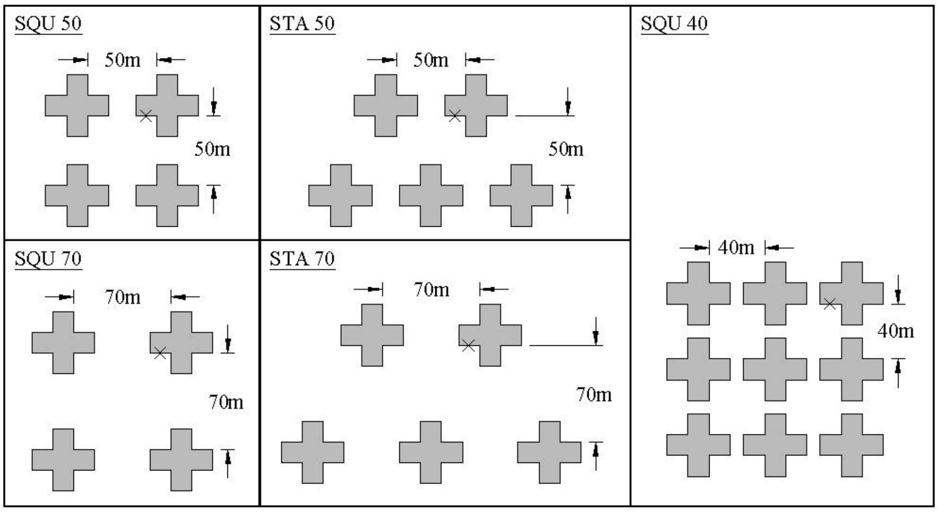


Figure 8.9 Building layouts for correlation analysis between *VDF* and *OPA*

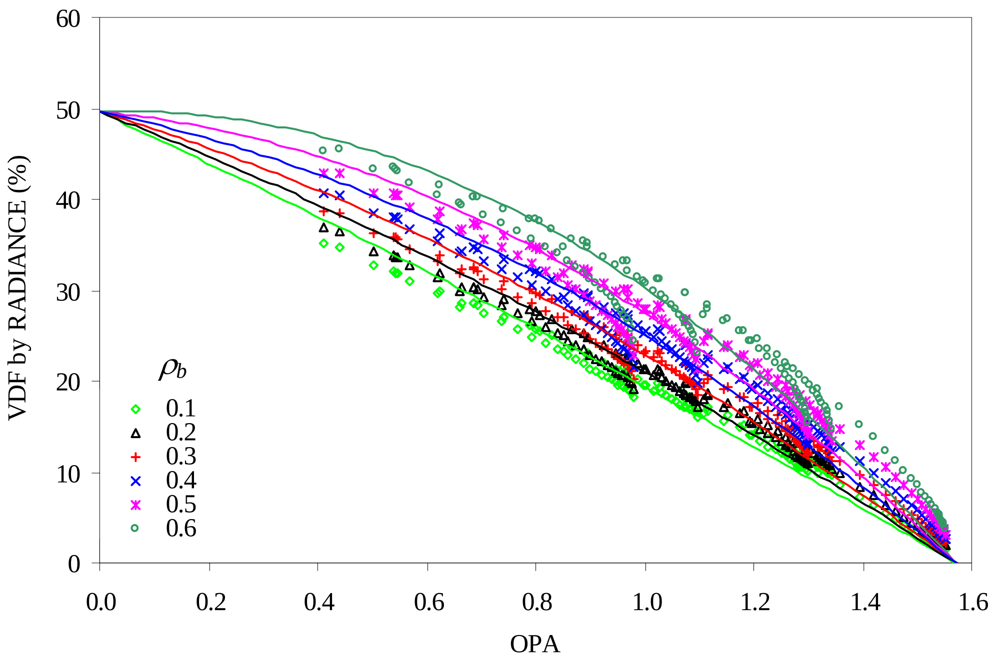


Figure 8.10 Correlation between *VDF* and *OPA*

8.4 Independent test for the performance of UVA and OPA method

Both the UVA and OPA methods are said to be useful in estimation of *VDF*. In order to compare the performance between the UVA and OPA methods, an independent test was performed to predict the *VDF* using both UVA and OPA methods. The building layout for this independent test is shown in Figure 8.11. All the building blocks are 3 units in depth. The width of street is kept constant at 3 units. The widths of the building blocks vary with different values of a and b. Please refer to Table 8.2 for the combinations of a and b. Totally 45 layouts were tested. The obstruction and ground reflectances are equal to 0.2. Six points marked with crosses are selected to be the reference points of calculation. As the regression equations of the UVA method were found for *H/W* ratios of 2, 3 and 4, two obstruction heights of 9 units and 12 units were tested in order to simulate a densely packed building environment. The *VDF* values were estimated by both the UVA and OPA methods according to the equations mentioned previously. At the same time, the *VDF* results were simulated by RADIANCE for comparison. The numerical values of *VDF*, which were simulated by RADIANCE and calculated both by UVA and OPA methods, are tabulated in Appendix G2. The graph of correlation is given in Figure 8.12. The mean bias errors (MBE) were calculated to be -65.8% and -6.8% for the UVA and OPA methods respectively, while the root mean square errors (RMSE) were calculated to be 66.5% and 15.5% respectively. It is concluded that the OPA method generally predicts *VDF* with a higher degree of confidence.

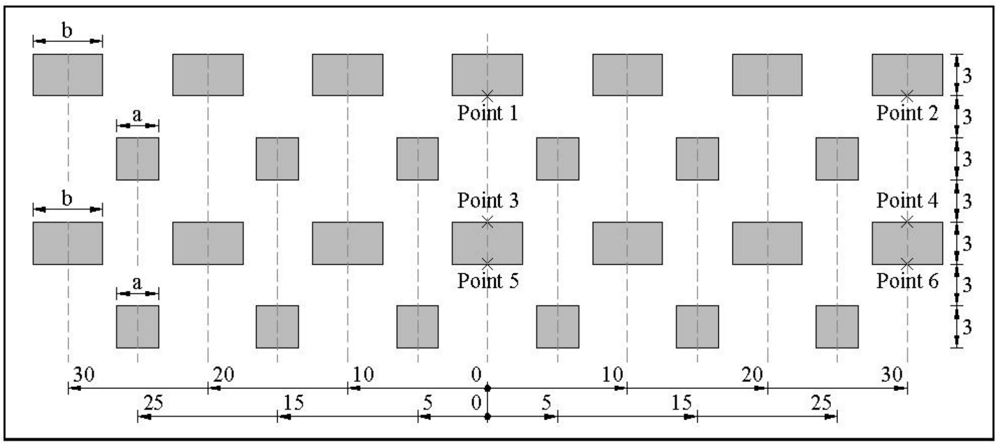


Figure 8.11 Building layout for independent test

Table 8.2 Combinations of a and b

Layout No.	a	b	Layout No.	a	b	Layout No.	a	b
1	1	9	16	2	2	31	5	5
2	1	8	17	2	1	32	5	4
3	1	7	18	3	7	33	5	3
4	1	6	19	3	6	34	5	2
5	1	5	20	3	5	35	5	1
6	1	4	21	3	4	36	6	4
7	1	3	22	3	3	37	6	3
8	1	2	23	3	2	38	6	2
9	1	1	24	3	1	39	6	1
10	2	8	25	4	6	40	7	3
11	2	7	26	4	5	41	7	2
12	2	6	27	4	4	42	7	1
13	2	5	28	4	3	43	8	2
14	2	4	29	4	2	44	8	1
15	2	3	30	4	1	45	9	1

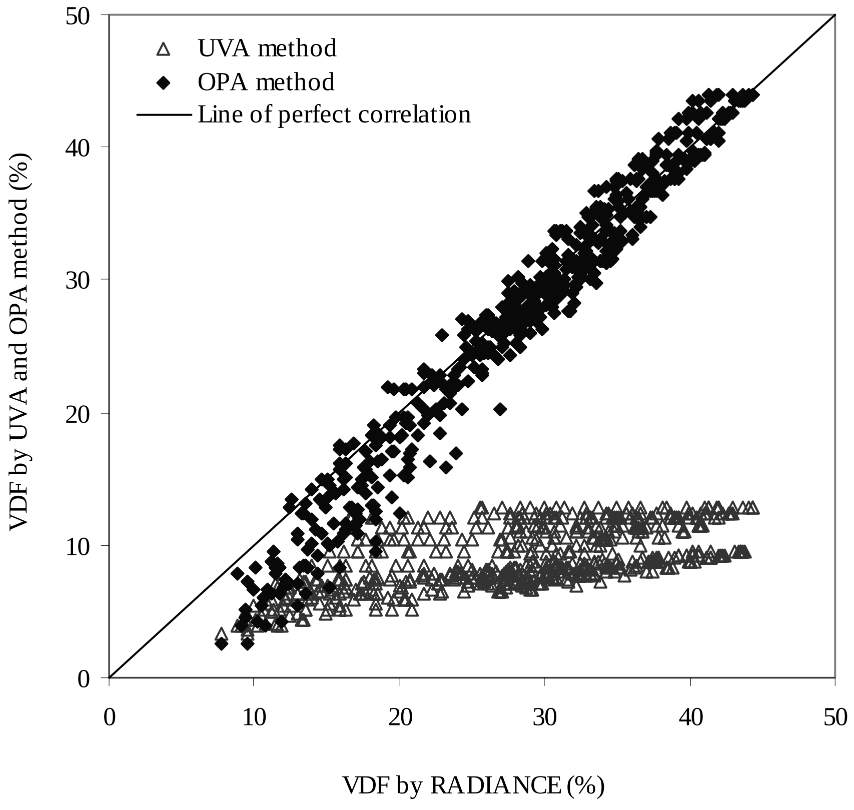


Figure 8.12 Graph of correlation for the UVA and OPA method

It is noticed that the UVA method underestimates the value of *VDF* for all the cases. The error becomes even larger for higher values of *VDF*. It may be explained by a possibility that this method was designed only for densely packed building environment. The regression equations relating *VDF* and *UVA* were deduced from site layouts of high building density. Therefore, the equations may not be suitable to estimate high values of *VDF* which are resulted from layouts of low building density. With reference to building layout shown in Figure 8.11, when the obstruction height (H) is equal to 9 units, the values of *UVA* at point 1, point 3 and point 5 are in fact the same. As the length of the cone for *UVA* calculation is equal to 9 units, the obstruction outside this cone will not affect the value of *UVA*. Then, same *UVA* will be resulted for these three points. Therefore, the UVA method predicts the same value of *VDF* for points which actually face different extent of obstruction. It also happens to point 2, point 4 and point 6 when H is equal to 9. Nevertheless, the UVA method ignores the effect of obstruction on the two sides of the 100° cone. It is true that the contribution of illuminance due to the light flux coming from the two sides is relatively smaller. However, this small amount of light may become very significant when the amount of daylight available from the 100° cone is small. This phenomenon may cause further error in the estimate of *VDF*. For most of the cases, the UVA method will only underestimate a daylighting performance, but not overestimate it. As an alternative measure for regulatory control of daylighting in buildings, the UVA method can safeguard the daylight provision of an interior by ensuring the *VDF* to be higher than a predetermined value.

Similar to the UVA method, the OPA method also tends to underestimate the results for lower values of *VDF*. However, the effect of underestimation tends to disappear when the *VDF* becomes larger. This characteristic is in fact in advantage when the OPA method is adopted as a performance based approach to assess a daylighting performance of an interior. For a densely packed building environment, the daylight availability at the window is so low that it would result in low value of *VDF*. The OPA method may underestimate a little the daylighting performance of the window. Then this method will be able to safeguard the daylight provision of an interior by ensuring the *VDF* to be higher than a predetermined value. The small underestimation provides a safety margin so that when the OPA method demonstrates that a building layout satisfies the *VDF* requirement, it is almost sure that the layout will satisfy the *VDF* requirement even if rigorous computer simulation is performed. When the daylight availability becomes higher, the OPA method should generally predict *VDF* reliably. Besides, the OPA method is developed to allow different surface reflectances of external buildings. It will increase the design flexibility in satisfying the daylighting performance-based requirements.

8.5 Conclusion

In this chapter, the UVA method was reviewed. A new method called the orthographically projected area (OPA) method was developed for fast evaluation of *VDF* at the window centre. An independent test comparing the performance of UVA and OPA methods was carried out. It suggests that the UVA method may be a poor indicator of daylight availability at the external surface of the window when *VDF* is used as the assessment parameter. Besides, it is found that the OPA method, which requires similar calculation effort as the UVA method, predicts *VDF* reliably.

CHAPTER 9
CONCLUSION

9.1 Summary of research results

In this research study, daylighting design and assessment methods were developed for high-rise residential buildings in dense urban environment. They offer clear procedures for daylighting performance assessment, so that the building design for natural light can be optimized. The methods were developed for both general and detailed evaluation of a natural lighting environment. For general evaluation, new calculation methods of average daylight factors, vertical daylight factor and probable sunlight duration were presented. Average daylight factor is accepted worldwide as a useful assessment indicator of interior daylight performance. It expresses the efficiency of a room and its windows as a natural lighting system. It is suitable to be used for general evaluation of daylighting performance. In the context of a dense urban environment, daylight availability at a window is considered to be the most critical factor affecting the interior daylighting environment. Therefore the daylight availability at a window is a useful parameter for general evaluation of daylighting performance. The daylight availability at a window can be generally divided into sunlight and skylight availability. Probable sunlight duration is selected to quantify the sunlight availability of a window. As for the skylight availability at a window, vertical daylight factor, which takes into account the direct skylight and reflected light of surrounding buildings and ground, is selected to quantify the skylight availability of a window. In Hong Kong, which is one of the most populated cities in the world, a performance-based approach using vertical daylight factor on window is adopted as an alternative measure for regulatory control of daylighting in residential buildings (Buildings Department, 2003). Vertical daylight factor should be a useful parameter to quantify the general skylight availability of a window in a dense urban environment.

In a high-rise building environment, skylines as seen from the windows are usually complicated and uneven. The calculation methods should be simple yet accurate and applicable to irregular skylines. The calculations of average daylight factors and vertical daylight factor depend on the concept that the external view of the window is divided azimuthally into 36 segments, so that the exterior environment can be defined by 36 pairs of altitude angles. As for the calculation of probable sunlight duration, a sky map of annual cumulative probable sunlight duration was constructed. It relies on the concept that the sky hemisphere is divided azimuthally and altitudinally into 1,296 sky patches, so that it gives the amount of probable sunlight from every sky patch. A computer spreadsheet was developed to calculate the average daylight factors, vertical daylight factor and probable sunlight duration received by a window. The input parameters include the room and window dimensions, interior surface reflectances, obstruction and ground reflectances, window transmittance and azimuth angle, 36 obstruction angles and dimensions of external shading. It offers a clear approach of site layout planning and external shading design to block the summer sunlight and maximize the winter sunlight exposure at the same time. Apart from the calculation methods of assessment parameters, suitable daylighting design criteria are also important for setting out the guidelines for daylighting design. In order to develop a set of criteria for general daylighting performance evaluation, a questionnaire survey was conducted in two residential building estates in Hong Kong. Based on the results of the questionnaire survey, a set of daylighting requirement is proposed. It is divided into two sections.

One is the skylight provision which is assessed by the vertical daylight factor and the other is the sunlight provision which is assessed by the annual probable sunlight duration. The daylighting requirements are developed for use in habitable rooms in residential buildings. It can be used for individual daylight assessment or it can be used for the voluntary daylighting assessment scheme for the overall performance of a building in a high-rise building environment, like the HK-BEAM.

Average daylight factors, vertical daylight factor and probable sunlight duration were selected to be used for general evaluation of a daylight environment. As for the detailed evaluation, the exterior vertical illuminance and annual daylight exposure received at the external surface of a window were used. The exterior vertical illuminance quantifies the daylight availability at a window at a particular time. Its calculation method is based on the vertical skylight coefficients approach. It is applicable to any sky type whose sky luminance distribution is known. The methods can be used to predict the hourly vertical daylight illuminance at a window, so that a year profile of exterior vertical illuminance can be resulted. Besides, the hourly data can be reorganized to evaluate the number of hours in a year for which the exterior vertical daylight level falls into a predefined range of “useful daylight”. It provides useful information for annual energy performance analysis, like the energy saving analysis for integrated daylighting and electrical lighting control. If the annual total daylight availability of a window over the course of a year has to be evaluated, the annual daylight exposure can be calculated. An annual cumulative sky and an annual cumulative sun were constructed to predict the annual daylight exposure. It can be used to determine the effectiveness of using photovoltaic (PV) power system on a vertical surface.

As Hong Kong is one of the urban areas with very high building density, its regulatory control of daylighting in buildings is of great value to other cities. The performance-based approach, which uses the vertical daylight factor at the centre of the window pane as the performance requirement, was reviewed. A simplified assessment method called the unobstructed vision area method is recommended by the Buildings Department as a reliable way to demonstrate compliance to the vertical daylight factor requirements for daylighting in buildings. A new method called the orthographically projected area method was developed for fast evaluation of vertical daylight factor at the window. An independent test comparing the performance of the two methods was carried out. The result suggests that the unobstructed vision area method may be a poor indicator of daylight availability at the external surface of the window when vertical daylight factor is used as the assessment parameter. It also indicates that the orthographically projected area method, which requires similar calculation effort as the unobstructed vision area method, predicts vertical daylight factor reliably.

9.2 Limitations of the research

The daylighting performance assessment method using vertical daylight factor, probable sunlight duration and exterior vertical illuminance focuses on the daylight availability at the external surface of the window, which is assumed to be the most critical parameter affecting the daylighting performance of an interior. In an environment of high building density, vertical daylight factor and probable sunlight duration, which assess the skylight availability and sunlight availability respectively, should generally work well at the early design stage. For the detailed design stage, the cumulative frequency of exterior vertical illuminance and annual daylight exposure received by the window can be computed for energy performance analysis. The research results do not give much recommendation on the assessment of the interior daylight environment. Average daylight factor can be used to evaluate the general daylighting performance of an interior space, but it gives no accurate daylight level across all the sky conditions. For the calculation of interior illuminance under variable sky, advanced computer similuation programme, like RADIANCE, is suggested to be used.

Most of the calculation methods developed in this study rely on the concept that the sky hemisphere or external view is divided into many segments or small patches. The size of the segment and the angular width and height of the patches are standardized to be 5°. The accuracy of the calculation methods would depend on the ability of the group of patches to represent the external obstruction. For obstruction with sharp changing outlines and located very near to the window, the division of 5° may not be small enough to describe the shape of the obstruction. Then the effect of obstruction due to these protruded or recessed elements would be underestimated or overestimated. However, for common building shapes, the calculation methods should perform generally well. Another insufficiency of the methods is that the assessment parameters are calculated point-by-point. They are computed at the centre point of the window, so that the daylight availability at the window centre is used to represent the daylight availability of the whole window. This assumption could induce certain errors for large windows.

The design criteria using vertical daylight factor and annual sunlight duration factor are based on the questionnaire survey conducted in two residential estates in Hong Kong. There are several uncertainties of the questionnaire survey. First, the subjects of the survey were not selected randomly from the population. The two building estates were selected deliberately. Therefore, the respondents may not be representative of the whole population. Secondly, the age-related effects on the subjective sensations to the daylight environment were not studied. The age of the respondents ranged from less than 20 to more than 60. There is a possibility that the task performance and glare sensation are highly related to the age of respondents. Besides, as the respondents may not be consciously aware of the daylight environment before the survey and they were given only one month to complete the questionnaires, their responses may be those of the days of completing the questionnaires. The survey collected no information of the weather and sky condition when the respondent was completing the questionnaire, so this problem was not investigated further. All of the above uncertainties may reduce the validity of the design criteria.

9.3 Further research study

For the general evaluation of the sunlight availability at the window, probable sunlight duration, which accounts for the duration of bright sunshine falling on a surface directly, is calculated. The contribution of reflected sunlight from the obstruction and ground is not considered. It is calculated only in the detailed evaluation method. In sunny locations, reflected sunlight is a very valuable source of natural light. Furthermore, the reflected sunlight from opposite facades can provide significant illuminance to a window. It would be useful if a simple method for the evaluation of reflected sunlight can be developed, so that the contribution of reflected sunlight from the external obstruction can be estimated at the early design stage. The annual cumulative sun constructed in section 7.7 can be further studied to develop an alternative method for the evaluation of reflected sunlight in summer, winter and the whole year. This method would be very useful, especially for the north façade which receive no direct sunlight.

This thesis focuses on the daylighting performance assessment methods for residential buildings. The author would like to make the following recommendations for the daylighting performance evaluation of commercial buildings. In commercial building, the floor area is much larger than in residential building and ceiling height is at ergonomic minimum. The office rooms are usually side-lit by windows on one side of the external wall. The zone of utilizing daylight is normally located in the shallow perimeter area near the window. For the deeper room space, the interior daylight level is very low, so that electric light has to be switched on for most of the time. In order to assess the daylighting performance of commercial buildings, two criteria are recommended. One is daylight availability at the external surface of the window which is the same as that for residential buildings. In densely packed building environment, it is still the most critical factor affecting the daylighting performance of a building. The other is the use of daylight redirecting device, like lightshelf. As office rooms are usually large and ceiling heights are low, it is critical that daylight should be redirected to the inner part of the room. In order to promote the use of natural light in commercial buildings, an appropriate assessment method should be developed.

9.4 Conclusion

The parameters and methods used for daylighting design and assessment were reviewed. The survey was conducted for building standards, published literature, design codes and design guides. The average daylight factor, vertical daylight factor and probable sunlight duration are selected to be used for general evaluation of daylighting performance of a space in a dense urban environment. As for the detailed evaluation of daylighting performance, the exterior vertical illuminance and annual daylight exposure received at a window are proposed to be used. The calculation methods of these assessment parameters were modified and developed such that they are applicable to a densely packed building environment. They offer clear procedures of daylighting performance assessment so that the building design for natural light can be optimized. The input parameters can be easily manipulated geometrically during the early design stages. Although some of the daylighting design and assessment methods were developed based on the meteorological data in Hong Kong, they should be generally applicable to other cities where high-rise building blocks are closely packed in a limited useful land area. The results of the study can help the building developers, architects, engineers, lighting designers, building environment assessors as well as legislators to set up an effective daylighting assessment scheme for high-rise buildings in a densely packed building environment.

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Appendix A1: UVA requirement specified by Practice Note PNAP278

The UVA requirement specified by Practice Note PNAP278 is listed in the following tables. It is copied from the Table 1 and Table 2 of PNAP278.

Height of building (m)	Minimum UVA (m^2) for habitable room (VDF = 8%)		
	Glazing area: 10% of usable floor area	Glazing area: 15% of usable floor area	Glazing area: 20% of usable floor area
10	50	30	20
20	100	100	60
30	250	200	150
40	400	300	200
50	600	500	400
60	900	700	500
70	1,200	900	700
80	1,600	1,200	900
90	2,000	1,500	1,100
100	2,400	1,800	1,300
110	2,900	2,200	1,600
120	3,500	2,600	1,900
130	4,100	3,100	2,200
140	4,800	3,600	2,600
150	5,400	4,100	3,000
160	6,200	4,600	3,400
170	7,000	5,200	3,800
180	7,800	5,900	4,300
190	8,700	6,500	4,700
200	9,600	7,200	5,200

Height of building (m)	Minimum UVA (m^2) for domestic kitchen (VDF = 4%)		
	Glazing area: 10% of usable floor area	Glazing area: 15% of usable floor area	Glazing area: 20% of usable floor area
10	20	15	10
20	60	40	30
30	150	100	70
40	200	200	100
50	400	300	200
60	500	400	300
70	700	500	400
80	900	700	500
90	1,100	900	700
100	1,300	1,000	800
110	1,600	1,300	1,000
120	1,900	1,500	1,200
130	2,200	1,700	1,400
140	2,600	2,000	1,600
150	3,000	2,300	1,800
160	3,400	2,600	2,000
170	3,800	2,900	2,300
180	4,300	3,300	2,600
190	4,700	3,700	2,900
200	5,200	4,000	3,200

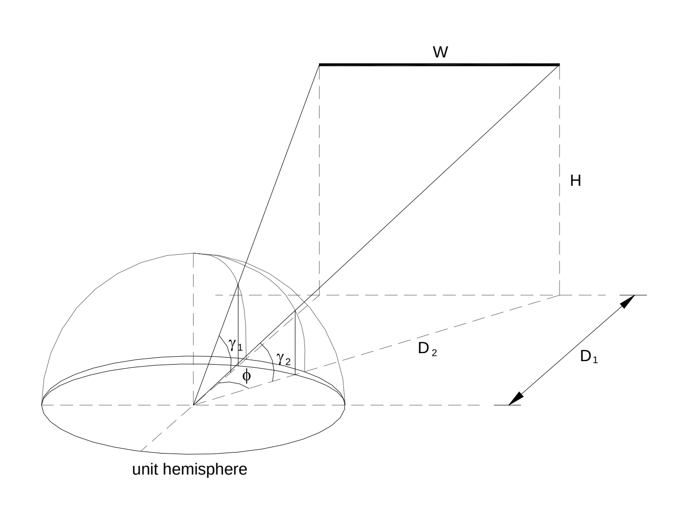
Appendix A2: UVA requirement suggested by Buildings Department consultancy report

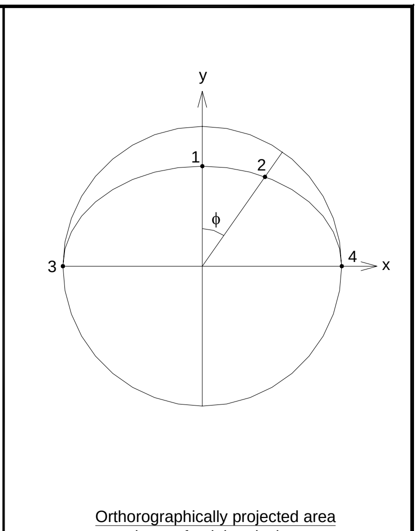
The UVA requirement suggested by the Buildings Department consultancy report is listed by the following table. It is copied from the Table 011 of the consultancy report.

	Minimum UVA (m^2)			
Height of building (m)	VDF = 8%	VDF = 6%	VDF = 4%	VDF = 3%
10	50	30	20	15
20	100	100	60	40
30	250	200	150	100
40	400	300	200	200
50	600	500	400	300
60	900	700	500	400
70	1,200	900	700	500
80	1,600	1,200	900	700
90	2,000	1,500	1,100	900
100	2,400	1,800	1,300	1,000
110	2,900	2,200	1,600	1,300
120	3,500	2,600	1,900	1,500
130	4,100	3,100	2,200	1,700
140	4,800	3,600	2,600	2,000
150	5,400	4,100	3,000	2,300
160	6,200	4,600	3,400	2,600
170	7,000	5,200	3,800	2,900
180	7,800	5,900	4,300	3,300
190	8,700	6,500	4,700	3,700
200	9,600	7,200	5,200	4,000

Note: Based on 10% window glazing to floor area ratio.

Appendix B1: Projection of parallel lines to base of unit hemisphere





A parallel line is orthographically projected onto the base of the unit hemisphere at the reference point. Its length is W and its height is H above the reference point. The projection of the parallel line is represented by the x-y coordinates. The centre of the unit hemisphere is set to be the centre (0,0) of the coordinate system. The angles γ_1 and γ_2 are subtended by the two ends of the line to the reference point. The distances D_1 and D_2 and the angle ϕ are calculated by the following equations:

$$D_1 = \frac{H}{\tan\gamma_1}$$

$$D_2 = \frac{H}{\tan\gamma_2}$$

$$\cos\phi = \frac{D_1}{D_2} = \frac{\tan\gamma_2}{\tan\gamma_1} = \frac{\sin\gamma_2\cos\gamma_1}{\sin\gamma_1\cos\gamma_2}$$

Coordinates of point 1, 2, 3 and 4 are:

Point 1:	$x = 0$	, $y = \cos\gamma_1$
Point 2:	$x = \cos\gamma_2 \sin\phi$	, $y = \cos\gamma_2 \cos\phi$
Point 3:	$x = -1$	, $y = 0$
Point 4:	$x = 1$	, $y = 0$

To prove points 1, 2, 3 and 4 lie on the same ellipse:

Let the following equation be the ellipse passing points 1, 2, 3 and 4.

$$\frac{(x-h)^2}{a^2}+\frac{(y-k)^2}{b^2}=1$$

Try the centre of the ellipse to be (0,0). Then

$$h=0,\ k=0$$

For an ellipse with its centre at (0,0) to pass through points 1, 3 and 4, the lengths of the major and minor axes would be:

$$a=1$$
$$b=\cos\gamma_1$$

Then, the equation becomes:

$$x^2+\frac{y^2}{\cos^2\gamma_1}=1$$

Substitute point 2: $(\cos\gamma_2\sin\phi,\ \cos\gamma_2\cos\phi)$ into the equation:

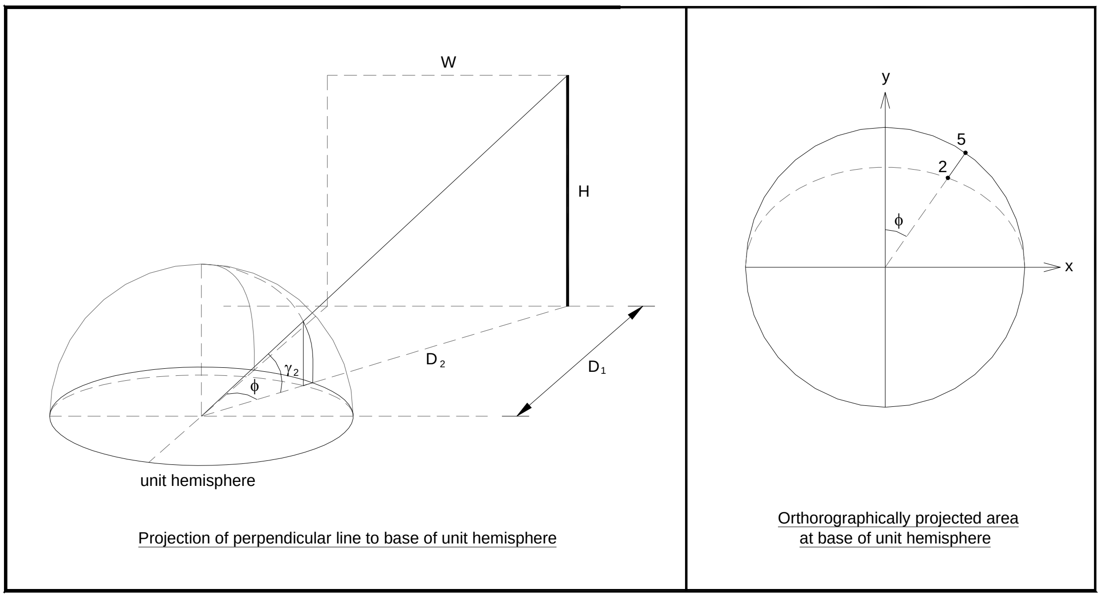
$$\begin{aligned}
\text{Left hand side} &= \cos^2\gamma_2\sin^2\phi+\frac{\cos^2\gamma_2\cos^2\phi}{\cos^2\gamma_1}\\
&= \cos^2\gamma_2\left(1-\cos^2\phi\right)+\frac{\cos^2\gamma_2}{\cos^2\gamma_1}\left(\frac{\sin^2\gamma_2\cos^2\gamma_1}{\sin^2\gamma_1\cos^2\gamma_2}\right)\\
&= \cos^2\gamma_2-\cos^2\gamma_2\left(\frac{\sin^2\gamma_2\cos^2\gamma_1}{\sin^2\gamma_1\cos^2\gamma_2}\right)+\frac{\sin^2\gamma_2}{\sin^2\gamma_1}\\
&= \cos^2\gamma_2-\frac{\sin^2\gamma_2\cos^2\gamma_1}{\sin^2\gamma_1}+\frac{\sin^2\gamma_2}{\sin^2\gamma_1}\\
&= \cos^2\gamma_2+\sin^2\gamma_2\left(\csc^2\gamma_1-\cot^2\gamma_1\right)\\
&= \cos^2\gamma_2+\sin^2\gamma_2\\
&= 1\\
&= \text{Right hand side}
\end{aligned}$$

Therefore, it is proved that the points 1, 2, 3 and 4 lie on the same ellipse of equation:

$$x^2+\frac{y^2}{\cos^2\gamma_1}=1$$

Thus, it is proved that the projection of a line to the base of the unit hemisphere on a plane parallel to this line is in form of an ellipse.

Appendix B2: Projection of perpendicular lines to base of unit hemisphere



A perpendicular line is orthographically projected onto the base of the unit hemisphere at the reference point. The projection of the line is represented by the x-y coordinates. The centre of the unit hemisphere is set to be the centre (0,0) of the coordinate system. The angle γ_2 is subtended by the top end of the line to the reference point. The distances D_2 and the angle γ_2 are calculated by the following equations:

$$D_2 = \frac{D_1}{\cos\phi}$$

$$\tan\gamma_2 = \frac{H}{D_2}$$

Coordinates of points 2 and 5 are:

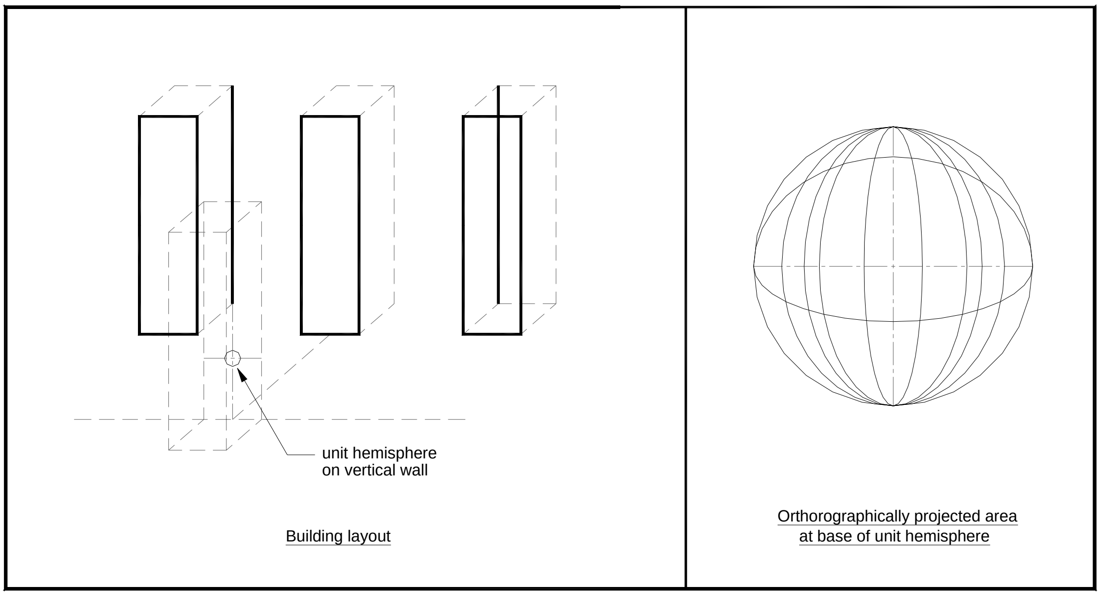
Point 2: $x = \cos\gamma_2 \sin\phi$, $y = \cos\gamma_2 \cos\phi$

Point 5: $x = \sin\phi$, $y = \cos\phi$

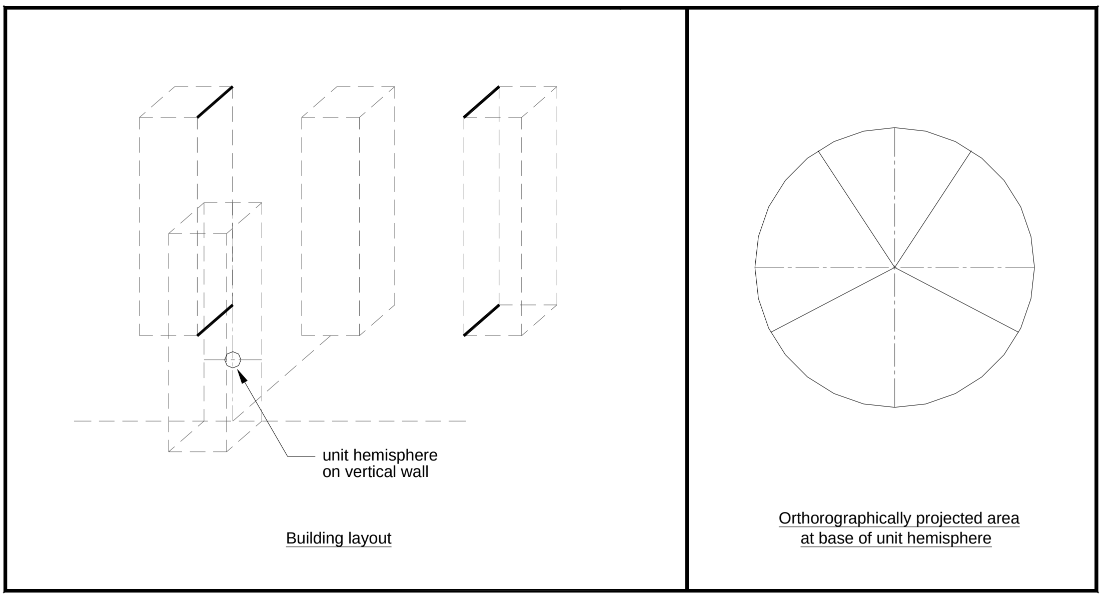
The projection of a perpendicular line to the base of a unit hemisphere is a radial line from the hemisphere centre.

Appendix B3: Examples of projection to base of unit hemisphere

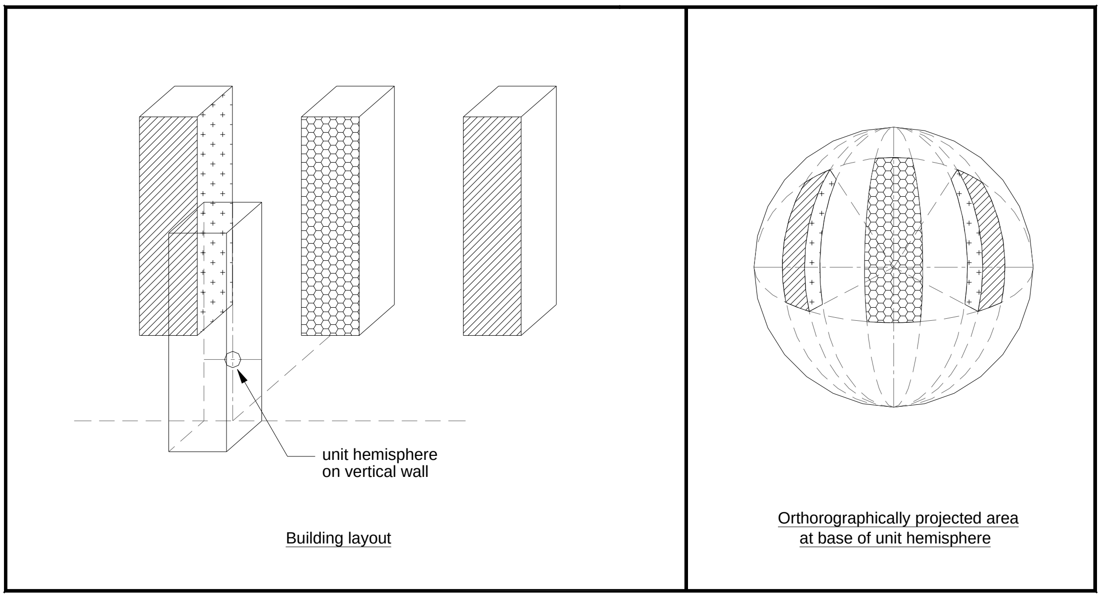
Projection of parallel lines:



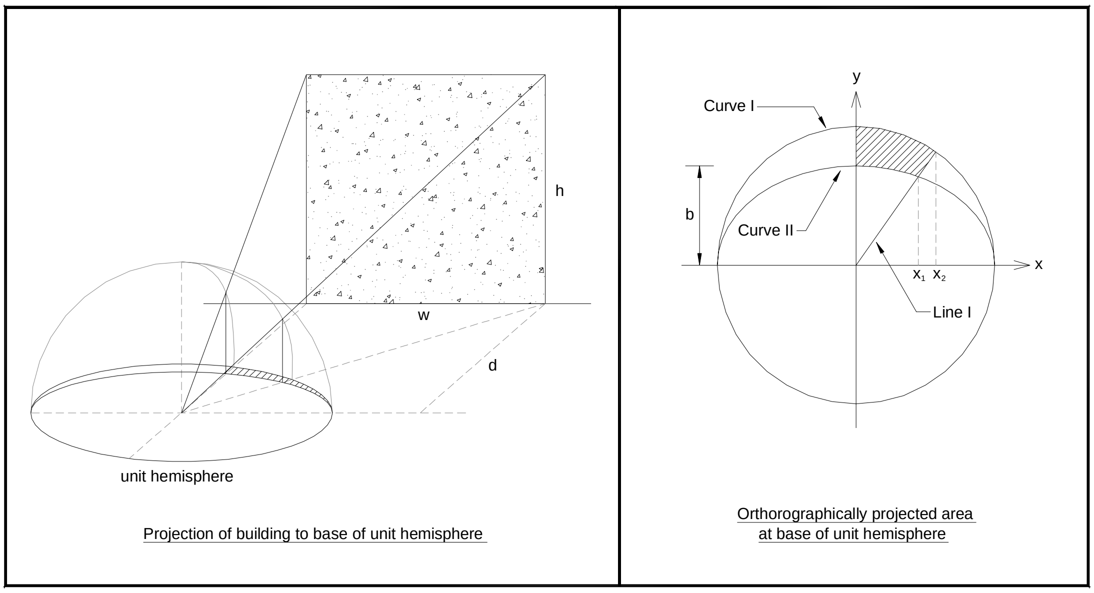
Projections of perpendicular lines:



Projection of buildings:



Appendix B4: Orthographically projected area of building



The calculation of orthographically projected area of building to a horizontal point is explained below. The calculation is done by integrating the area under curves. The general equation of the area under an ellipse bounded by two points on x-axis is explained first.

The general equation of an ellipse:

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}=1$$
$$y=\sqrt{b^2-\frac{b^2x^2}{a^2}}$$
$$y=\frac{b}{a}\sqrt{a^2-x^2}$$

Then the area under ellipse bounded by x_1 and x_2 can be calculated by the following expression:

$$\int_{x_1}^{x_2}\frac{b}{a}\sqrt{a^2-x^2}\,dx$$

Let $x=a\sin t$

$$dx=(a\cos t)dt$$

The area under ellipse bounded by x_1 and x_2 is equal to:

$$\frac{b}{a}\int_{t_1}^{t_2}\sqrt{a^2 - a^2\sin^2 t}\,(a\cos t)dt$$
$$= \frac{b}{a}\int_{t_1}^{t_2} a\cos t(a\cos t)dt$$
$$= ab\int_{t_1}^{t_2}\cos^2 tdt$$
$$= ab\int_{t_1}^{t_2}\frac{1}{2}(\cos 2t + 1)dt$$
$$= \frac{ab}{4}\left|\sin 2t + 2t\right|_{t_1}^{t_2}$$
$$= \frac{ab}{4}(\sin 2t_2 - \sin 2t_1 + 2t_2 - 2t_1)$$
$$= \frac{ab}{4}\left[\sin 2\left(\sin^{-1}\frac{x_2}{a}\right) - \sin 2\left(\sin^{-1}\frac{x_1}{a}\right) + 2\left(\sin^{-1}\frac{x_2}{a}\right) - 2\left(\sin^{-1}\frac{x_1}{a}\right)\right]$$

The general equation of a line crossing the origin:

$$y = mx$$

The area under this line bounded by x_1 and x_2 can be calculated by the following expression:

$$\int_{x_1}^{x_2} mxdx$$
$$= \frac{m}{2}\left(x_2^{\,2} - x_1^{\,2}\right)$$

Then the orthographically projected area of the building shown in the figure on previous page can be calculated by the following steps:

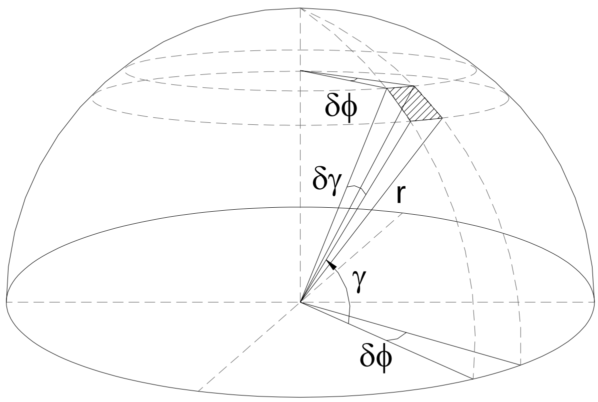
Equation of curve I:
$$x^2 + y^2 = 1$$

Equation of curve II:
$$x^2 + \frac{y^2}{b^2} = 1 \quad \text{where } b = \cos\left(\tan^{-1}\frac{h}{d}\right)$$

Equation of line I:
$$y = \frac{d}{w}x$$

Orthographically projected area
$$= \frac{1}{4}\left[\sin 2\left(\sin^{-1} x_1\right) + 2\left(\sin^{-1} x_1\right)\right] - \frac{b}{4}\left[\sin 2\left(\sin^{-1} x_1\right) + 2\left(\sin^{-1} x_1\right)\right]$$
$$+ \frac{1}{4}\left[\sin 2\left(\sin^{-1} x_2\right) - \sin 2\left(\sin^{-1} x_1\right) + 2\left(\sin^{-1} x_2\right) - 2\left(\sin^{-1} x_1\right)\right] - \frac{d}{2w}\left(x_2^{\,2} - x_1^{\,2}\right)$$

Appendix B5: Orthographically projected area on horizontal plane



The illuminance at the reference point due to the light source can be calculated by the following expression:

$$\begin{aligned}
\delta E &= \frac{L(r\delta\gamma)(r\cos\gamma\delta\phi)}{r^2}\cos(90-\gamma) \\
&= L(\sin\gamma\cos\gamma)\delta\gamma\delta\phi \\
E &= L\int_{\phi_1}^{\phi_2}\int_{\gamma_1}^{\gamma_2}(\sin\gamma\cos\gamma)d\gamma d\phi \\
&= L\int_{\phi_1}^{\phi_2}\left|\frac{1}{2}\sin^2\gamma\right|_{\gamma_1}^{\gamma_2} d\phi \\
&= \frac{L(\phi_2-\phi_1)}{2}\left(\sin^2\gamma_2-\sin^2\gamma_1\right)
\end{aligned}$$

According to the unit hemisphere method, the illuminance due to a uniformly diffusing light source is given by multiplying its luminance and orthographically projected area at the base of the unit hemisphere. Then the illuminance can also be evaluated by the expression below:

$$E = L \times \text{orthographically projected area}$$

Then the orthographically projected area of the light source at the base of the unit hemisphere on a horizontal plane (OPAH) is expressed as:

$$OPAH = \frac{(\phi_2-\phi_1)}{2}\left(\sin^2\gamma_2-\sin^2\gamma_1\right)$$

If the angles are expressed in degrees, then the expression becomes:

$$OPAH = \frac{(\phi_2-\phi_1)\pi}{360}\left(\sin^2\gamma_2-\sin^2\gamma_1\right)$$

Appendix B6: Orthographically projected area on vertical plane

When the light source is projected on a vertical plane, then the angle of incidence becomes:

Angle of incidence = $\cos^{-1}(\cos\phi\cos\gamma)$

The illuminance on a vertical plane due to the light source can be calculated by the following expression:

$$
\begin{aligned}
\delta E &= \frac{L(r\delta\gamma)(r\cos\gamma\delta\phi)}{r^2}\cos\phi\cos\gamma \\
&= L(\cos\phi\cos^2\gamma)\delta\gamma\delta\phi \\
E &= L\int_{\phi_1}^{\phi_2}\int_{\gamma_1}^{\gamma_2}(\cos\phi\cos^2\gamma)d\gamma d\phi \\
&= L\int_{\phi_1}^{\phi_2}\int_{\gamma_1}^{\gamma_2}\cos\phi\left[\frac{1}{2}(\cos 2\gamma+1)\right]d\gamma d\phi \\
&= \frac{L}{2}\int_{\phi_1}^{\phi_2}\int_{\gamma_1}^{\gamma_2}(\cos\phi\cos 2\gamma)d\gamma d\phi+\frac{L}{2}\int_{\phi_1}^{\phi_2}\int_{\gamma_1}^{\gamma_2}(\cos\phi)d\gamma d\phi \\
&= \frac{L}{4}(\sin 2\gamma_2-\sin 2\gamma_1)(\sin\phi_2-\sin\phi_1)+\frac{L}{2}(\sin\phi_2-\sin\phi_1)(\gamma_2-\gamma_1) \\
&= L(\sin\phi_2-\sin\phi_1)\left(\frac{\gamma_2-\gamma_1}{2}+\frac{\sin 2\gamma_2-\sin 2\gamma_1}{4}\right)
\end{aligned}
$$

According to the unit hemisphere method, the illuminance due to a uniformly diffusing light source is given by multiplying its luminance and orthographically projected area at the base of the unit hemisphere. Then the illuminance can also be evaluated by the expression below:

$$E = L\times\text{orthographically projected area}$$

Then the orthographically projected area of the light source at the base of the unit hemisphere on a verticall plane (OPAV) is expressed as:

$$OPAV = (\sin\phi_2-\sin\phi_1)\left(\frac{\gamma_2-\gamma_1}{2}+\frac{\sin 2\gamma_2-\sin 2\gamma_1}{4}\right)$$

If the angles are expressed in degrees, then the expression becomes:

$$OPAV = (\sin\phi_2-\sin\phi_1)\left[\frac{(\gamma_2-\gamma_1)\pi}{360}+\frac{\sin 2\gamma_2-\sin 2\gamma_1}{4}\right]$$

Appendix C1: Questionnaire (English version)

15 June 2002

Dear occupants,

Questionnaire survey of natural light environment in residential buildings

Hong Kong is one of the world's most densely populated cities. A large number of densely-packed building estates are built to meet the demand of residential flats. The building blocks are so closely packed that it results in severe sky obstruction and limitation of the admittance of natural light. In order to investigate the daylight environment of residential buildings in Hong Kong, the Department of Building Services Engineering of the Hong Kong Polytechnic University is conducting a questionnaire survey on the this issue. The purpose of this survey is to find out a satisfactory daylighting design criteria for future building development.

Choi Ming Court (Tin Shing Court) is selected as the survey site because it is located in one of the newly developed districts which are mainly for residential purpose. Every questionnaire is very important to us. Please spend a few minutes (less than five minutes) to finish this questionnaire and send back to us using the enclosed envelope. A small gift is prepared for the respondent who completes and returns the questionnaire before 15 July 2002. Should you have any queries, please feel free to contact Miss Cheung at 2766 4699. Data collected with this questionnaire will be used for academic study only. The data will be kept in strict confidence and will be destroyed after the study.

Thank you for your time in answering these questions.

Yours faithfully,

Department of Building Services Engineering
The Hong Kong Polytechnic University

1. The blinds/curtains of the window in your living room are usually:

☐	☐	☐	☐	☐
all drawn	drawn more than a half	drawn a half	drawn less than a half	not drawn

2. What is the reason for you to draw the blinds/curtains in your living room? (Please choose one only.)

☐	☐	☐	☐	☐
too bright / too glaring	reflected glare	too hot	to protect privacy	others: __________

3. How often do you switch on the electrical lighting while reading (e.g. newspaper) in your living room during the daytime?

☐ never	☐ rarely	☐ sometimes	☐ often

4. How often do you feel uncomfortable because of the strong light or reflected glare in your living room?

☐ never	☐ rarely	☐ sometimes	☐ often

5. How often do you feel uncomfortable because of the heat from daylight entering your living room?

☐ never	☐ rarely	☐ sometimes	☐ often

6. How comfortable is the daylight environment in your living room without electrical lighting during the daytime?

☐ not comfortable at all	☐ not comfortable	☐ quite comfortable	☐ very comfortable	☐ extremely comfortable

7. How bright is the daylight environment in your living room without electrical lighting during the daytime?

☐ not bright at all	☐ not bright	☐ quite bright	☐ very bright	☐ extremely bright

8. How adequate is the daylight in your living room without electrical lighting during the daytime?

☐ far too little	☐ too little	☐ just right	☐ too much	☐ far too much

9. Do you think that the daylight environment of your living room have to be improved?

☐ need improvement	☐ need no improvement

10. Do you agree that the daylight environment of your living room is satisfactory?

☐ agree	☐ disagree

11. If 10 is the highest mark, what mark will you give to the daylight environment of your living room?

[ ]

12. What is the best time to have sunlight for the following rooms? Please tick the best time for every room.
(Please choose one only for every room.)

	morning	noon	afternoon	dusk	no special preference
living room	☐	☐	☐	☐	☐
dining room	☐	☐	☐	☐	☐
bedroom	☐	☐	☐	☐	☐
kitchen	☐	☐	☐	☐	☐
bathroom	☐	☐	☐	☐	☐

13. Which room do you think that sunlight is most important to?
(Please rank the importance from 1 representing the most important to 5 representing the least important.)

☐ living room	☐ dining room	☐ bedroom	☐ kitchen	☐ bathroom

14. Do you have other opinions of the daylight environment of your living room?

[ ]

15. Gender:

☐ Male ☐ Female

16. Age group:

☐ <20	☐ 20-30	☐ 30-40	☐ 40-50	☐ 50-60	☐ >60

Appendix C2: Questionnaire (Chinese version)

彩明苑(天盛苑)住戶台鑒:

住宅天然採光環境問卷調查

香港人口綢密, 居住環境擠迫, 間接令很多住宅未能獲得滿意的天然採光環境。爲了更了解香港市民對於天然採光居住環境的意見, 香港理工大學屋宇設備工程系正進行上述調查, 目的是找出良好天然採光標準, 爲未來的屋宇建設作好準備。

將軍澳(天水圍)是香港其中一個重點發展社區, 所以我們選擇了是彩明苑(天盛苑)的住戶作爲這次問卷的調查對像。每一份問卷對我們都是十分重要, 請你用幾分鐘時間(少於五分鐘)完成這份問卷, 然後用附函的回郵信封, 盡量在七月十五日前寄回給我們。如在七月十五日前寄回, 我們會送給你一套紀念禮筆以示感謝! 如有任何疑問, 請致電: 2766 4699 張小姐。問卷的資料會絕對保密, 資料經過電腦處理後, 會立刻被銷毀, 請你放心。

請大家爲未來的香港出一分力, 謹代表全香港市民多謝你。

此致

屋宇設備工程系
香港理工大學
二零零二年六月十五日

1. 你屋企客廳的窗簾通常是:

☐ 全閂	☐ 閂大部份	☐ 開一半 閂一半	☐ 開大部份	☐ 全開

2. 那麼你閂埋屋企客廳窗簾的主要原因是: (請選擇一個。)

☐ 太光 / 太刺眼	☐ 反光	☐ 太熱	☐ 保護私隱	☐ 其他: ________

3. 日間你在屋企客廳閱讀的時侯 (例如:讀報紙), 通常有幾多時間需要開電燈?

☐ 從不	☐ 很少	☐ 有時	☐ 經常

4. 在你印像中, 有幾多時間因曬入客廳的天然光, 令你覺得刺眼或反光而造成不舒服?

☐ 從不	☐ 很少	☐ 有時	☐ 經常

5. 在你印像中, 有幾多時間因曬入客廳的天然光, 令你覺得太熱而造成不舒服?

☐ 從不	☐ 很少	☐ 有時	☐ 經常

6. 日間在沒有開電燈的情況下, 你認為你屋企客廳的天然光視覺環境有幾舒服?

☐ 一點也不舒服	☐ 不是很舒服	☐ 有些舒服	☐ 很舒服	☐ 極為舒服

7. 日間在沒有開電燈的情況下, 你認為你屋企客廳有幾光猛?

☐ 一點也不光猛	☐ 不是很光猛	☐ 有些光猛	☐ 很光猛	☐ 極為光猛

8. 那麼你認為你屋企客廳的陽光是否足夠?

☐ 太少	☐ 少了點	☐ 剛剛好	☐ 多了點	☐ 太多

9. 總括來說, 你認為你屋企客廳的天然採光環境有沒有需要改善?

☐ 有需要改善	☐ 沒有需要改善

10. 總括來說, 你同不同意你屋企客廳有滿意的天然採光環境?

☐ 同意	☐ 不同意

11. 如果 10 是最高分, 你會俾你屋企 客廳的天然採光環境幾多分?

[ ]

12. 你認爲這幾間房最好那一段時間有陽光? 請在你認爲最好有陽光的那一段時間加上「√」號。
(請每一間房選擇一段時間。)

	上午	中午	下午	黃昏	冇所謂
客廳	☐	☐	☐	☐	☐
飯廳	☐	☐	☐	☐	☐
睡房	☐	☐	☐	☐	☐
廚房	☐	☐	☐	☐	☐
廁所	☐	☐	☐	☐	☐

13. 你認爲天然日光對以下這幾間房較重要?
(請須次序排列, 用 1 代表最重要, 用 5 代表最不重要, 如此類推。)

☐	☐	☐	☐	☐
客廳	飯廳	睡房	廚房	廁所

14. 你對你屋企客廳的天然採光環境有沒有其他意見?

[ ]

15. 性別:

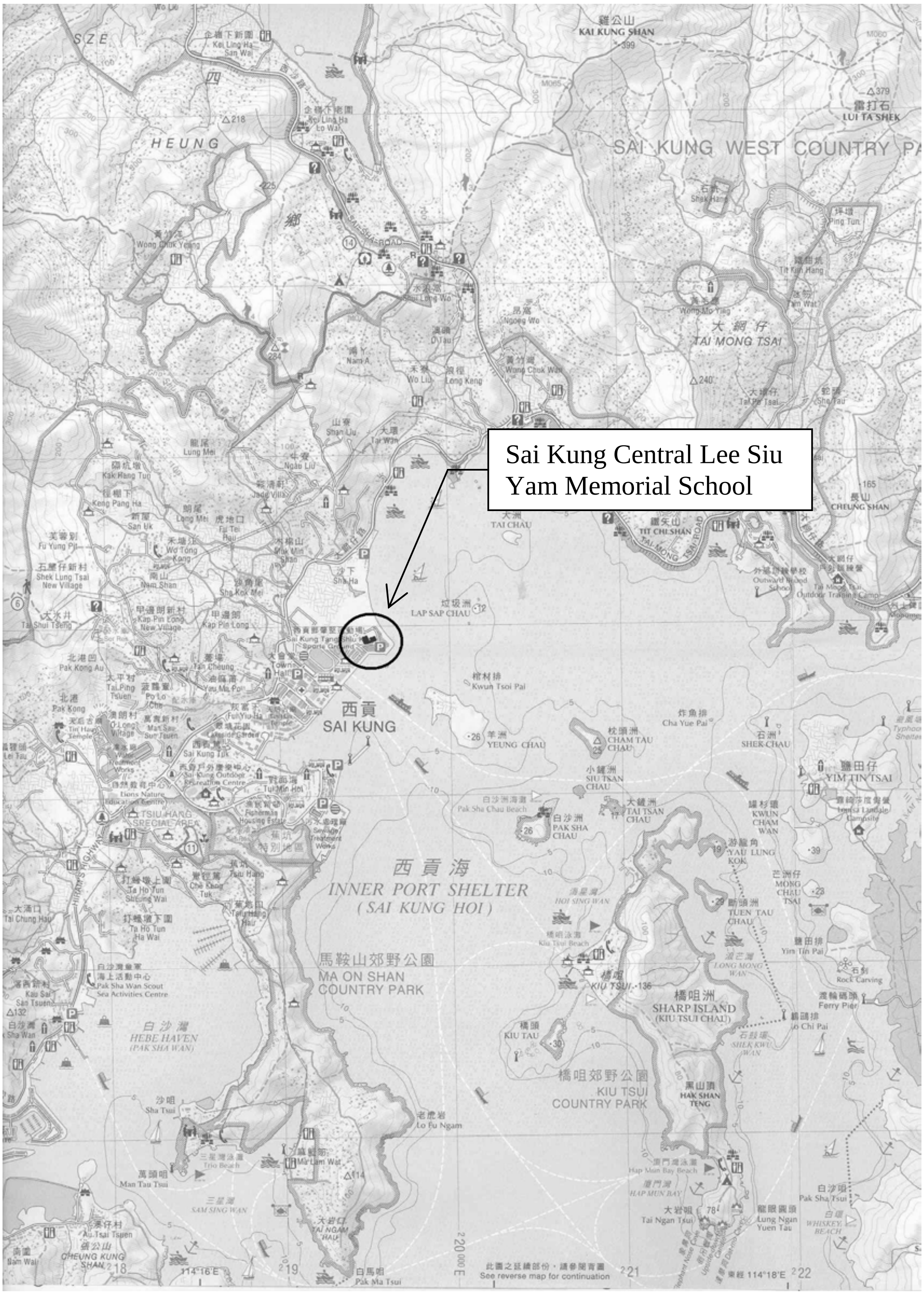
☐ 男 ☐ 女

16. 年齡:

☐	☐	☐	☐	☐	☐
<20	20-30	30-40	40-50	50-60	>60

Appendix D1: General information of the measurement site

The site location is a primary school called Sai Kung Central Lee Siu Yam Memorial School. It is located in Sai Kung which is one of the rural areas in Hong Kong.



Site map of Sai Kung

West elevation of Sai Kung Central Lee Siu Yam Memorial School

South elevation of Sai Kung Central Lee Siu Yam Memorial School


East view of site location


South view of site location


West view of site location


North view of site location

Appendix D2: Photos of measurement setup

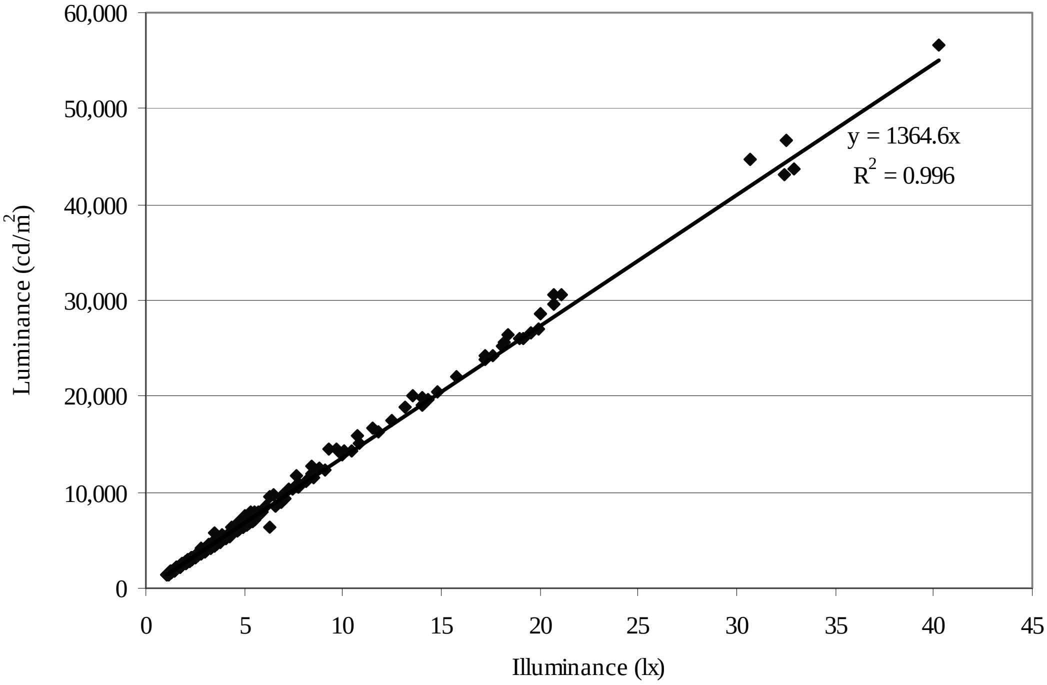
Measurement of global horizontal illuminance

Measurement of diffuse horizontal illuminance

Measurement of vertical illuminances at centres of vertical planes

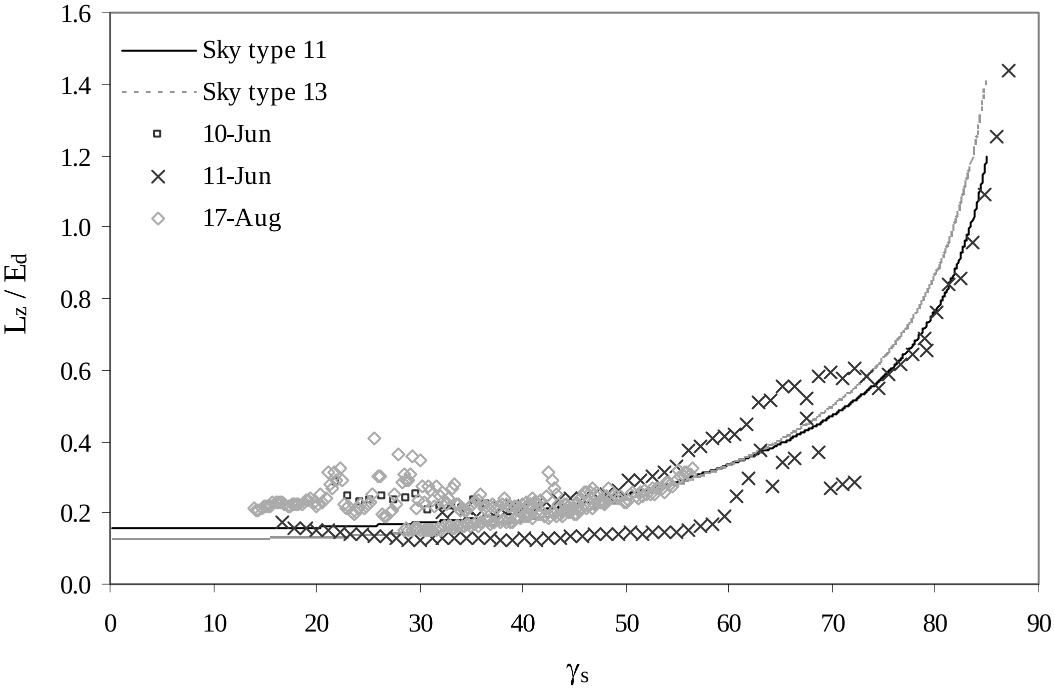
Measurement of sky zenith luminance

Appendix D3: Calibration of photocell for measurement of sky zenith luminance

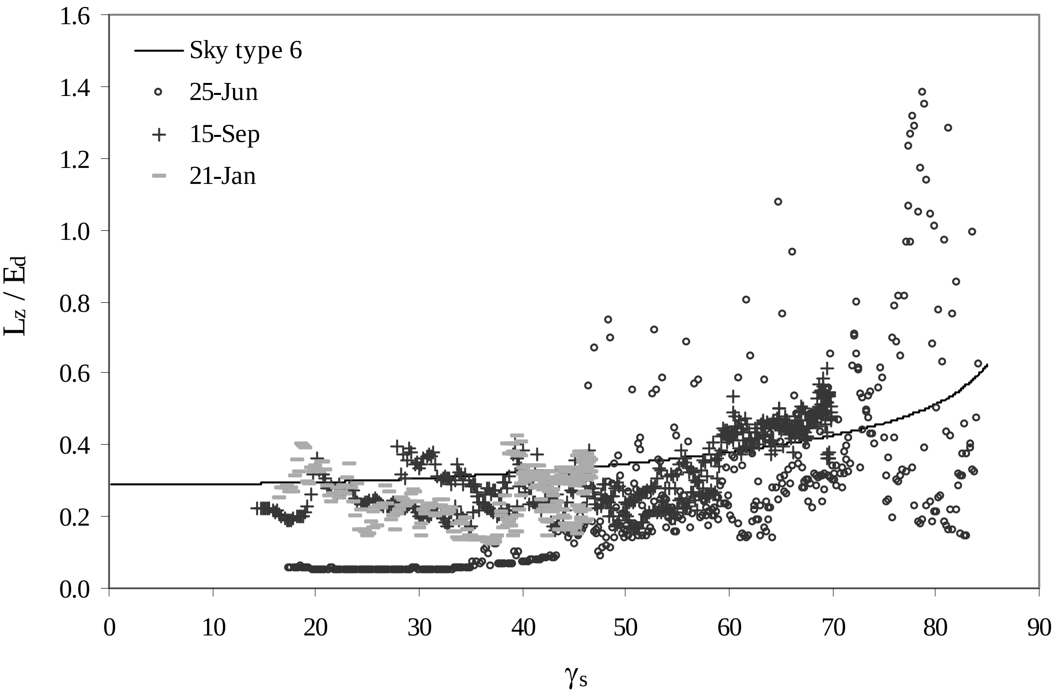


Luminance measurement by luminance meter plotted against the illuminance measurement by photocell installed in a tailor-made tube

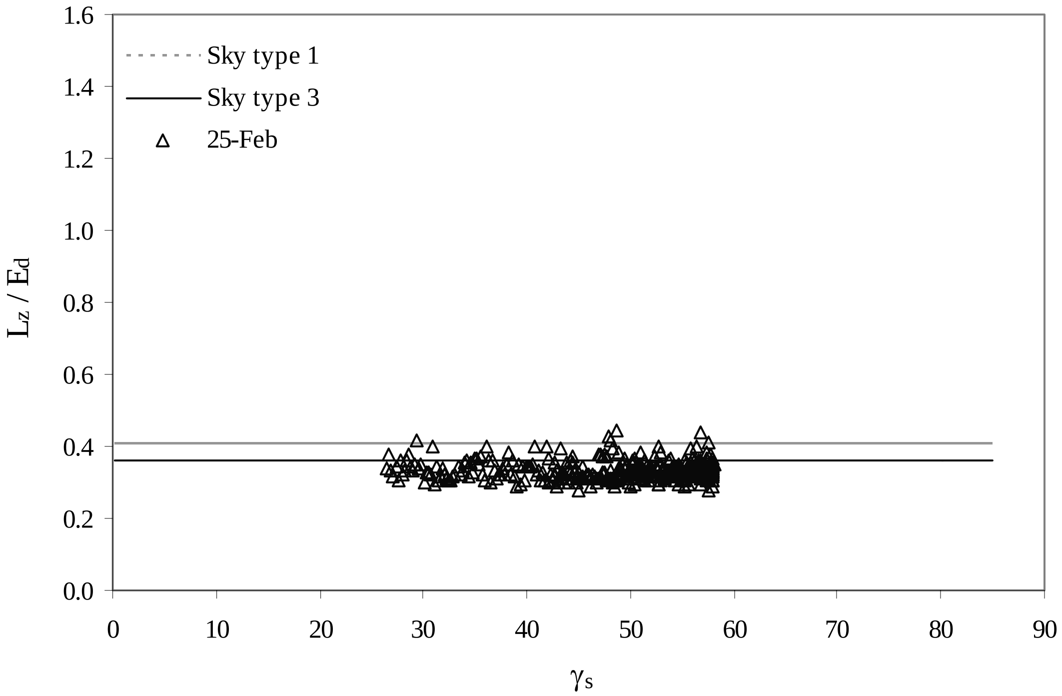
Appendix D4: Sky type classification for measurement data



Clear sky condition



Partly cloudy sky condition



Overcast sky condition

Appendix E1: Generation of spots in sunlight availability indicator

The sunlight availability indicator uses the bright sunshine hour data recorded by the Hong Kong Observatory as the base data. The bright sunshine hour is measured based on the apparent solar time. It represents the fraction of an hour that sunlight is received by an unobstructed horizontal plane. The data are recorded hourly with a Campbell Stokes recorder at the King's Park by the Hong Kong Observatory. 31 years of data from 1970 to 2000 are used for the generation of the spots. The bright sunshine hours of the same hour in a month are added up for every year. Then the sum for every hour in a month is averaged over 31 years. So a set of averaged hourly bright sunshine duration sum is resulted for every month. The hourly bright sunshine duration sums for all the months were summed in order to find the annual total bright sunshine hours. The annual total bright sunshine hours were then divided by 200 to give the number of bright sunshine hours H_s that one spot should indicate. H_s represents 0.5% of the annual total bright sunshine hours.

$$H_s = \frac{\text{annual total bright sunshine hours}}{200}$$

Then, a running total T_s was kept by adding up the hourly bright sunshine durations beginning in the first hour in January. If T_s exceeds H_s, a spot was plotted. A spot time was generated by linear interpolation between the hour before T_s exceeded H_s and the hour afterwards. The spots were then plotted on the sunpath indicator for the 15th day of every month.

Take the data in January as an example. The averaged hourly bright sunshine duration sums are listed as follows:

Solar time	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5
Bright sunshine duration sum	2.5	10.5	13.5	15	16	17	17	16.5	16	14	3.5	

Let's say H_s equal to 9 hrs. Then the bright sunshine duration sums for the hours centreed at 7 and 8 are first added together. The running total T_s then equal to 2.5 + 10.5 = 13 which exceeds H_s. Therefore, a spot should be plotted at solar time equal to:

$$7 + \frac{9 - 2.5}{10.5 - 2.5} = 7.8125$$

The running total T_s is then changed to 13 – 9 = 4. The same procedures repeat for the remaining hours of January. Then the same procedures continue for the other months. By the time all the bright sunshine duration sums have been used up, there should be 200 spots plotted on the indicator.

Appendix E2: Numerical values of the sky map of annual cumulative probable sunlight duration

Winter cumulative probable sunlight duration of every sky patch $P_{\phi\gamma}^{win}$:

φ / γ	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5
-177.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-172.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-167.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-162.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-157.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-152.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-147.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-142.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-137.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-132.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-127.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-122.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-117.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-112.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-107.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-102.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-97.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-92.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-87.5	0	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-82.5	0.08	1.17	0.89	0.41	0.06	0	0	0	0	0	0	0	0	0	0	0	0	0
-77.5	0.61	1.42	1.4	1.5	2.13	0.89	0.04	0	0	0	0	0	0	0	0	0	0	0
-72.5	1.35	1.52	1.38	2.38	3.1	2.62	1.84	0.47	0	0	0	0	0	0	0	0	0	0
-67.5	2.06	1.62	2.01	3.53	2.88	2.9	3.17	2.45	0.89	0	0	0	0	0	0	0	0	0
-62.5	1.6	2.73	4.98	4.82	4.03	3.07	3.18	3.28	2.4	1.05	0	0	0	0	0	0	0	0
-57.5	0	0.13	7.75	9.37	5.17	4.77	3.65	2.93	3.15	2.39	0.76	0	0	0	0	0	0	0
-52.5	0	0	0	3.61	11.28	6.58	4.69	3.42	3.03	3.05	1.97	0.21	0	0	0	0	0	0
-47.5	0	0	0	0	2.35	12	6.13	4.56	3.41	2.98	2.5	1.12	0	0	0	0	0	0
-42.5	0	0	0	0	0	2.62	11.7	5.65	4.21	2.88	2.81	1.84	0.15	0	0	0	0	0
-37.5	0	0	0	0	0	0	6.26	9.38	4.62	3.33	2.78	2.27	0.67	0	0	0	0	0
-32.5	0	0	0	0	0	0	0	10.85	5.7	3.93	2.77	2.52	1.15	0	0	0	0	0
-27.5	0	0	0	0	0	0	0	5.39	8.47	4.45	2.92	2.57	1.52	0.01	0	0	0	0
-22.5	0	0	0	0	0	0	0	0	11.53	4.78	3.24	2.62	1.73	0.16	0	0	0	0
-17.5	0	0	0	0	0	0	0	0	9.14	5.38	3.5	2.45	1.95	0.36	0	0	0	0
-12.5	0	0	0	0	0	0	0	0	7.33	6.12	3.68	2.47	2.14	0.49	0	0	0	0
-7.5	0	0	0	0	0	0	0	0	5.72	7.13	3.92	2.49	2.12	0.64	0	0	0	0
-2.5	0	0	0	0	0	0	0	0	4.88	7.62	4.06	2.5	2.17	0.64	0	0	0	0
2.5	0	0	0	0	0	0	0	0	4.88	7.62	4.06	2.5	2.17	0.64	0	0	0	0
7.5	0	0	0	0	0	0	0	0	5.73	7.13	3.92	2.49	2.12	0.64	0	0	0	0
12.5	0	0	0	0	0	0	0	0	7.53	6.29	3.8	2.49	2.14	0.49	0	0	0	0
17.5	0	0	0	0	0	0	0	0	9.39	5.57	3.68	2.42	2	0.37	0	0	0	0
22.5	0	0	0	0	0	0	0	0	11.84	5.01	3.4	2.55	1.87	0.16	0	0	0	0
27.5	0	0	0	0	0	0	0	5.73	8.79	4.67	3	2.54	1.66	0.01	0	0	0	0
32.5	0	0	0	0	0	0	0	11.62	6.12	4.19	2.83	2.52	1.24	0	0	0	0	0
37.5	0	0	0	0	0	0	6.75	9.97	5.08	3.63	2.77	2.37	0.72	0	0	0	0	0
42.5	0	0	0	0	0	2.99	12.87	6.13	4.59	3.12	2.84	2	0.16	0	0	0	0	0
47.5	0	0	0	0	2.68	13.51	6.87	5.11	3.72	3.07	2.59	1.19	0	0	0	0	0	0
52.5	0	0	0	4.51	13.17	7.37	5.39	4	3.25	3.09	2.08	0.22	0	0	0	0	0	0
57.5	0	0.2	9.65	11.46	6.31	5.51	4.27	3.39	3.36	2.51	0.82	0	0	0	0	0	0	0
62.5	2.32	3.74	6.1	5.94	4.95	3.81	3.62	3.57	2.69	1.16	0	0	0	0	0	0	0	0
67.5	2.67	2.22	2.63	4.4	3.63	3.54	3.53	2.74	1.02	0	0	0	0	0	0	0	0	0
72.5	1.84	1.98	1.7	2.91	3.69	3.06	2.14	0.55	0	0	0	0	0	0	0	0	0	0
77.5	0.76	1.66	1.68	1.8	2.51	1.05	0.05	0	0	0	0	0	0	0	0	0	0	0
82.5	0.09	1.4	0.99	0.4	0.07	0	0	0	0	0	0	0	0	0	0	0	0	0
87.5	0	0.17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
97.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
102.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
107.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
112.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
117.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
122.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
127.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
132.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
137.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
142.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
147.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
152.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
157.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
162.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
167.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
172.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
177.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Summer cumulative probable sunlight duration of every sky patch $P_{\phi\gamma}^{sum}$:

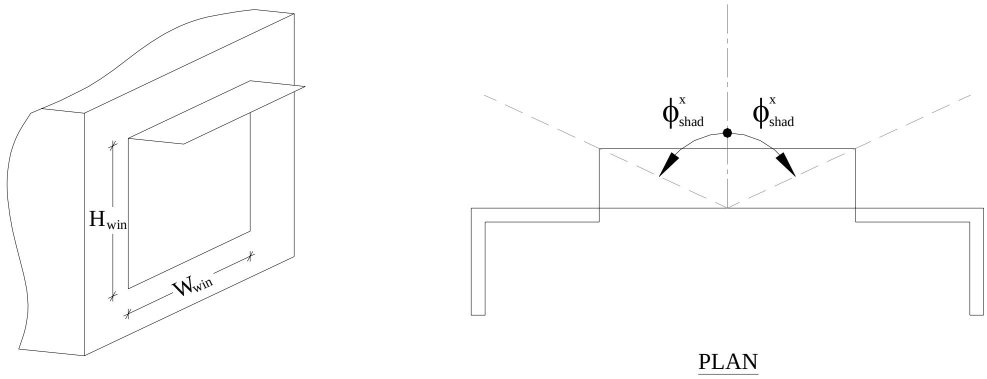
φ / γ	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5
-177.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-172.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.23
-167.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.04
-162.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15
-157.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.08
-152.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.14
-147.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.13
-142.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15
-137.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.21
-132.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
-127.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.26
-122.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.36
-117.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.47
-112.5	2.15	2.56	0.97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.71
-107.5	1.18	1.64	3.21	8.96	6.73	3.69	0.05	0	0	0	0	0	0	0	0	0	0	1.22
-102.5	0.64	0.8	2.24	4.53	5.44	7.8	10.96	9.01	7.15	4.76	0.78	0	0	0	0	0	1.59	1.25
-97.5	0.32	0.44	2.39	3.09	3.35	4.24	4.97	5.4	6.57	7.65	10.01	9.69	7.96	6.6	5.78	5.3	4.05	0.83
-92.5	0.08	0.47	2.06	2.29	2.57	3.65	3.76	3.8	4.26	4.4	4.51	4.95	4.88	4.76	4.32	3.55	2.1	0.74
-87.5	0.01	0.59	1.57	1.8	2.19	2.87	2.97	3.21	3.58	3.46	3.37	3.73	3.59	3.22	2.9	2.49	1.75	0.66
-82.5	0	0	0.18	0.7	2.31	2.76	2.61	2.72	2.92	3.04	3.09	2.96	2.91	2.74	2.41	1.95	1.48	0.61
-77.5	0	0	0	0	0.28	1.48	2.47	2.86	2.66	2.52	2.72	2.85	2.48	2.37	2.17	1.74	1.22	0.56
-72.5	0	0	0	0	0	0	0.45	2.18	2.71	2.47	2.36	2.46	2.42	2.09	1.92	1.62	1.16	0.53
-67.5	0	0	0	0	0	0	0	0.07	1.49	2.45	2.59	2.1	2.13	2.12	1.67	1.51	1.09	0.48
-62.5	0	0	0	0	0	0	0	0	0	1.2	2.34	2.26	1.86	1.94	1.71	1.36	1.05	0.43
-57.5	0	0	0	0	0	0	0	0	0	0	1.37	2.15	1.88	1.73	1.65	1.29	0.93	0.48
-52.5	0	0	0	0	0	0	0	0	0	0	0.12	1.74	1.97	1.57	1.6	1.2	0.96	0.4
-47.5	0	0	0	0	0	0	0	0	0	0	0	0.73	1.95	1.55	1.43	1.22	0.87	0.39
-42.5	0	0	0	0	0	0	0	0	0	0	0	0.07	1.6	1.64	1.35	1.19	0.89	0.44
-37.5	0	0	0	0	0	0	0	0	0	0	0	0	0.97	1.62	1.29	1.16	0.78	0.38
-32.5	0	0	0	0	0	0	0	0	0	0	0	0	0.52	1.61	1.22	1.18	0.78	0.41
-27.5	0	0	0	0	0	0	0	0	0	0	0	0	0.12	1.53	1.22	1.11	0.79	0.4
-22.5	0	0	0	0	0	0	0	0	0	0	0	0	0	1.38	1.22	1.09	0.74	0.37
-17.5	0	0	0	0	0	0	0	0	0	0	0	0	0	1.12	1.26	1.08	0.74	0.39
-12.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0.97	1.24	1.04	0.76	0.37
-7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0.87	1.28	1.02	0.79	0.36
-2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0.82	1.25	1.03	0.75	0.35
2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0.82	1.25	1.03	0.75	0.35
7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0.87	1.28	1.02	0.79	0.36
12.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0.97	1.24	1.04	0.76	0.37
17.5	0	0	0	0	0	0	0	0	0	0	0	0	0	1.12	1.26	1.08	0.74	0.39
22.5	0	0	0	0	0	0	0	0	0	0	0	0	0	1.42	1.22	1.09	0.74	0.37
27.5	0	0	0	0	0	0	0	0	0	0	0	0	0.13	1.53	1.22	1.11	0.79	0.4
32.5	0	0	0	0	0	0	0	0	0	0	0	0	0.55	1.61	1.21	1.15	0.78	0.41
37.5	0	0	0	0	0	0	0	0	0	0	0	0	1.03	1.58	1.25	1.16	0.78	0.38
42.5	0	0	0	0	0	0	0	0	0	0	0	0.07	1.68	1.59	1.29	1.19	0.89	0.44
47.5	0	0	0	0	0	0	0	0	0	0	0	0.77	1.94	1.53	1.38	1.2	0.87	0.39
52.5	0	0	0	0	0	0	0	0	0	0	0.13	1.87	1.92	1.53	1.58	1.16	0.95	0.4
57.5	0	0	0	0	0	0	0	0	0	0	1.47	2.15	1.83	1.65	1.65	1.25	0.93	0.48
62.5	0	0	0	0	0	0	0	0	0	1.26	2.43	2.17	1.79	1.9	1.67	1.33	1.05	0.43
67.5	0	0	0	0	0	0	0	0.07	1.53	2.61	2.49	2.02	2.14	2.14	1.63	1.47	1.08	0.48
72.5	0	0	0	0	0	0	0.46	2.31	2.87	2.52	2.28	2.46	2.54	2.04	1.88	1.6	1.17	0.53
77.5	0	0	0	0	0.29	1.59	2.69	3.01	2.68	2.68	2.92	2.97	2.45	2.29	2.14	1.75	1.23	0.56
82.5	0	0	0.22	0.79	2.5	3.05	2.87	2.9	3.28	3.38	3.21	2.9	2.84	2.7	2.41	1.99	1.45	0.61
87.5	0	0.66	1.58	1.78	2.27	3.16	3.37	3.63	3.75	3.49	3.46	3.64	3.52	3.21	2.89	2.46	1.75	0.66
92.5	0.07	0.43	2.09	2.43	2.93	3.99	3.84	3.85	4.44	4.57	4.67	4.92	4.91	4.74	4.24	3.47	2.06	0.74
97.5	0.35	0.54	2.66	3.29	3.51	4.52	5.4	5.77	6.81	7.83	10.13	9.7	7.91	6.58	5.78	5.29	4.05	0.83
102.5	0.76	0.95	2.53	5.02	5.79	8.08	11.23	9.21	7.22	4.8	0.78	0	0	0	0	0	1.59	1.25
107.5	1.51	2.11	3.87	9.44	7.18	3.94	0.05	0	0	0	0	0	0	0	0	0	0	1.22
112.5	2.68	3.15	1.18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.71
117.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.47
122.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.36
127.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.26
132.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
137.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.21
142.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15
147.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.13
152.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.14
157.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.08
162.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15
167.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.04
172.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.23
177.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

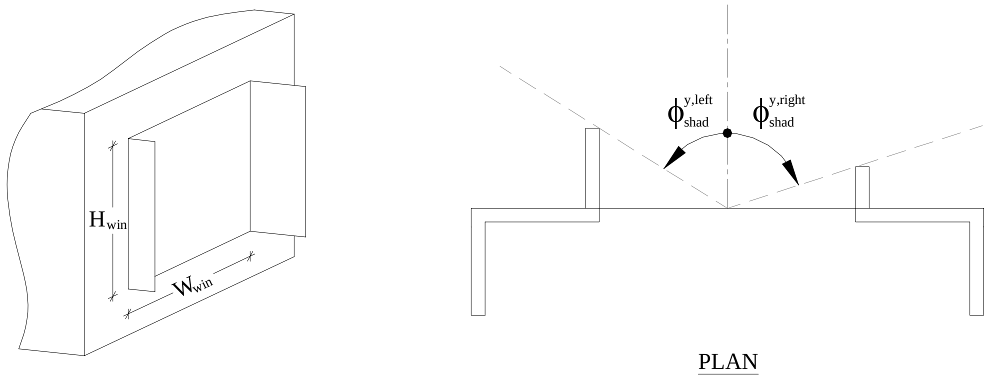
Annual cumulative probable sunlight duration of every sky patch $P_{\phi\gamma}^{ann}$:

ϕ / γ	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5
-177.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-172.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.23
-167.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.04
-162.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15
-157.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.08
-152.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.14
-147.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.13
-142.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15
-137.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.21
-132.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
-127.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.26
-122.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.36
-117.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.47
-112.5	2.15	2.56	0.97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.71
-107.5	1.18	1.64	3.21	8.96	6.73	3.69	0.05	0	0	0	0	0	0	0	0	0	0	1.22
-102.5	0.64	0.8	2.24	4.53	5.44	7.8	10.96	9.01	7.15	4.76	0.78	0	0	0	0	0	1.59	1.25
-97.5	0.32	0.44	2.39	3.09	3.35	4.24	4.97	5.4	6.57	7.65	10.01	9.69	7.96	6.6	5.78	5.3	4.05	0.83
-92.5	0.08	0.47	2.06	2.29	2.57	3.65	3.76	3.8	4.26	4.4	4.51	4.95	4.88	4.76	4.32	3.55	2.1	0.74
-87.5	0.01	0.76	1.57	1.8	2.19	2.87	2.97	3.21	3.58	3.46	3.37	3.73	3.59	3.22	2.9	2.49	1.75	0.66
-82.5	0.08	1.17	1.07	1.12	2.37	2.76	2.61	2.72	2.92	3.04	3.09	2.96	2.91	2.74	2.41	1.95	1.48	0.61
-77.5	0.61	1.42	1.4	1.5	2.41	2.36	2.51	2.86	2.66	2.52	2.72	2.85	2.48	2.37	2.17	1.74	1.22	0.56
-72.5	1.35	1.52	1.38	2.38	3.1	2.62	2.29	2.65	2.71	2.47	2.36	2.46	2.42	2.09	1.92	1.62	1.16	0.53
-67.5	2.06	1.62	2.01	3.53	2.88	2.9	3.17	2.52	2.38	2.45	2.59	2.1	2.13	2.12	1.67	1.51	1.09	0.48
-62.5	1.6	2.73	4.98	4.82	4.03	3.07	3.18	3.28	2.4	2.24	2.34	2.26	1.86	1.94	1.71	1.36	1.05	0.43
-57.5	0	0.13	7.75	9.37	5.17	4.77	3.65	2.93	3.15	2.39	2.13	2.15	1.88	1.73	1.65	1.29	0.93	0.48
-52.5	0	0	0	3.61	11.28	6.58	4.69	3.42	3.03	3.05	2.09	1.94	1.97	1.57	1.6	1.2	0.96	0.4
-47.5	0	0	0	0	2.35	12	6.13	4.56	3.41	2.98	2.5	1.85	1.95	1.55	1.43	1.22	0.87	0.39
-42.5	0	0	0	0	0	2.62	11.7	5.65	4.21	2.88	2.81	1.91	1.75	1.64	1.35	1.19	0.89	0.44
-37.5	0	0	0	0	0	0	6.26	9.38	4.62	3.33	2.78	2.27	1.64	1.62	1.29	1.16	0.78	0.38
-32.5	0	0	0	0	0	0	0	10.85	5.7	3.93	2.77	2.52	1.67	1.61	1.22	1.18	0.78	0.41
-27.5	0	0	0	0	0	0	0	5.39	8.47	4.45	2.92	2.57	1.64	1.54	1.22	1.11	0.79	0.4
-22.5	0	0	0	0	0	0	0	0	11.53	4.78	3.24	2.62	1.73	1.54	1.22	1.09	0.74	0.37
-17.5	0	0	0	0	0	0	0	0	9.14	5.38	3.5	2.45	1.95	1.48	1.26	1.08	0.74	0.39
-12.5	0	0	0	0	0	0	0	0	7.33	6.12	3.68	2.47	2.14	1.46	1.24	1.04	0.76	0.37
-7.5	0	0	0	0	0	0	0	0	5.72	7.13	3.92	2.49	2.12	1.51	1.28	1.02	0.79	0.36
-2.5	0	0	0	0	0	0	0	0	4.88	7.62	4.06	2.5	2.17	1.45	1.25	1.03	0.75	0.35
2.5	0	0	0	0	0	0	0	0	4.88	7.62	4.06	2.5	2.17	1.45	1.25	1.03	0.75	0.35
7.5	0	0	0	0	0	0	0	0	5.73	7.13	3.92	2.49	2.12	1.51	1.28	1.02	0.79	0.36
12.5	0	0	0	0	0	0	0	0	7.53	6.29	3.8	2.49	2.14	1.46	1.24	1.04	0.76	0.37
17.5	0	0	0	0	0	0	0	0	9.39	5.57	3.68	2.42	2	1.49	1.26	1.08	0.74	0.39
22.5	0	0	0	0	0	0	0	0	11.84	5.01	3.4	2.55	1.87	1.59	1.22	1.09	0.74	0.37
27.5	0	0	0	0	0	0	0	5.73	8.79	4.67	3	2.54	1.79	1.54	1.22	1.11	0.79	0.4
32.5	0	0	0	0	0	0	0	11.62	6.12	4.19	2.83	2.52	1.79	1.61	1.21	1.15	0.78	0.41
37.5	0	0	0	0	0	0	6.75	9.97	5.08	3.63	2.77	2.37	1.75	1.58	1.25	1.16	0.78	0.38
42.5	0	0	0	0	0	2.99	12.87	6.13	4.59	3.12	2.84	2.08	1.83	1.59	1.29	1.19	0.89	0.44
47.5	0	0	0	0	2.68	13.51	6.87	5.11	3.72	3.07	2.59	1.96	1.94	1.53	1.38	1.2	0.87	0.39
52.5	0	0	0	4.51	13.17	7.37	5.39	4	3.25	3.09	2.21	2.09	1.92	1.53	1.58	1.16	0.95	0.4
57.5	0	0.2	9.65	11.46	6.31	5.51	4.27	3.39	3.36	2.51	2.29	2.15	1.83	1.65	1.65	1.25	0.93	0.48
62.5	2.32	3.74	6.1	5.94	4.95	3.81	3.62	3.57	2.69	2.42	2.43	2.17	1.79	1.9	1.67	1.33	1.05	0.43
67.5	2.67	2.22	2.63	4.4	3.63	3.54	3.53	2.8	2.56	2.61	2.49	2.02	2.14	2.14	1.63	1.47	1.08	0.48
72.5	1.84	1.98	1.7	2.91	3.69	3.06	2.6	2.86	2.87	2.52	2.28	2.46	2.54	2.04	1.88	1.6	1.17	0.53
77.5	0.76	1.66	1.68	1.8	2.79	2.64	2.74	3.01	2.68	2.68	2.92	2.97	2.45	2.29	2.14	1.75	1.23	0.56
82.5	0.09	1.4	1.2	1.2	2.57	3.05	2.87	2.9	3.28	3.38	3.21	2.9	2.84	2.7	2.41	1.99	1.45	0.61
87.5	0	0.82	1.59	1.78	2.27	3.16	3.37	3.63	3.75	3.49	3.46	3.64	3.52	3.21	2.89	2.46	1.75	0.66
92.5	0.07	0.43	2.09	2.43	2.93	3.99	3.84	3.85	4.44	4.57	4.67	4.92	4.91	4.74	4.24	3.47	2.06	0.74
97.5	0.35	0.54	2.66	3.29	3.51	4.52	5.4	5.77	6.81	7.83	10.13	9.7	7.91	6.58	5.78	5.29	4.05	0.83
102.5	0.76	0.95	2.53	5.02	5.79	8.08	11.23	9.21	7.22	4.8	0.78	0	0	0	0	0	1.59	1.25
107.5	1.51	2.11	3.87	9.44	7.18	3.94	0.05	0	0	0	0	0	0	0	0	0	0	1.22
112.5	2.68	3.15	1.18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.71
117.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.47
122.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.36
127.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.26
132.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2
137.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.21
142.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15
147.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.13
152.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.14
157.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.08
162.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15
167.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.04
172.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.23
177.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix E3: Calculation procedures of probable sunlight duration in calculation spreadsheet

Symbol	Description	Sign convention
ϕ_{win}	Window wall azimuth	It is measured from the south. It is negative when the normal is to the east of south and positive when it is to the west of south.
$\theta_L^{Obs(\phi)}$	Obstruction angle for segment ϕ	Positive
ϕ_{shad}^{x}	Azimuth angle of the corner of the overhang	Positive
$\phi_{shad}^{y,left}$	Azimuth angle of the corner of the sidefin on the left	Negative
$\phi_{shad}^{y,right}$	Azimuth angle of the corner of the sidefin on the right	Positive
ϕ	Azimuth of sky patch	It is measured from the south. It is negative when the centre of the sky patch is to the east of south and positive when it is to the west of south.
γ	Altitude of sky patch	It is measured from the horizon to the centre of the sky patch. It is always positive.
$\phi_{win}^{sky(\phi)}$	Azimuth angle of sky patches in the segment ϕ relative to the window	It is measured from the normal to the wall. It is negative when the azimuth angle of the sky patch is measured in anti-clockwise direction and positive when it is measured in clockwise direction.
$\theta_H^{sky(\phi)}$	Upper limit of visible sky for sky patches segment ϕ	Positive
$\theta_L^{sky(\phi)}$	Lower limit of visible sky for sky patches segment ϕ	Positive
$\theta_L^{sidefin(\phi)}$	Lower limit of visible sky for sky patches segment ϕ due to the sidefins	Positive





The parameters: ϕ_{win} and $\theta_L^{Obs(\phi)}$ are the inputs for specifying the reference wall and obstructing environment. The latter can be calculated from the distance and height of the obstruction from the reference point in the segment ϕ. Three parameters: ϕ_{shad}^{x}, $\phi_{shad}^{y,left}$ and $\phi_{shad}^{y,right}$ are used to specify the external shading. The definitions of the parameters are shown in above figures. They can be calculated from the depth of the overhang and sidefins.

$$\phi_{shad}^{x} = \tan^{-1}\left(\frac{W_{win}}{2S_x}\right)$$

$$\phi_{shad}^{y,left} = \begin{cases} -\tan^{-1}\left(\dfrac{W_{win}}{2S_{y,left}}\right) & \text{if } S_{y,left} \neq 0 \\ -90 & \text{if } S_{y,left} = 0 \end{cases}$$

$$\phi_{shad}^{y,right} = \begin{cases} \tan^{-1}\left(\dfrac{W_{win}}{2S_{y,right}}\right) & \text{if } S_{y,right} \neq 0 \\ 90 & \text{if } S_{y,right} = 0 \end{cases}$$

where S_x, $S_{y,right}$ and $S_{y,left}$ are the depth of the overhang and sidefins on the right and left. A sky patch is defined by its azimuth angle ϕ and altitude angle γ. The azimuth angle of sky patches in the segment ϕ relative to the window can be calculated by the following expression:

$$\phi_{win}^{sky(\phi)} = \begin{cases} \phi - \phi_{win} + 360 & \text{if } \phi - \phi_{win} < -180 \\ \phi - \phi_{win} & \text{if } -180 < \phi - \phi_{win} < 180 \\ \phi - \phi_{win} - 360 & \text{if } \phi - \phi_{win} > 180 \end{cases}$$

The portion of visible sky can be defined by the upper and lower limit of the visible in every segment division. The upper limit of visible sky for the sky segment ϕ can be evaluated from the expression below.

$$\theta_H^{sky(\phi)} = \begin{cases} 0 & \text{if} \left|\phi_{win}^{sky(\phi)}\right| > 90 \\ \tan^{-1}\left(\dfrac{H_{win}}{2S_x}\cos|\phi|\right) & \text{if } \left|\phi_{win}^{sky(\phi)}\right| < \phi_{shad}^{x} \text{ and } S_x \neq 0 \\ \tan^{-1}\left(\dfrac{H_{win}}{W_{win}}\sin|\phi|\right) & \text{if } \phi_{\mathrm{shad}}^{\mathrm{x}} < \left|\phi_{\mathrm{win}}^{\mathrm{sky}(\phi)}\right| < 90 \text{ and } S_x \neq 0 \\ 90 & \text{if } S_x = 0 \end{cases}$$

As for the lower limit of the visible sky, it can be calculated by the expression below.

$$\theta_L^{sky(\phi)} = \begin{cases} \theta_L^{obs(\phi)} & \text{if } \theta_L^{obs(\phi)} > \theta_L^{sidefin(\phi)} \\ \theta_L^{sidefin(\phi)} & \text{otherwise} \end{cases}$$

where $\theta_L^{sidefin(\phi)}$ is the lower limit of visible sky for the sky segment ϕ due to the sidefins. It is calculated by the following expression:

$$\theta_L^{sidefin(\phi)} = \begin{cases} 90 & \text{if } \left|\phi_{win}^{sky(\phi)}\right| > 90 \\ \tan^{-1}\left(\dfrac{H_{win}}{W_{win}}\sin|\phi|\right) & \text{if } \phi_{win}^{sky(\phi)} < \phi_{shad}^{y,left} \text{ or } \phi_{win}^{sky(\phi)} > \phi_{shad}^{y,right} \\ 0 & \text{if } \phi_{\mathrm{shad}}^{y,left} < \phi_{win}^{sky(\phi)} < \phi_{shad}^{y,right} \end{cases}$$

The visibility of the sky patch $sky(\phi,\gamma)$ to the centre of a window is described by a parameter $V_{\phi\gamma}$. It is equal to 1 when the sky patch is visible. On the contrast, it is equal to 0 when the sky patch is invisible to the centre of a window. It can be calculated from the following equations.

$$V_{\phi\gamma} = \begin{cases} 1 & \text{if } \theta_L^{sky(\phi)} < \gamma < \theta_H^{sky(\phi)} \\ 0 & \text{otherwise} \end{cases}$$

Finally, the summer and window probable sunlight durations received at the centre of a window can be evaluated by the expressions below:

Summer probable sunlight duration received at the centre of the window

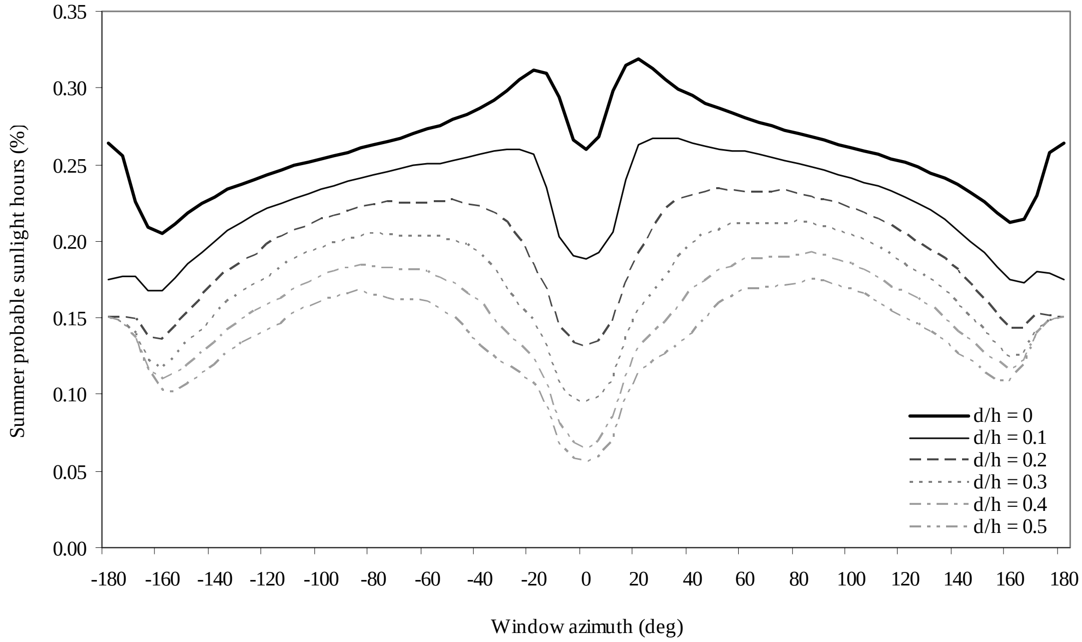
$$= \sum_{\phi=-177.5}^{177.5} \sum_{\gamma=2.5}^{87.5} \left(P_{\phi\gamma}^{sum} V_{\phi\gamma} \right)$$

Winter probable sunlight duration received at the centre of the window

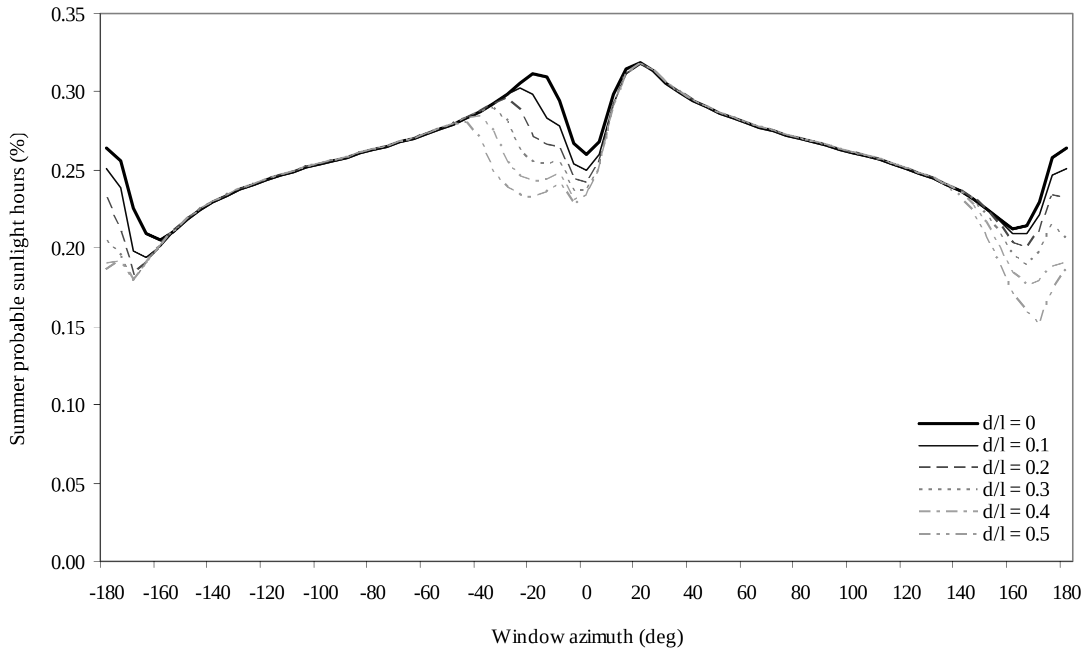
$$= \sum_{\phi=-177.5}^{177.5} \sum_{\gamma=2.5}^{87.5} \left(P_{\phi\gamma}^{win} V_{\phi\gamma} \right)$$

where $P_{\phi\gamma}^{sum}$ and $P_{\phi\gamma}^{win}$ are the summer and winter cumulative probable sunlight duration for the sky patch $sky(\phi, \gamma)$.

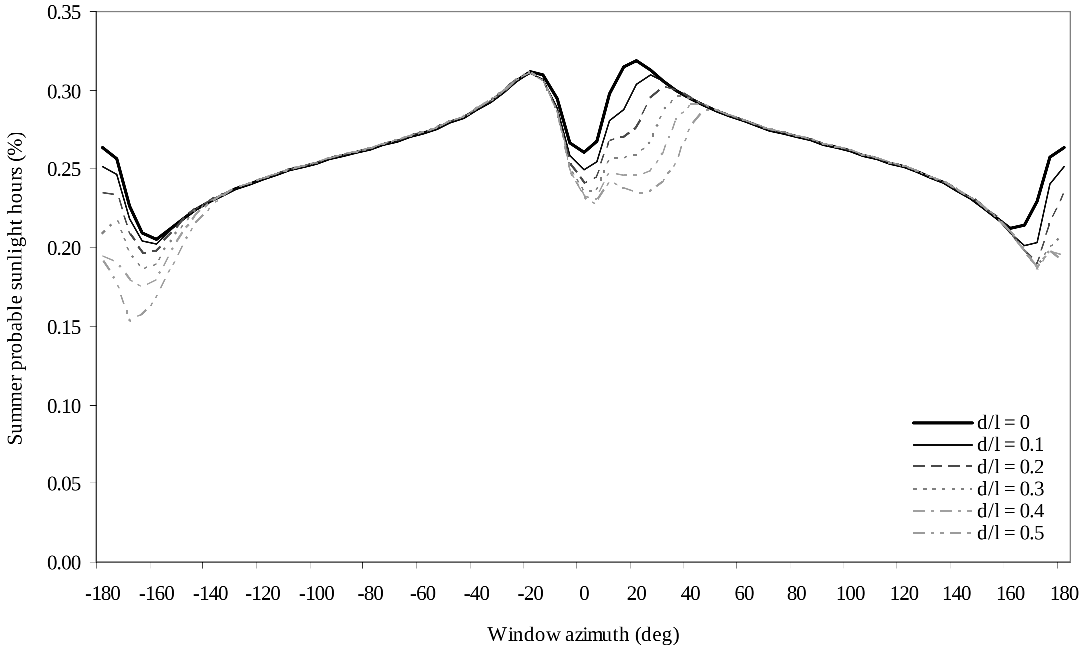
Appendix E4: Probable sunlight duration received by windows of various orientations and various external shading devices



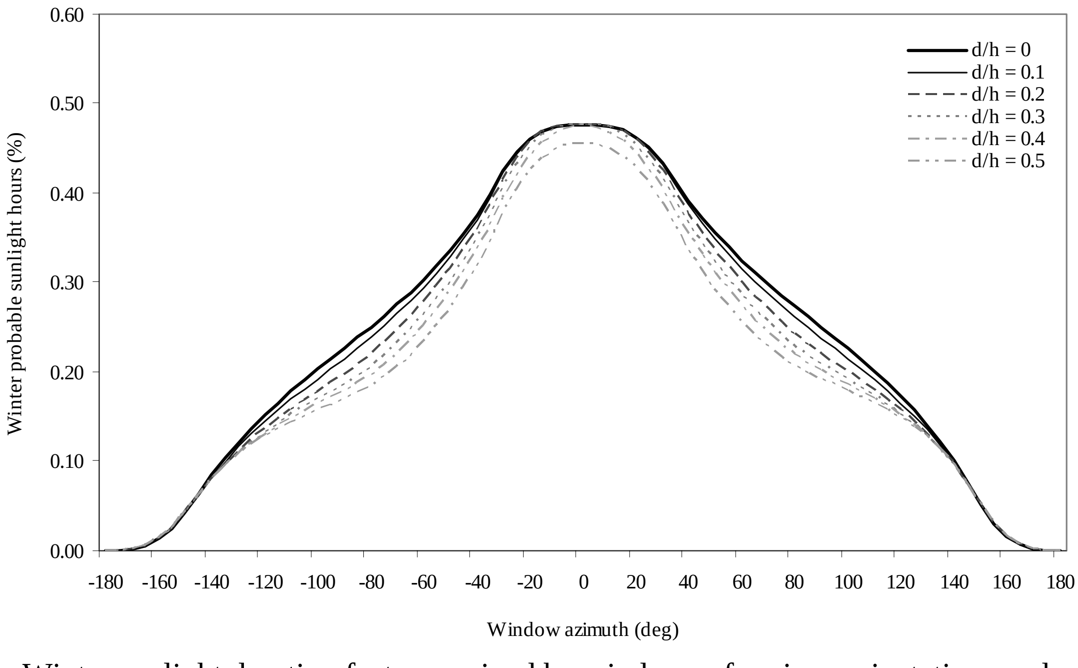
Summer sunlight duration factor received by windows of various orientations and depths of overhang



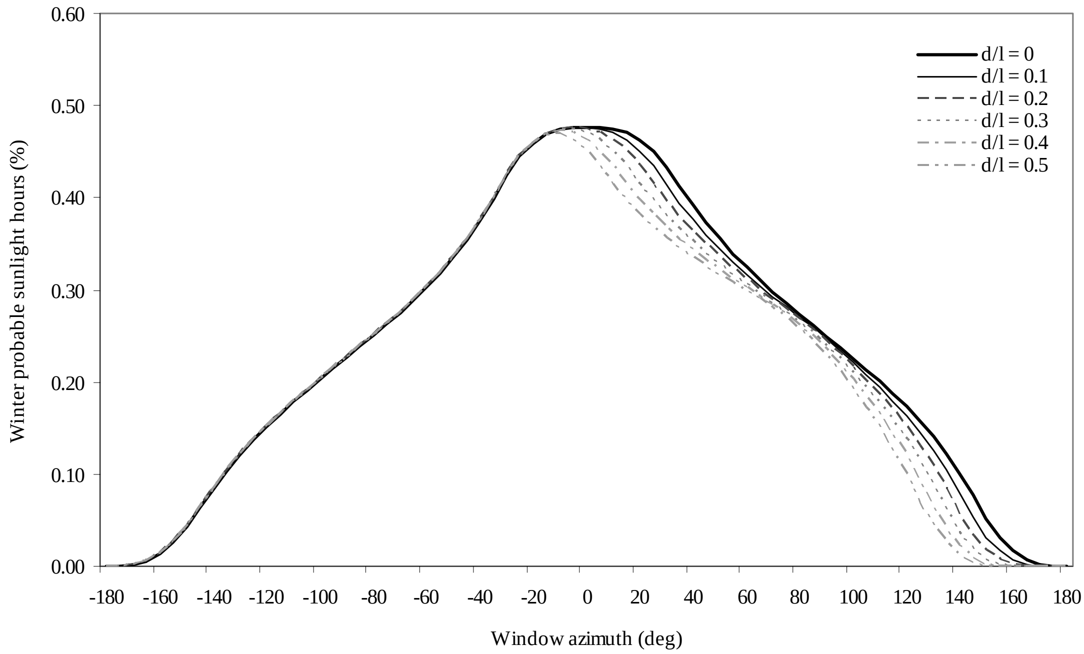
Summer sunlight duration factor received by windows of various orientations and depths of sidefin on the left



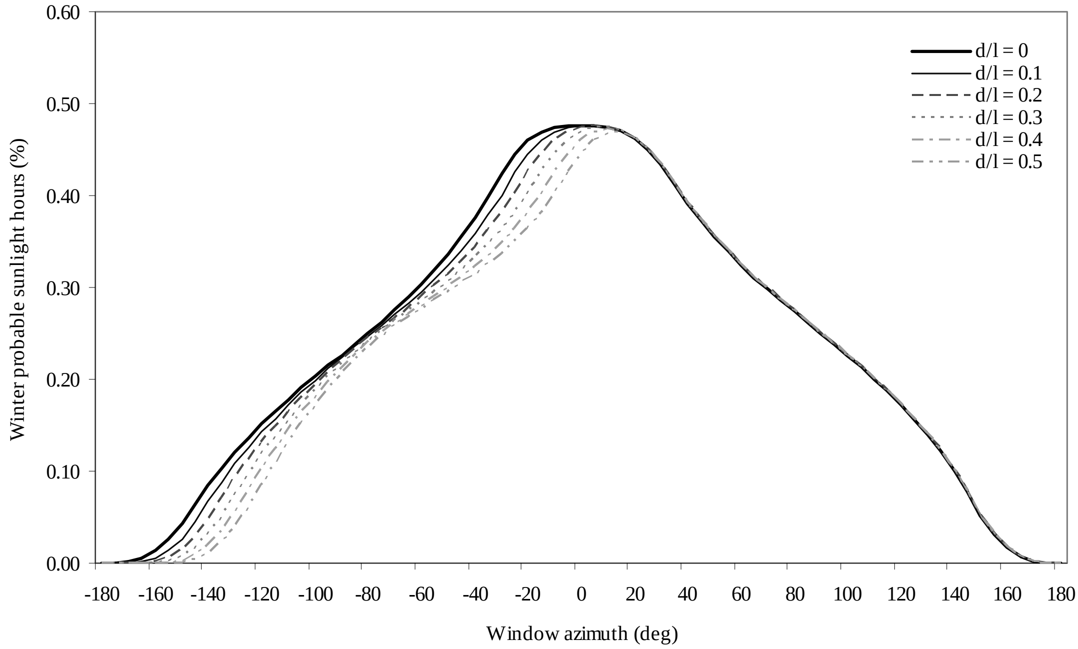
Summer sunlight duration factor received by windows of various orientations and depths of sidefin on the right



Winter sunlight duration factor received by windows of various orientations and depths of overhang

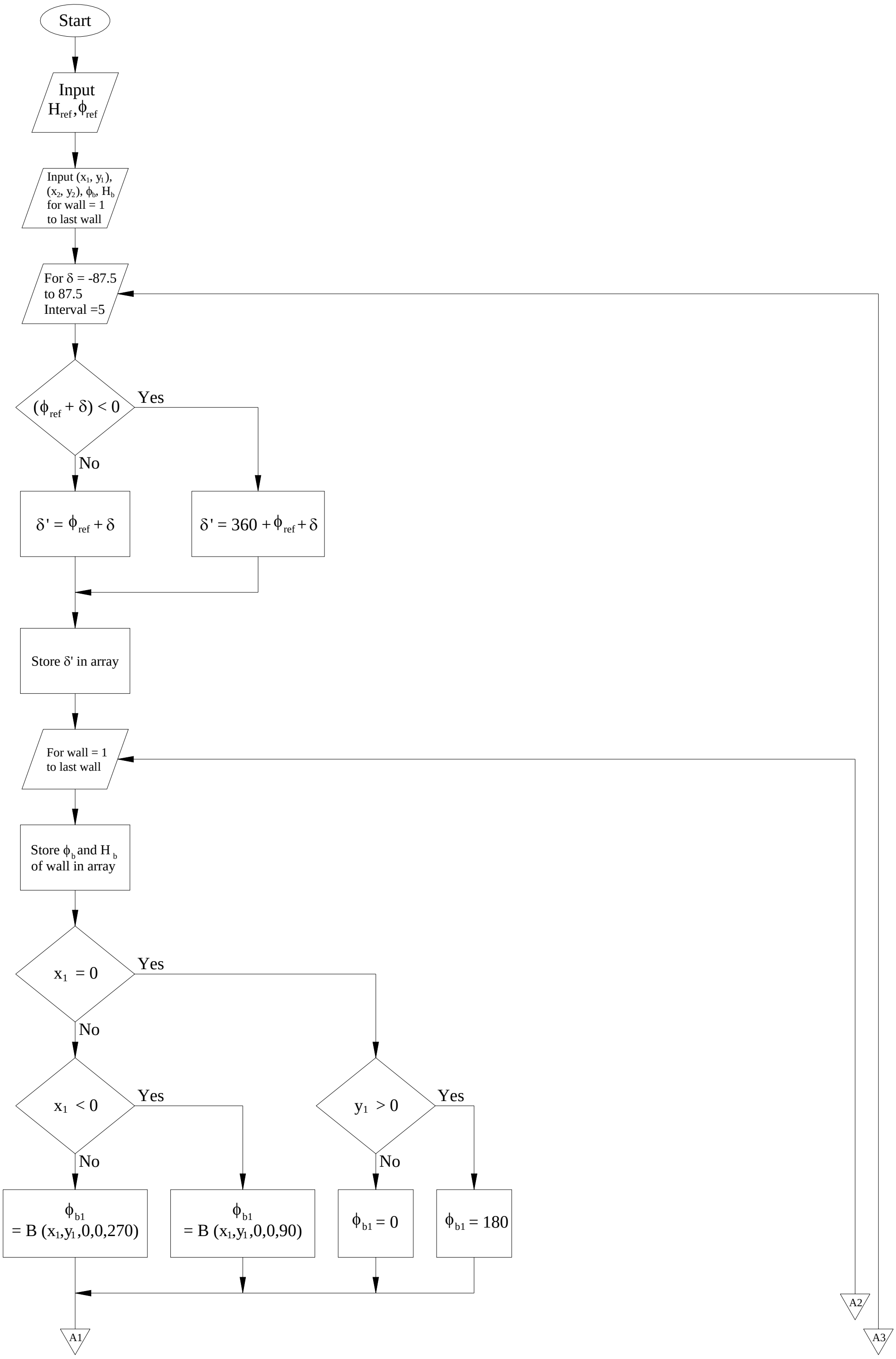


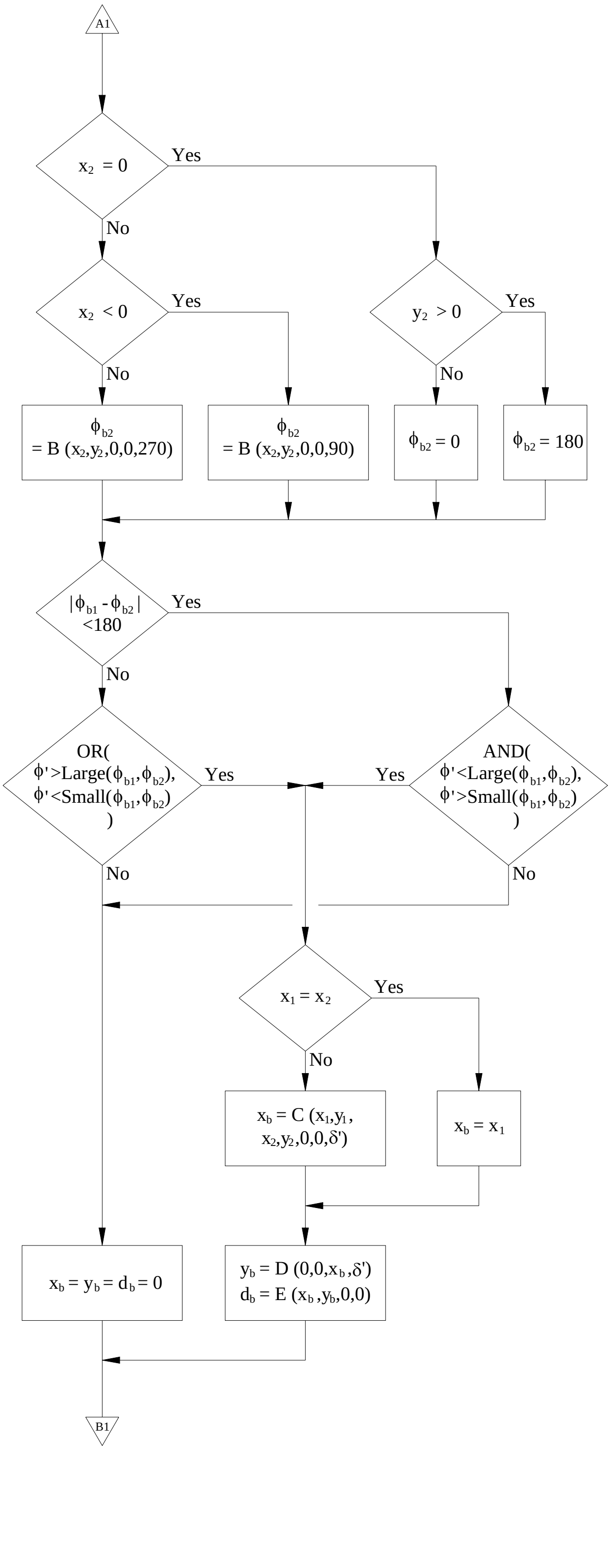
Winter sunlight duration factor received by windows of various orientations and depths of sidefin on the left

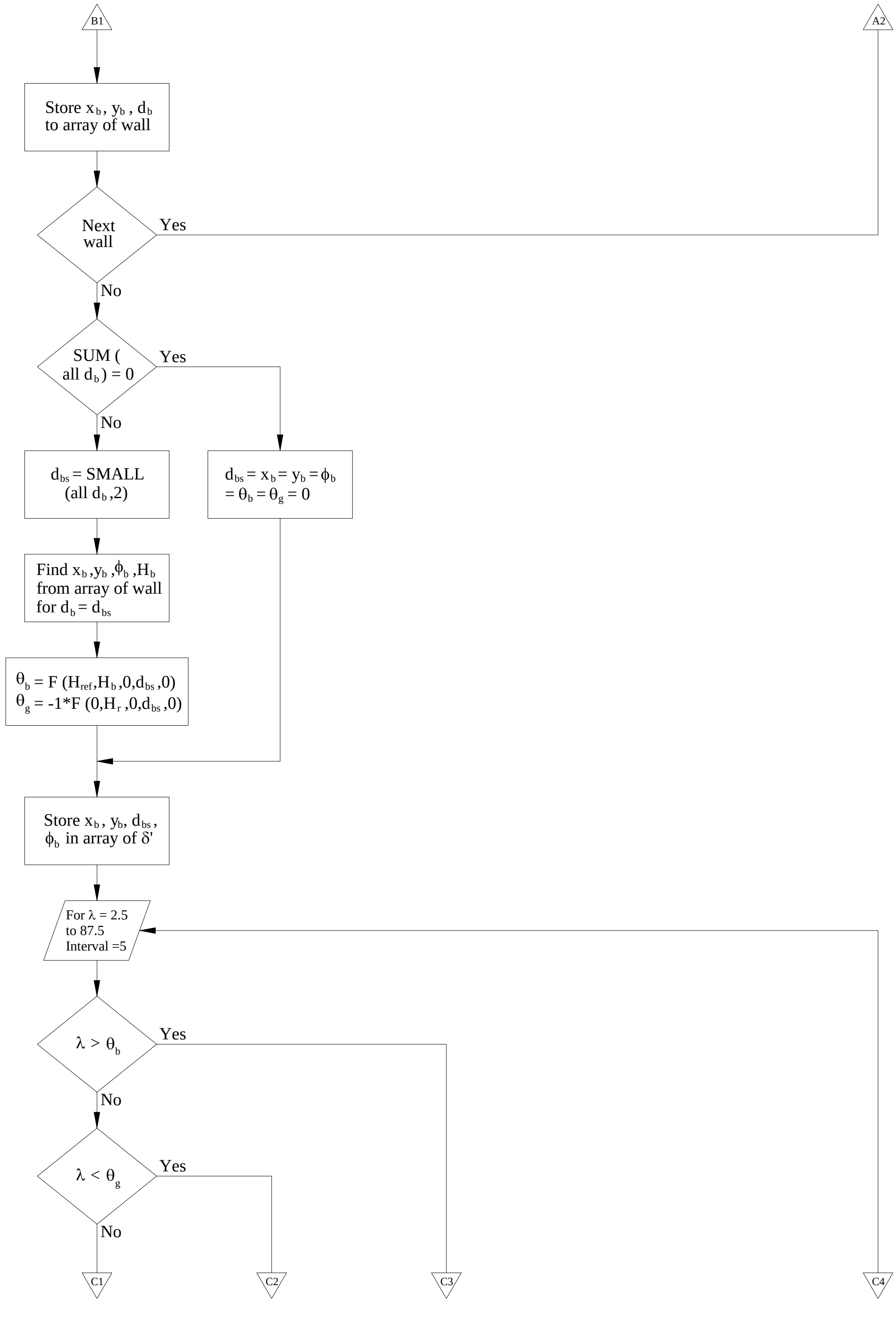


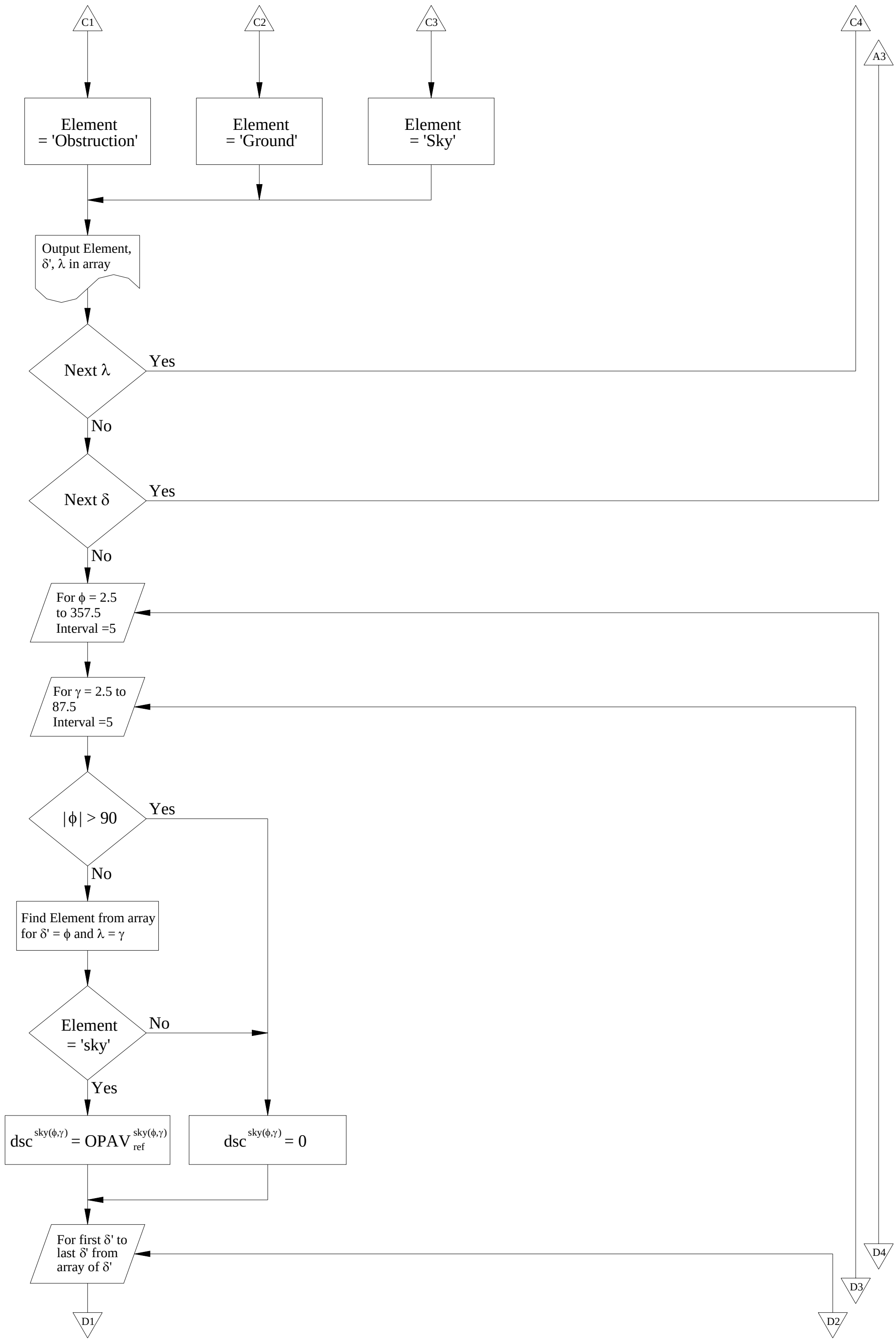
Winter sunlight duration factor received by windows of various orientations and depths of sidefin on the right

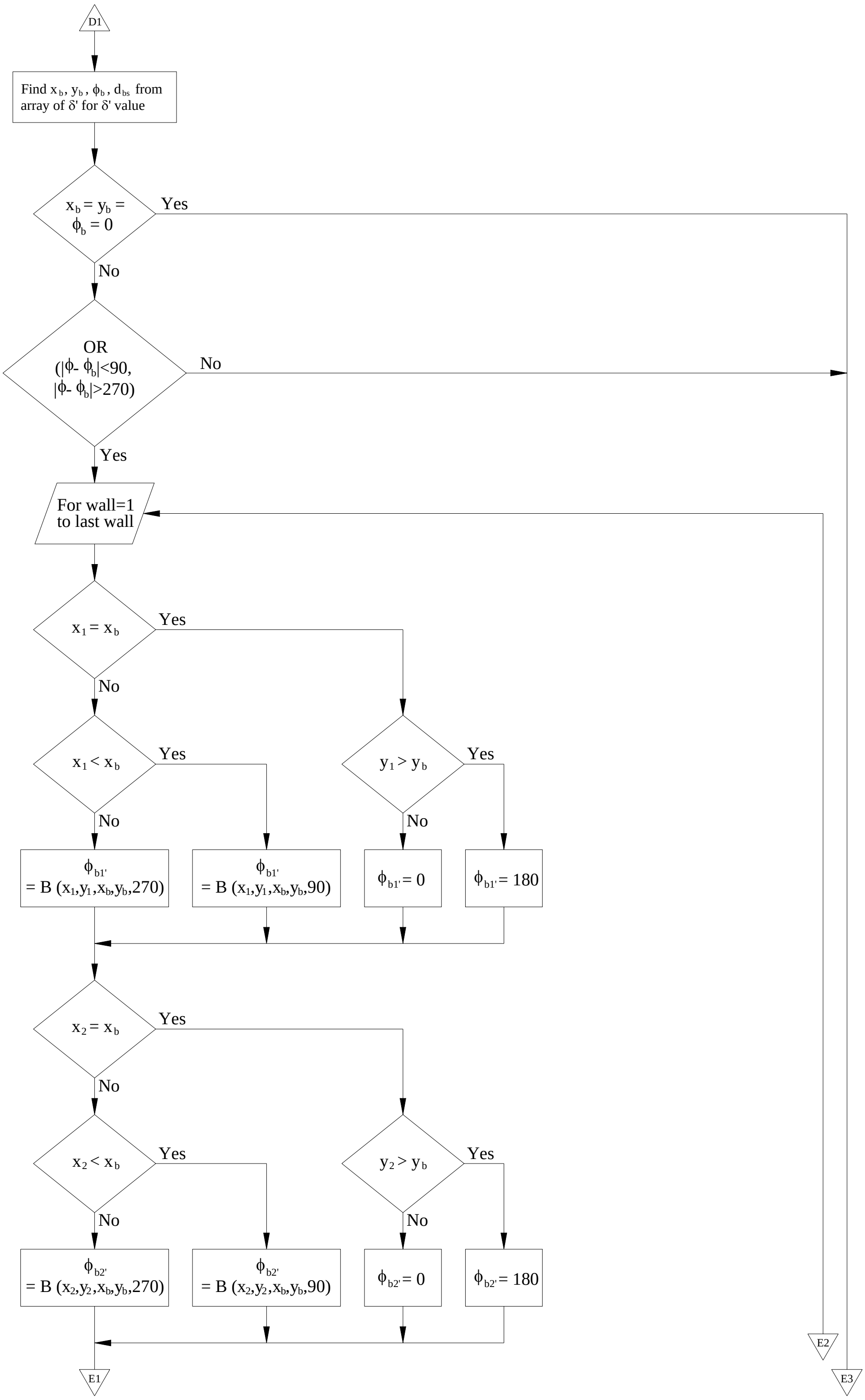
Appendix F1: Flowchart diagram for the vertical skylight coefficients calculation spreadsheet

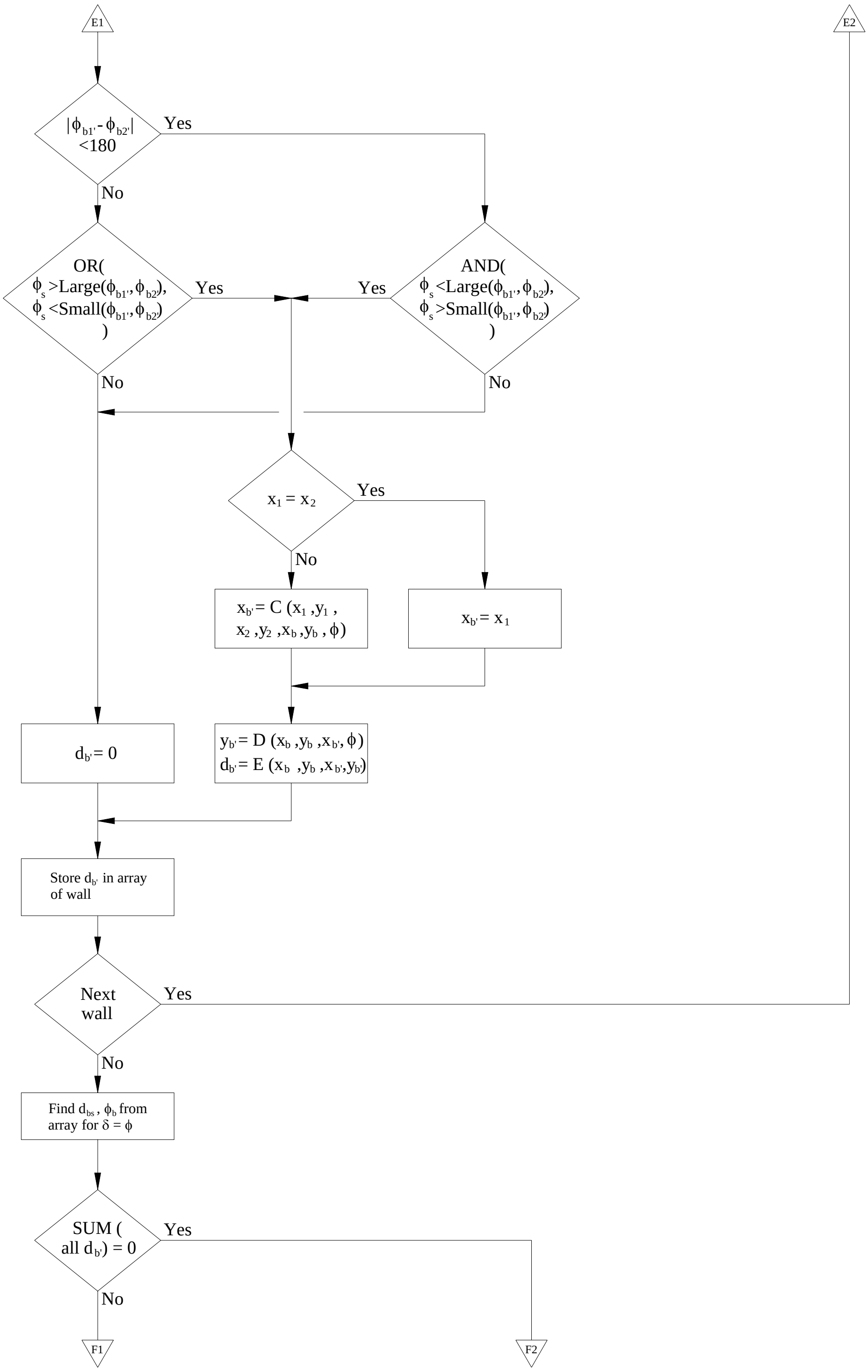


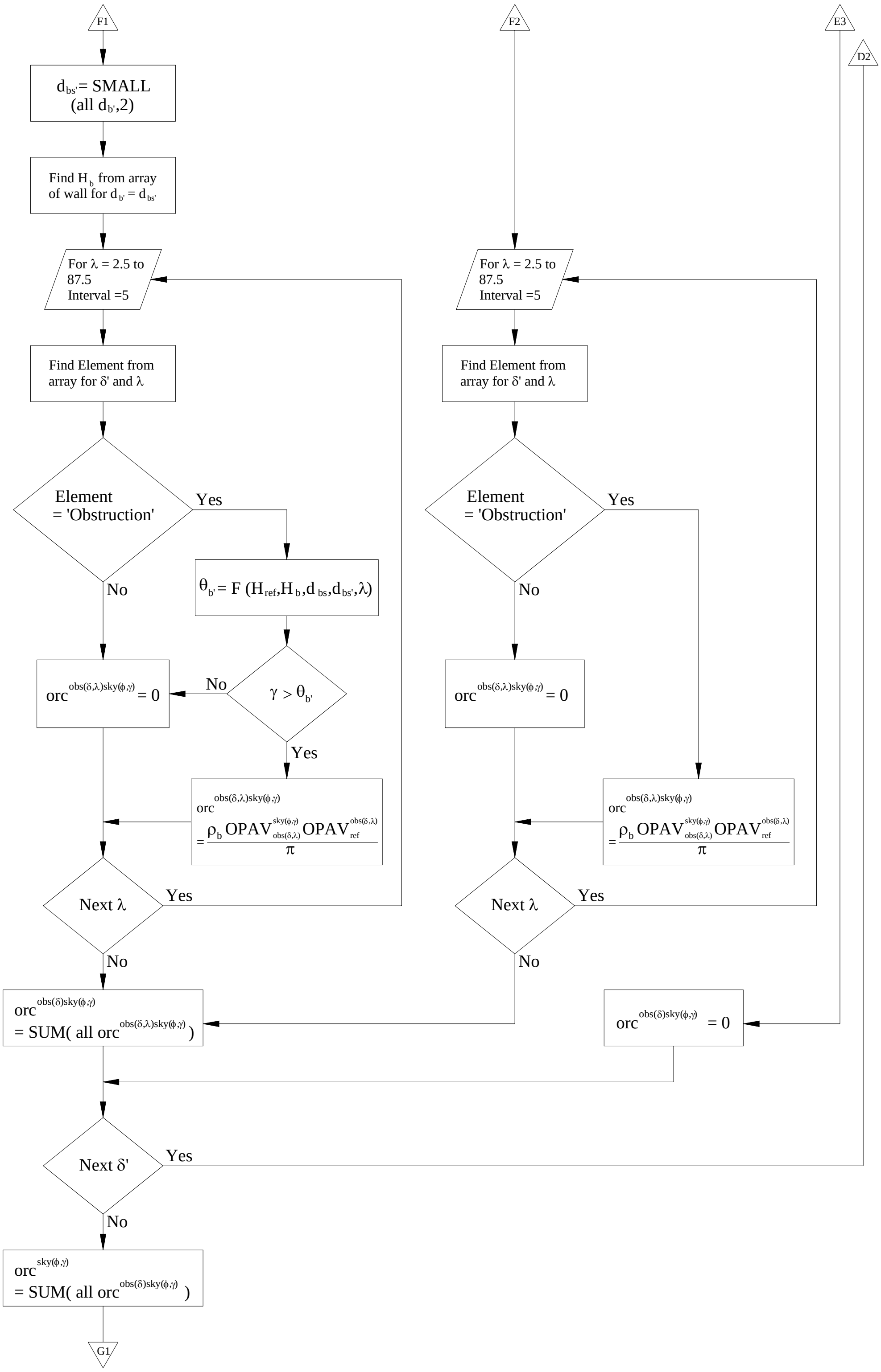

A1
x2 = 0
Yes
No
x2 < 0
Yes
No
y2 > 0
Yes
No
φb2 = B (x2,y2,0,0,270)
φb2 = B (x2,y2,0,0,90)
φb2 = 0
φb2 = 180
|φb1 - φb2| <180
Yes
No
OR(φ'>Large(φb1,φb2), φ'<Small(φb1,φb2))
Yes
No
AND(φ'<Large(φb1,φb2), φ'>Small(φb1,φb2))
Yes
No
x1 = x2
Yes
No
xb = C (x1,y1, x2,y2,0,0,δ')
xb = x1
xb = yb = db = 0
yb = D (0,0,xb,δ')
db = E (xb,yb,0,0)
B1

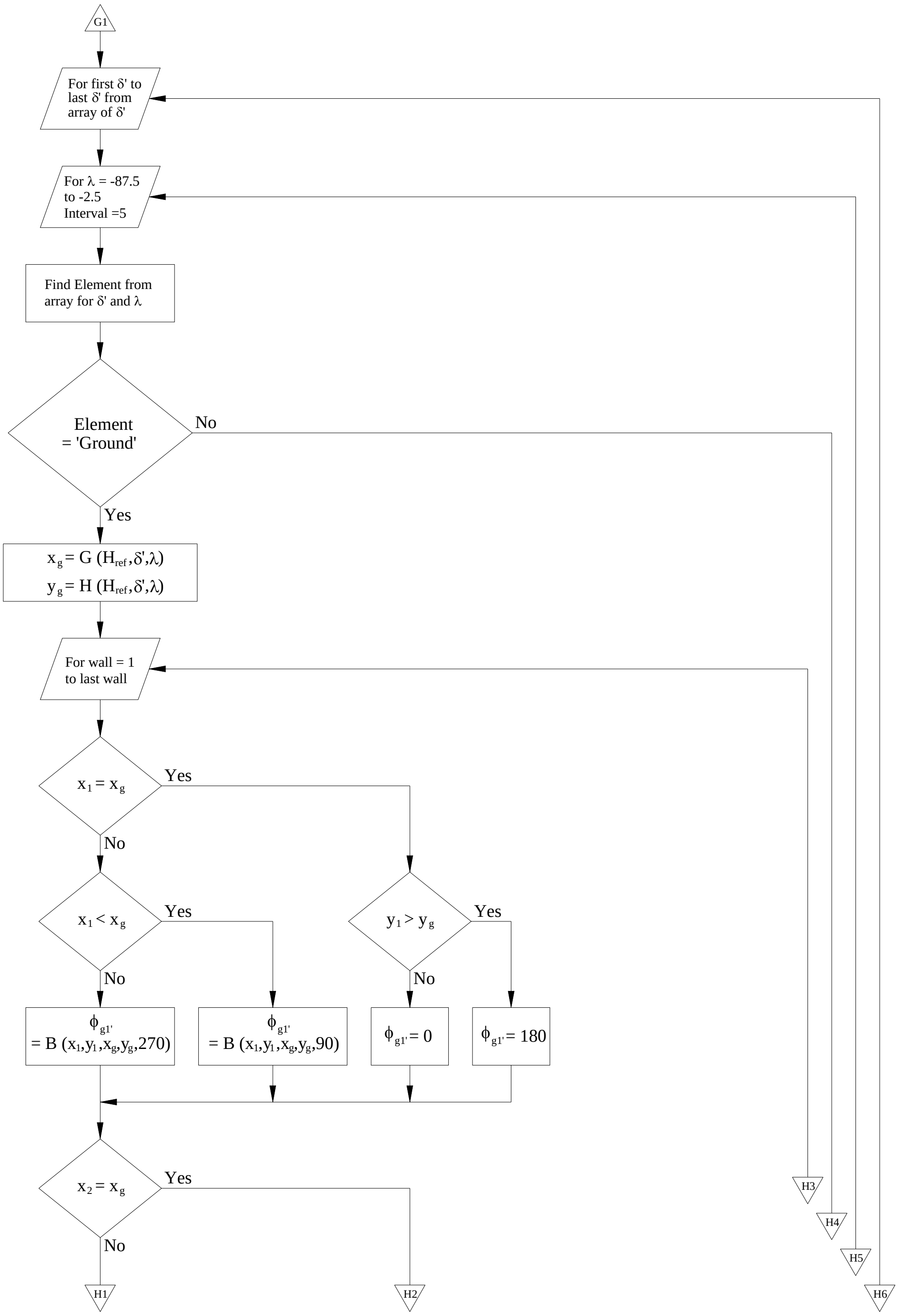

B1
A2
Store x_b, y_b, d_b to array of wall
Next wall
Yes
No
SUM (all d_b) = 0
Yes
No
d_{bs} = SMALL (all d_b ,2)
$d_{bs} = x_b = y_b = \phi_b = \theta_b = \theta_g = 0$
Find x_b, y_b, ϕ_b, H_b from array of wall for $d_b = d_{bs}$
$\theta_b = F(H_{ref}, H_b, 0, d_{bs}, 0)$
$\theta_g = -1*F(0, H_r, 0, d_{bs}, 0)$
Store x_b, y_b, d_{bs}, ϕ_b in array of δ'
For λ = 2.5 to 87.5 Interval =5
$\lambda > \theta_b$
Yes
No
$\lambda < \theta_g$
Yes
No
C1
C2
C3
C4

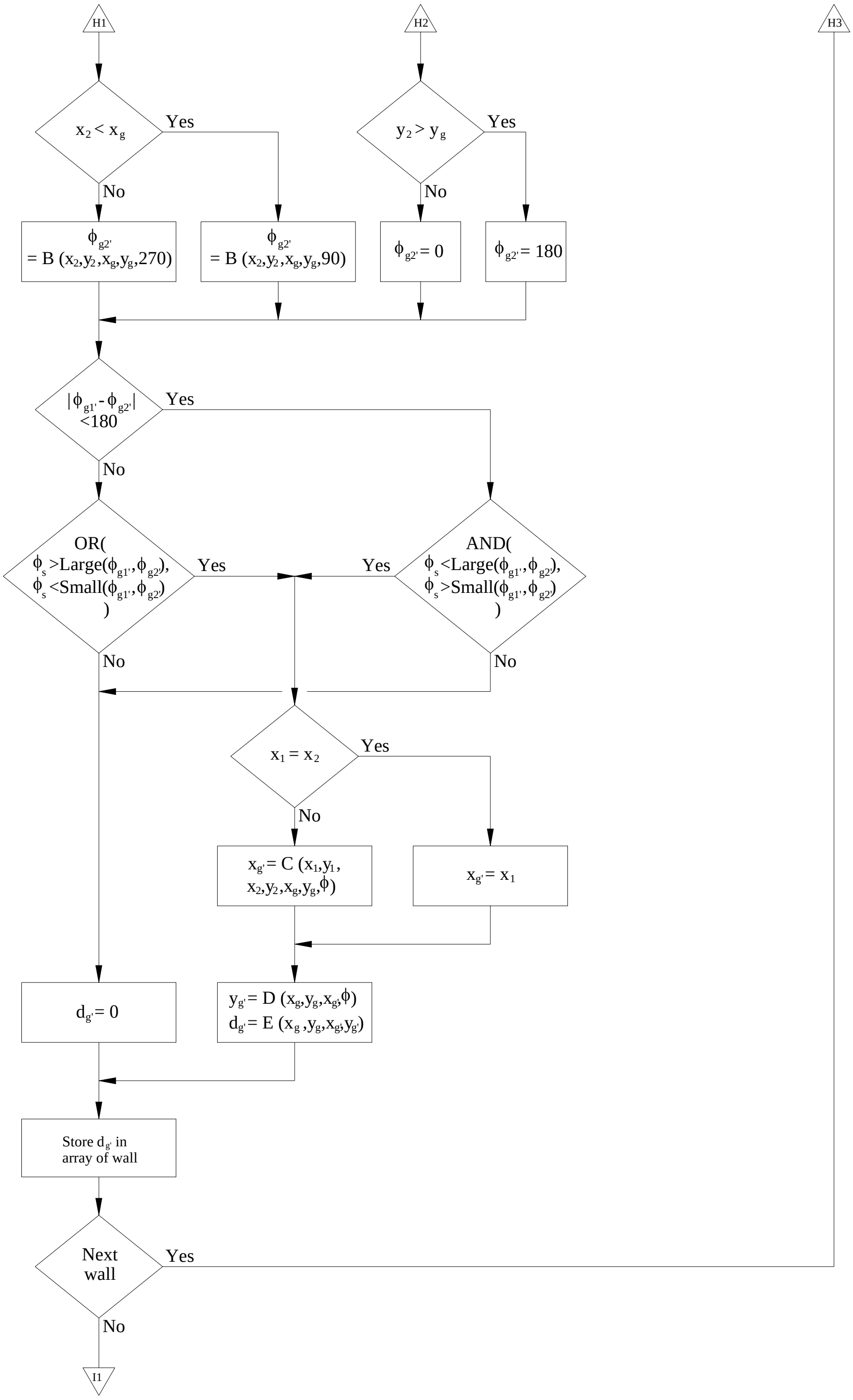

C1
C2
C3
C4
A3
Element = 'Obstruction'
Element = 'Ground'
Element = 'Sky'
Output Element, δ', λ in array
Next λ
Yes
No
Next δ
Yes
No
For ϕ = 2.5 to 357.5 Interval =5
For γ = 2.5 to 87.5 Interval =5
|ϕ| > 90
Yes
No
Find Element from array for δ' = ϕ and λ = γ
Element = 'sky'
No
Yes
dsc sky(ϕ,γ) = OPAV sky(ϕ,γ) ref
dsc sky(ϕ,γ) = 0
For first δ' to last δ' from array of δ'
D1
D2
D3
D4

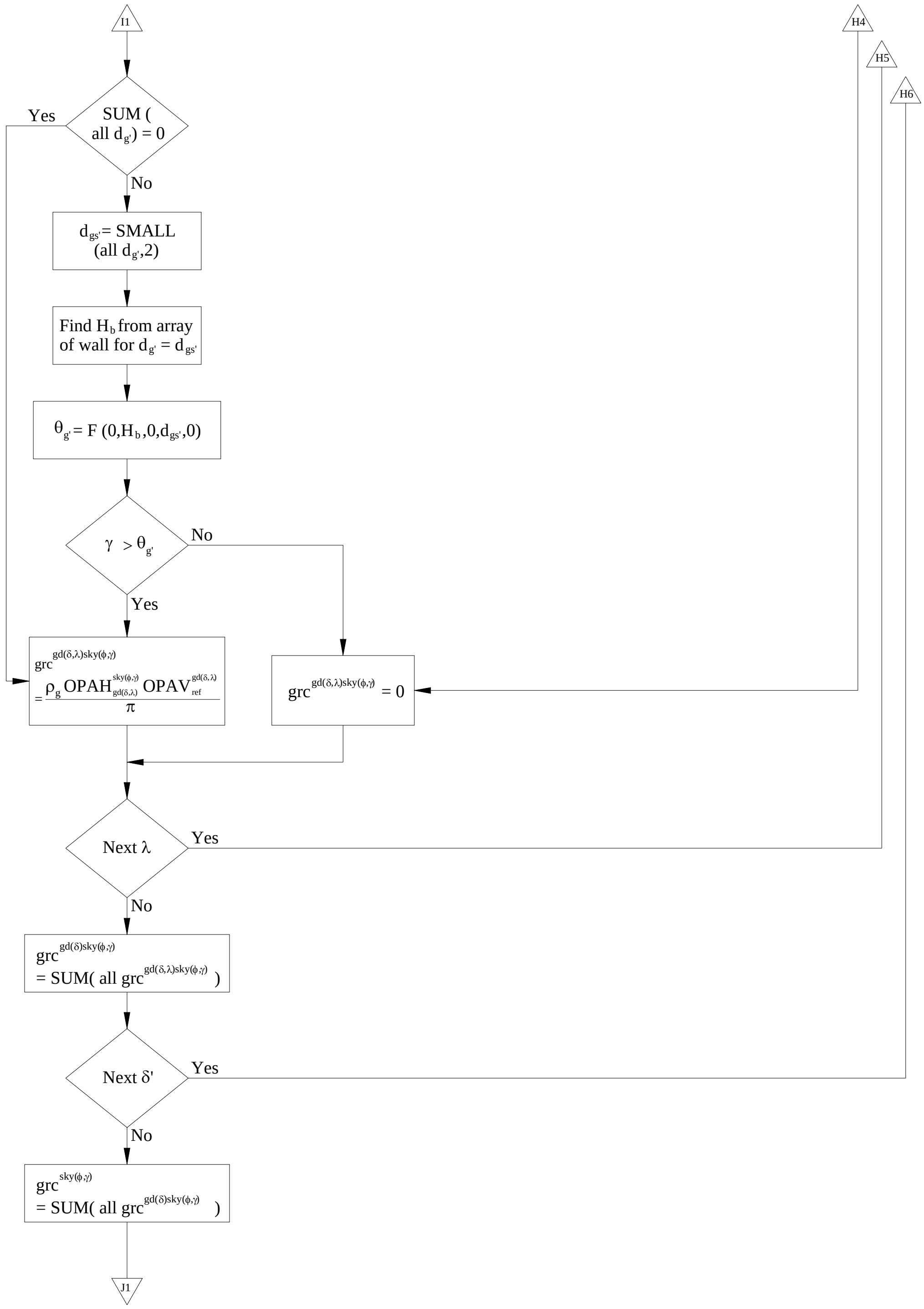

D1
Find x_b, y_b, ϕ_b, d_{bs} from array of δ' for δ' value
$x_b = y_b = \phi_b = 0$
Yes
No
OR ($|\phi - \phi_b| < 90$, $|\phi - \phi_b| > 270$)
No
Yes
For wall=1 to last wall
$x_1 = x_b$
Yes
No
$x_1 < x_b$
$y_1 > y_b$
$\phi_{b1'} = B(x_1,y_1,x_b,y_b,270)$
$\phi_{b1'} = B(x_1,y_1,x_b,y_b,90)$
$\phi_{b1'} = 0$
$\phi_{b1'} = 180$
$x_2 = x_b$
$x_2 < x_b$
$y_2 > y_b$
$\phi_{b2'} = B(x_2,y_2,x_b,y_b,270)$
$\phi_{b2'} = B(x_2,y_2,x_b,y_b,90)$
$\phi_{b2'} = 0$
$\phi_{b2'} = 180$
E1
E2
E3

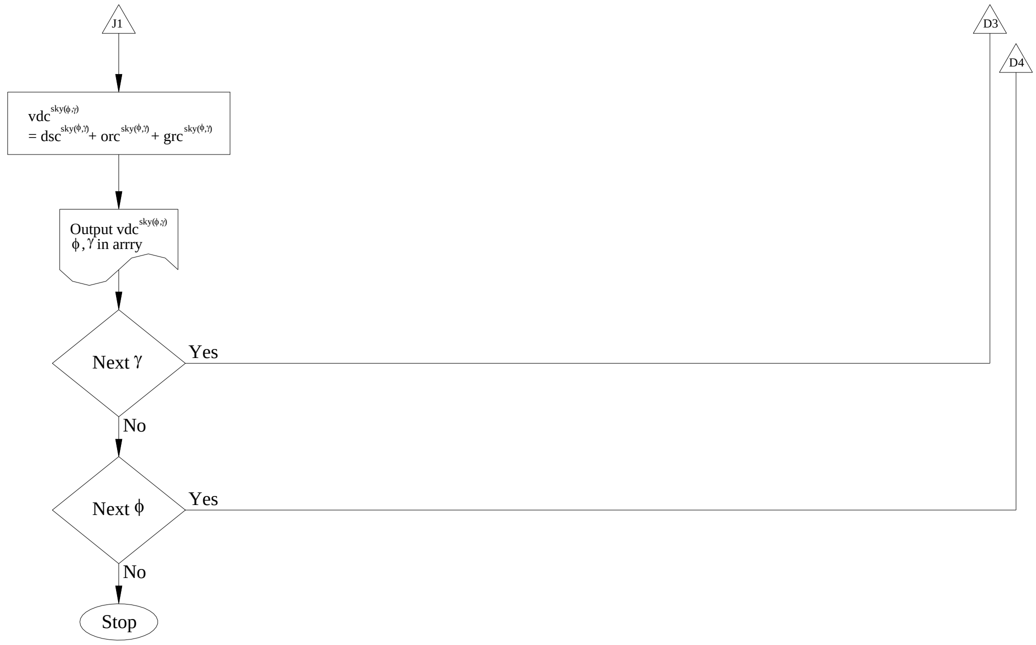

E1
E2
$|\phi_{b1'} - \phi_{b2'}|$ <180
Yes
No
OR(ϕ_s >Large($\phi_{b1'},\phi_{b2'}$), ϕ_s <Small($\phi_{b1'},\phi_{b2'}$))
AND(ϕ_s <Large($\phi_{b1'},\phi_{b2'}$), ϕ_s >Small($\phi_{b1'},\phi_{b2'}$))
$x_1 = x_2$
$x_{b'}$ = C (x_1, y_1, x_2, y_2, x_b, y_b, ϕ)
$x_{b'} = x_1$
$d_{b'} = 0$
$y_{b'}$ = D (x_b, y_b, $x_{b'}$, ϕ)
$d_{b'}$ = E (x_b, y_b, $x_{b'}$, $y_{b'}$)
Store $d_{b'}$ in array of wall
Next wall
Find d_{bs}, ϕ_b from array for $\delta = \phi$
SUM (all $d_{b'}$) = 0
F1
F2


F1
F2
E3
D2
dbs' = SMALL (all db',2)
Find Hb from array of wall for db' = dbs'
For λ = 2.5 to 87.5 Interval =5
Find Element from array for δ' and λ
Element = 'Obstruction'
Yes
No
θb' = F (Href, Hb, dbs, dbs', λ)
γ > θb'
orc obs(δ,λ)sky(φ,γ) = 0
orc obs(δ,λ)sky(φ,γ) = ρb OPAV sky(φ,γ) obs(δ,λ) OPAV obs(δ,λ) ref / π
Next λ
orc obs(δ)sky(φ,γ) = SUM(all orc obs(δ,λ)sky(φ,γ))
orc obs(δ)sky(φ,γ) = 0
Next δ'
orc sky(φ,γ) = SUM(all orc obs(δ)sky(φ,γ))
G1


G1
For first δ' to last δ' from array of δ'
For λ = -87.5 to -2.5 Interval =5
Find Element from array for δ' and λ
Element = 'Ground'
No
Yes
$x_g = G(H_{ref}, \delta', \lambda)$
$y_g = H(H_{ref}, \delta', \lambda)$
For wall = 1 to last wall
$x_1 = x_g$
Yes
No
$x_1 < x_g$
Yes
No
$y_1 > y_g$
Yes
No
$\phi_{g1'} = B(x_1, y_1, x_g, y_g, 270)$
$\phi_{g1'} = B(x_1, y_1, x_g, y_g, 90)$
$\phi_{g1'} = 0$
$\phi_{g1'} = 180$
$x_2 = x_g$
Yes
No
H1
H2
H3
H4
H5
H6


H1
H2
H3
x2 < xg
Yes
No
y2 > yg
Yes
No
φg2' = B (x2,y2,xg,yg,270)
φg2' = B (x2,y2,xg,yg,90)
φg2' = 0
φg2' = 180
|φg1' - φg2'| <180
Yes
No
OR(φs >Large(φg1',φg2'), φs <Small(φg1',φg2'))
Yes
No
AND(φs <Large(φg1',φg2'), φs >Small(φg1',φg2'))
Yes
No
x1 = x2
Yes
No
xg' = C (x1,y1, x2,y2,xg,yg,φ)
xg' = x1
dg' = 0
yg' = D (xg,yg,xg',φ)
dg' = E (xg ,yg,xg',yg')
Store dg' in array of wall
Next wall
Yes
No
I1


I1
SUM (all d_g') = 0
Yes
No
d_gs' = SMALL (all d_g',2)
Find H_b from array of wall for d_g' = d_gs'
θ_g' = F (0,H_b,0,d_gs',0)
γ > θ_g'
No
Yes
grc^gd(δ,λ)sky(φ,γ) = ρ_g OPAH^sky(φ,γ)_gd(δ,λ) OPAV^gd(δ,λ)_ref / π
grc^gd(δ,λ)sky(φ,γ) = 0
H4
H5
H6
Next λ
Yes
No
grc^gd(δ)sky(φ,γ) = SUM(all grc^gd(δ,λ)sky(φ,γ))
Next δ'
Yes
No
grc^sky(φ,γ) = SUM(all grc^gd(δ)sky(φ,γ))
J1



$$B(b_1, b_2, b_3, b_4, b_5) = b_5 - \tan^{-1}\left(\frac{b_2 - b_4}{b_1 - b_3}\right)$$

$$C(c_1, c_2, c_3, c_4, c_5, c_6, c_7) = \frac{\dfrac{(c_4 - c_2)c_1}{c_3 - c_1} - c_2 - c_5 \tan(90 - c_7) + c_6}{\dfrac{c_4 - c_2}{c_3 - c_1} - \tan(90 - c_7)}$$

$$D(d_1, d_2, d_3, d_4) = (d_3 - d_1)\tan(90 - d_4) + d_2$$

$$E(e_1, e_2, e_3, e_4) = \sqrt{(e_3 - e_1)^2 + (e_4 - e_2)^2}$$

$$F(f_1, f_2, f_3, f_4, f_5) = \left|\tan^{-1}\left(\frac{f_2 - f_1 - f_3 \tan f_5}{f_4}\right)\right|$$

$$G(g_1, g_2, g_3) = \frac{g_1 \sin g_2}{\tan g_3}$$

$$H(h_1, h_2, h_3) = \frac{h_1 \cos h_2}{\tan h_3}$$

Appendix F2: Numerical values of vertical skylight coefficients for different site layouts

Numerical values of vertical skylight coefficients for an unobstructed vertical plane:

(ρ_g = 0.2)

ϕ / γ	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5
-177.5	0.0000	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-172.5	0.0000	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-167.5	0.0000	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-162.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-157.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-152.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-147.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-142.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-137.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-132.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-127.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-122.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-117.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-112.5	0.0000	0.0001	0.0001	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-107.5	0.0000	0.0001	0.0001	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-102.5	0.0000	0.0001	0.0001	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-97.5	0.0000	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-92.5	0.0000	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-87.5	0.0004	0.0004	0.0005	0.0005	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0005	0.0005	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
-82.5	0.0010	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0010	0.0010	0.0009	0.0008	0.0007	0.0006	0.0004	0.0003	0.0002	0.0001	0.0000
-77.5	0.0017	0.0017	0.0017	0.0017	0.0017	0.0016	0.0015	0.0014	0.0013	0.0012	0.0010	0.0009	0.0007	0.0005	0.0004	0.0003	0.0001	0.0000
-72.5	0.0023	0.0023	0.0023	0.0023	0.0022	0.0021	0.0020	0.0018	0.0016	0.0014	0.0012	0.0010	0.0008	0.0006	0.0004	0.0003	0.0001	0.0000
-67.5	0.0029	0.0030	0.0029	0.0029	0.0027	0.0026	0.0024	0.0022	0.0020	0.0017	0.0015	0.0012	0.0010	0.0007	0.0005	0.0003	0.0002	0.0000
-62.5	0.0035	0.0035	0.0035	0.0034	0.0033	0.0031	0.0028	0.0026	0.0023	0.0020	0.0017	0.0014	0.0011	0.0008	0.0006	0.0003	0.0002	0.0000
-57.5	0.0041	0.0041	0.0040	0.0039	0.0037	0.0035	0.0032	0.0029	0.0026	0.0022	0.0019	0.0015	0.0012	0.0009	0.0006	0.0004	0.0002	0.0000
-52.5	0.0047	0.0046	0.0046	0.0044	0.0042	0.0039	0.0036	0.0033	0.0029	0.0025	0.0021	0.0017	0.0013	0.0010	0.0007	0.0004	0.0002	0.0000
-47.5	0.0052	0.0051	0.0050	0.0049	0.0046	0.0043	0.0040	0.0036	0.0032	0.0027	0.0023	0.0018	0.0014	0.0010	0.0007	0.0004	0.0002	0.0000
-42.5	0.0056	0.0056	0.0055	0.0053	0.0050	0.0047	0.0043	0.0039	0.0034	0.0029	0.0024	0.0020	0.0015	0.0011	0.0007	0.0004	0.0002	0.0001
-37.5	0.0061	0.0060	0.0059	0.0057	0.0054	0.0050	0.0046	0.0041	0.0036	0.0031	0.0026	0.0021	0.0016	0.0012	0.0008	0.0005	0.0002	0.0001
-32.5	0.0064	0.0064	0.0063	0.0060	0.0057	0.0053	0.0049	0.0044	0.0039	0.0033	0.0027	0.0022	0.0017	0.0012	0.0008	0.0005	0.0002	0.0001
-27.5	0.0068	0.0067	0.0066	0.0063	0.0060	0.0056	0.0051	0.0046	0.0040	0.0034	0.0029	0.0023	0.0018	0.0013	0.0008	0.0005	0.0002	0.0001
-22.5	0.0070	0.0070	0.0068	0.0066	0.0062	0.0058	0.0053	0.0048	0.0042	0.0036	0.0030	0.0024	0.0018	0.0013	0.0009	0.0005	0.0002	0.0001
-17.5	0.0073	0.0072	0.0071	0.0068	0.0064	0.0060	0.0055	0.0049	0.0043	0.0037	0.0030	0.0024	0.0019	0.0013	0.0009	0.0005	0.0002	0.0001
-12.5	0.0074	0.0074	0.0072	0.0070	0.0066	0.0061	0.0056	0.0050	0.0044	0.0038	0.0031	0.0025	0.0019	0.0014	0.0009	0.0005	0.0002	0.0001
-7.5	0.0076	0.0075	0.0073	0.0071	0.0067	0.0062	0.0057	0.0051	0.0045	0.0038	0.0032	0.0025	0.0019	0.0014	0.0009	0.0005	0.0002	0.0001
-2.5	0.0076	0.0076	0.0074	0.0071	0.0067	0.0063	0.0057	0.0051	0.0045	0.0038	0.0032	0.0025	0.0019	0.0014	0.0009	0.0005	0.0002	0.0001
2.5	0.0076	0.0076	0.0074	0.0071	0.0067	0.0063	0.0057	0.0051	0.0045	0.0038	0.0032	0.0025	0.0019	0.0014	0.0009	0.0005	0.0002	0.0001
7.5	0.0076	0.0075	0.0073	0.0071	0.0067	0.0062	0.0057	0.0051	0.0045	0.0038	0.0032	0.0025	0.0019	0.0014	0.0009	0.0005	0.0002	0.0001
12.5	0.0074	0.0074	0.0072	0.0070	0.0066	0.0061	0.0056	0.0050	0.0044	0.0038	0.0031	0.0025	0.0019	0.0014	0.0009	0.0005	0.0002	0.0001
17.5	0.0073	0.0072	0.0071	0.0068	0.0064	0.0060	0.0055	0.0049	0.0043	0.0037	0.0030	0.0024	0.0019	0.0013	0.0009	0.0005	0.0002	0.0001
22.5	0.0070	0.0070	0.0068	0.0066	0.0062	0.0058	0.0053	0.0048	0.0042	0.0036	0.0030	0.0024	0.0018	0.0013	0.0009	0.0005	0.0002	0.0001
27.5	0.0068	0.0067	0.0066	0.0063	0.0060	0.0056	0.0051	0.0046	0.0040	0.0034	0.0029	0.0023	0.0018	0.0013	0.0008	0.0005	0.0002	0.0001
32.5	0.0064	0.0064	0.0063	0.0060	0.0057	0.0053	0.0049	0.0044	0.0039	0.0033	0.0027	0.0022	0.0017	0.0012	0.0008	0.0005	0.0002	0.0001
37.5	0.0061	0.0060	0.0059	0.0057	0.0054	0.0050	0.0046	0.0041	0.0036	0.0031	0.0026	0.0021	0.0016	0.0012	0.0008	0.0005	0.0002	0.0001
42.5	0.0056	0.0056	0.0055	0.0053	0.0050	0.0047	0.0043	0.0039	0.0034	0.0029	0.0024	0.0020	0.0015	0.0011	0.0007	0.0004	0.0002	0.0001
47.5	0.0052	0.0051	0.0050	0.0049	0.0046	0.0043	0.0040	0.0036	0.0032	0.0027	0.0023	0.0018	0.0014	0.0010	0.0007	0.0004	0.0002	0.0000
52.5	0.0047	0.0046	0.0046	0.0044	0.0042	0.0039	0.0036	0.0033	0.0029	0.0025	0.0021	0.0017	0.0013	0.0010	0.0007	0.0004	0.0002	0.0000
57.5	0.0041	0.0041	0.0040	0.0039	0.0037	0.0035	0.0032	0.0029	0.0026	0.0022	0.0019	0.0015	0.0012	0.0009	0.0006	0.0004	0.0002	0.0000
62.5	0.0035	0.0035	0.0035	0.0034	0.0033	0.0031	0.0028	0.0026	0.0023	0.0020	0.0017	0.0014	0.0011	0.0008	0.0006	0.0003	0.0002	0.0000
67.5	0.0029	0.0030	0.0029	0.0029	0.0027	0.0026	0.0024	0.0022	0.0020	0.0017	0.0015	0.0012	0.0010	0.0007	0.0005	0.0003	0.0002	0.0000
72.5	0.0023	0.0023	0.0023	0.0023	0.0022	0.0021	0.0020	0.0018	0.0016	0.0014	0.0012	0.0010	0.0008	0.0006	0.0004	0.0003	0.0001	0.0000
77.5	0.0017	0.0017	0.0017	0.0017	0.0017	0.0016	0.0015	0.0014	0.0013	0.0012	0.0010	0.0009	0.0007	0.0005	0.0004	0.0003	0.0001	0.0000
82.5	0.0010	0.0011	0.0011	0.0011	0.0011	0.0011	0.0011	0.0010	0.0010	0.0009	0.0008	0.0007	0.0006	0.0004	0.0003	0.0002	0.0001	0.0000
87.5	0.0004	0.0004	0.0005	0.0005	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0005	0.0005	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
92.5	0.0000	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
97.5	0.0000	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
102.5	0.0000	0.0001	0.0001	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
107.5	0.0000	0.0001	0.0001	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
112.5	0.0000	0.0001	0.0001	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
117.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
122.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
127.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
132.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
137.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
142.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
147.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
152.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
157.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
162.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
167.5	0.0000	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
172.5	0.0000	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
177.5	0.0000	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000

Numerical values of vertical skylight coefficients for a vertical point with large obstruction:

(ρ_b = 0.2, ρ_g = 0.2)

ϕ / γ	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5
-177.5	0.0010	0.0010	0.0010	0.0010	0.0009	0.0009	0.0008	0.0008	0.0007	0.0006	0.0005	0.0004	0.0004	0.0003	0.0002	0.0001	0.0001	0.0000
-172.5	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009	0.0008	0.0007	0.0007	0.0006	0.0005	0.0004	0.0003	0.0003	0.0002	0.0001	0.0001	0.0000
-167.5	0.0009	0.0009	0.0009	0.0009	0.0009	0.0008	0.0008	0.0007	0.0007	0.0006	0.0005	0.0004	0.0003	0.0003	0.0002	0.0001	0.0001	0.0000
-162.5	0.0008	0.0009	0.0009	0.0009	0.0008	0.0008	0.0008	0.0007	0.0006	0.0006	0.0005	0.0004	0.0003	0.0003	0.0002	0.0001	0.0001	0.0000
-157.5	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0007	0.0007	0.0006	0.0006	0.0005	0.0004	0.0003	0.0003	0.0002	0.0001	0.0001	0.0000
-152.5	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0006	0.0006	0.0005	0.0005	0.0004	0.0003	0.0003	0.0002	0.0001	0.0001	0.0000
-147.5	0.0006	0.0006	0.0007	0.0007	0.0007	0.0006	0.0006	0.0006	0.0005	0.0005	0.0004	0.0004	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000
-142.5	0.0005	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0005	0.0005	0.0004	0.0004	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000
-137.5	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000
-132.5	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000
-127.5	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000
-122.5	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000
-117.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000
-112.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000
-107.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000
-102.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000
-97.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000
-92.5	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
-87.5	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000
-82.5	0.0010	0.0010	0.0010	0.0010	0.0009	0.0009	0.0008	0.0008	0.0007	0.0006	0.0005	0.0004	0.0004	0.0003	0.0002	0.0001	0.0001	0.0000
-77.5	0.0017	0.0016	0.0016	0.0016	0.0015	0.0014	0.0013	0.0012	0.0010	0.0009	0.0008	0.0006	0.0005	0.0004	0.0002	0.0002	0.0001	0.0000
-72.5	0.0023	0.0023	0.0022	0.0021	0.0020	0.0019	0.0017	0.0015	0.0014	0.0012	0.0010	0.0008	0.0006	0.0004	0.0003	0.0002	0.0001	0.0000
-67.5	0.0029	0.0029	0.0028	0.0027	0.0026	0.0024	0.0022	0.0019	0.0017	0.0014	0.0012	0.0010	0.0007	0.0005	0.0004	0.0002	0.0001	0.0000
-62.5	0.0035	0.0035	0.0034	0.0033	0.0031	0.0029	0.0026	0.0023	0.0020	0.0017	0.0014	0.0011	0.0009	0.0006	0.0004	0.0002	0.0001	0.0000
-57.5	0.0041	0.0041	0.0040	0.0038	0.0036	0.0034	0.0031	0.0027	0.0024	0.0020	0.0017	0.0013	0.0010	0.0007	0.0005	0.0003	0.0001	0.0000
-52.5	0.0046	0.0046	0.0045	0.0043	0.0041	0.0038	0.0034	0.0031	0.0027	0.0023	0.0019	0.0015	0.0011	0.0008	0.0005	0.0003	0.0001	0.0000
-47.5	0.0051	0.0051	0.0050	0.0048	0.0045	0.0042	0.0038	0.0034	0.0030	0.0026	0.0021	0.0017	0.0012	0.0009	0.0006	0.0003	0.0001	0.0000
-42.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0037	0.0032	0.0027	0.0022	0.0018	0.0013	0.0009	0.0006	0.0003	0.0001	0.0000
-37.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0035	0.0030	0.0024	0.0019	0.0014	0.0010	0.0006	0.0004	0.0002	0.0000
-32.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0037	0.0031	0.0026	0.0020	0.0015	0.0011	0.0007	0.0004	0.0002	0.0000
-27.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0039	0.0033	0.0027	0.0022	0.0016	0.0011	0.0007	0.0004	0.0002	0.0000
-22.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0035	0.0029	0.0023	0.0017	0.0012	0.0007	0.0004	0.0002	0.0000
-17.5	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0036	0.0030	0.0023	0.0018	0.0012	0.0008	0.0004	0.0002	0.0000
-12.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0036	0.0030	0.0024	0.0018	0.0012	0.0008	0.0004	0.0002	0.0000
-7.5	0.0000	0.0000	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0038	0.0031	0.0025	0.0019	0.0013	0.0008	0.0004	0.0002	0.0000
-2.5	0.0000	0.0000	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0038	0.0031	0.0025	0.0019	0.0013	0.0008	0.0004	0.0002	0.0000
2.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0038	0.0031	0.0025	0.0019	0.0013	0.0008	0.0004	0.0002	0.0000
7.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0037	0.0031	0.0024	0.0018	0.0013	0.0008	0.0004	0.0002	0.0000
12.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0036	0.0030	0.0024	0.0018	0.0012	0.0008	0.0004	0.0002	0.0000
17.5	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0036	0.0030	0.0024	0.0018	0.0012	0.0008	0.0004	0.0002	0.0000
22.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0035	0.0029	0.0023	0.0017	0.0012	0.0007	0.0004	0.0002	0.0000
27.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0039	0.0033	0.0028	0.0022	0.0016	0.0011	0.0007	0.0004	0.0002	0.0000
32.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0037	0.0032	0.0026	0.0021	0.0016	0.0011	0.0007	0.0004	0.0002	0.0000
37.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0035	0.0030	0.0024	0.0019	0.0014	0.0010	0.0006	0.0004	0.0002	0.0000
42.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0037	0.0032	0.0027	0.0023	0.0018	0.0013	0.0009	0.0006	0.0003	0.0001	0.0000
47.5	0.0051	0.0051	0.0050	0.0048	0.0045	0.0042	0.0038	0.0034	0.0030	0.0026	0.0021	0.0017	0.0012	0.0009	0.0006	0.0003	0.0001	0.0000
52.5	0.0046	0.0046	0.0045	0.0043	0.0041	0.0038	0.0034	0.0031	0.0027	0.0023	0.0019	0.0015	0.0011	0.0008	0.0005	0.0003	0.0001	0.0000
57.5	0.0041	0.0041	0.0039	0.0038	0.0036	0.0033	0.0030	0.0027	0.0024	0.0020	0.0016	0.0013	0.0010	0.0007	0.0005	0.0003	0.0001	0.0000
62.5	0.0035	0.0035	0.0034	0.0033	0.0031	0.0029	0.0026	0.0023	0.0020	0.0017	0.0014	0.0011	0.0009	0.0006	0.0004	0.0002	0.0001	0.0000
67.5	0.0029	0.0029	0.0028	0.0027	0.0026	0.0024	0.0022	0.0019	0.0017	0.0014	0.0012	0.0009	0.0007	0.0005	0.0004	0.0002	0.0001	0.0000
72.5	0.0023	0.0023	0.0022	0.0021	0.0020	0.0019	0.0017	0.0016	0.0014	0.0012	0.0010	0.0008	0.0006	0.0005	0.0003	0.0002	0.0001	0.0000
77.5	0.0017	0.0016	0.0016	0.0015	0.0015	0.0014	0.0013	0.0011	0.0010	0.0009	0.0008	0.0006	0.0005	0.0004	0.0002	0.0002	0.0001	0.0000
82.5	0.0010	0.0010	0.0010	0.0010	0.0009	0.0009	0.0008	0.0008	0.0007	0.0006	0.0005	0.0004	0.0004	0.0003	0.0002	0.0001	0.0001	0.0000
87.5	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000
92.5	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
97.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000
102.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000
107.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000
112.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000
117.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000
122.5	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000
127.5	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000
132.5	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000
137.5	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000
142.5	0.0005	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0005	0.0005	0.0004	0.0004	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000
147.5	0.0006	0.0006	0.0007	0.0007	0.0007	0.0006	0.0006	0.0006	0.0005	0.0005	0.0004	0.0004	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000
152.5	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0006	0.0006	0.0005	0.0005	0.0004	0.0003	0.0003	0.0002	0.0001	0.0001	0.0000
157.5	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0007	0.0007	0.0006	0.0006	0.0005	0.0004	0.0003	0.0003	0.0002	0.0001	0.0001	0.0000
162.5	0.0008	0.0009	0.0009	0.0009	0.0008	0.0008	0.0008	0.0007	0.0006	0.0006	0.0005	0.0004	0.0003	0.0003	0.0002	0.0001	0.0001	0.0000
167.5	0.0009	0.0009	0.0009	0.0009	0.0009	0.0008	0.0008	0.0007	0.0007	0.0006	0.0005	0.0004	0.0003	0.0003	0.0002	0.0001	0.0001	0.0000
172.5	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009	0.0008	0.0007	0.0007	0.0006	0.0005	0.0004	0.0003	0.0003	0.0002	0.0001	0.0001	0.0000
177.5	0.0010	0.0010	0.0010	0.0010	0.0009	0.0009	0.0008	0.0008	0.0007	0.0006	0.0005	0.0004	0.0004	0.0003	0.0002	0.0001	0.0001	0.0000

Numerical values of vertical skylight coefficients for a vertical point with large obstruction:

(ρ_b = 0.7, ρ_g = 0.7)

ϕ / γ	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5
-177.5	0.0033	0.0034	0.0034	0.0034	0.0033	0.0031	0.0029	0.0027	0.0024	0.0022	0.0019	0.0015	0.0012	0.0009	0.0007	0.0004	0.0002	0.0001
-172.5	0.0032	0.0033	0.0033	0.0032	0.0031	0.0030	0.0028	0.0026	0.0024	0.0021	0.0018	0.0015	0.0012	0.0009	0.0007	0.0004	0.0002	0.0001
-167.5	0.0031	0.0032	0.0032	0.0032	0.0031	0.0030	0.0028	0.0026	0.0023	0.0021	0.0018	0.0015	0.0012	0.0009	0.0007	0.0004	0.0002	0.0001
-162.5	0.0029	0.0030	0.0030	0.0030	0.0029	0.0028	0.0027	0.0025	0.0023	0.0020	0.0017	0.0015	0.0012	0.0009	0.0007	0.0004	0.0002	0.0001
-157.5	0.0027	0.0028	0.0028	0.0028	0.0027	0.0026	0.0025	0.0023	0.0021	0.0019	0.0017	0.0014	0.0012	0.0009	0.0006	0.0004	0.0002	0.0001
-152.5	0.0024	0.0025	0.0025	0.0026	0.0025	0.0024	0.0023	0.0022	0.0020	0.0018	0.0016	0.0014	0.0011	0.0009	0.0006	0.0004	0.0002	0.0001
-147.5	0.0021	0.0022	0.0023	0.0023	0.0023	0.0022	0.0022	0.0020	0.0019	0.0017	0.0015	0.0013	0.0011	0.0009	0.0006	0.0004	0.0002	0.0001
-142.5	0.0019	0.0020	0.0020	0.0021	0.0021	0.0020	0.0020	0.0019	0.0018	0.0017	0.0015	0.0013	0.0011	0.0008	0.0006	0.0004	0.0002	0.0001
-137.5	0.0014	0.0015	0.0016	0.0017	0.0017	0.0018	0.0018	0.0017	0.0017	0.0016	0.0014	0.0012	0.0010	0.0008	0.0006	0.0004	0.0002	0.0001
-132.5	0.0010	0.0011	0.0012	0.0013	0.0014	0.0015	0.0015	0.0016	0.0016	0.0015	0.0013	0.0012	0.0010	0.0008	0.0006	0.0004	0.0002	0.0001
-127.5	0.0007	0.0008	0.0009	0.0011	0.0012	0.0013	0.0014	0.0015	0.0014	0.0014	0.0012	0.0011	0.0009	0.0007	0.0006	0.0004	0.0002	0.0001
-122.5	0.0003	0.0005	0.0006	0.0008	0.0009	0.0011	0.0013	0.0013	0.0013	0.0013	0.0012	0.0010	0.0009	0.0007	0.0005	0.0004	0.0002	0.0001
-117.5	0.0001	0.0002	0.0004	0.0006	0.0008	0.0010	0.0012	0.0013	0.0012	0.0012	0.0011	0.0010	0.0008	0.0007	0.0005	0.0003	0.0002	0.0001
-112.5	0.0001	0.0002	0.0004	0.0006	0.0009	0.0010	0.0011	0.0012	0.0011	0.0011	0.0010	0.0009	0.0008	0.0006	0.0005	0.0003	0.0002	0.0001
-107.5	0.0001	0.0002	0.0004	0.0007	0.0009	0.0010	0.0010	0.0010	0.0010	0.0010	0.0009	0.0008	0.0007	0.0006	0.0005	0.0003	0.0002	0.0001
-102.5	0.0001	0.0002	0.0005	0.0007	0.0008	0.0009	0.0009	0.0009	0.0009	0.0009	0.0008	0.0008	0.0007	0.0006	0.0004	0.0003	0.0002	0.0001
-97.5	0.0001	0.0003	0.0005	0.0006	0.0007	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0007	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001
-92.5	0.0001	0.0003	0.0004	0.0005	0.0006	0.0006	0.0007	0.0007	0.0007	0.0007	0.0007	0.0006	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001
-87.5	0.0004	0.0004	0.0006	0.0006	0.0007	0.0008	0.0008	0.0008	0.0008	0.0008	0.0007	0.0007	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001
-82.5	0.0010	0.0011	0.0011	0.0011	0.0012	0.0012	0.0012	0.0012	0.0011	0.0010	0.0009	0.0008	0.0007	0.0006	0.0005	0.0003	0.0002	0.0001
-77.5	0.0017	0.0017	0.0017	0.0017	0.0017	0.0016	0.0015	0.0015	0.0014	0.0013	0.0011	0.0010	0.0008	0.0007	0.0005	0.0003	0.0002	0.0001
-72.5	0.0023	0.0023	0.0023	0.0023	0.0022	0.0021	0.0020	0.0018	0.0016	0.0015	0.0013	0.0011	0.0009	0.0007	0.0005	0.0004	0.0002	0.0001
-67.5	0.0029	0.0030	0.0029	0.0029	0.0028	0.0026	0.0024	0.0022	0.0019	0.0017	0.0015	0.0012	0.0010	0.0008	0.0006	0.0004	0.0002	0.0001
-62.5	0.0035	0.0036	0.0035	0.0034	0.0033	0.0031	0.0029	0.0027	0.0024	0.0020	0.0017	0.0014	0.0011	0.0009	0.0006	0.0004	0.0002	0.0001
-57.5	0.0041	0.0041	0.0041	0.0040	0.0039	0.0037	0.0034	0.0031	0.0028	0.0024	0.0020	0.0016	0.0013	0.0010	0.0007	0.0004	0.0002	0.0001
-52.5	0.0047	0.0047	0.0046	0.0045	0.0043	0.0041	0.0038	0.0035	0.0031	0.0027	0.0022	0.0018	0.0014	0.0010	0.0007	0.0005	0.0002	0.0001
-47.5	0.0052	0.0052	0.0051	0.0050	0.0049	0.0046	0.0043	0.0040	0.0036	0.0031	0.0026	0.0021	0.0016	0.0012	0.0008	0.0005	0.0003	0.0001
-42.5	0.0000	0.0001	0.0002	0.0003	0.0004	0.0004	0.0005	0.0041	0.0036	0.0031	0.0026	0.0021	0.0016	0.0012	0.0008	0.0005	0.0003	0.0001
-37.5	0.0001	0.0001	0.0002	0.0003	0.0004	0.0005	0.0006	0.0006	0.0040	0.0034	0.0029	0.0023	0.0018	0.0013	0.0008	0.0005	0.0003	0.0001
-32.5	0.0000	0.0001	0.0002	0.0003	0.0004	0.0005	0.0006	0.0007	0.0042	0.0037	0.0031	0.0025	0.0019	0.0014	0.0009	0.0006	0.0003	0.0001
-27.5	0.0001	0.0001	0.0002	0.0004	0.0004	0.0005	0.0006	0.0007	0.0044	0.0039	0.0033	0.0027	0.0020	0.0014	0.0009	0.0006	0.0003	0.0001
-22.5	0.0001	0.0002	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008	0.0008	0.0041	0.0035	0.0028	0.0022	0.0015	0.0010	0.0006	0.0003	0.0001
-17.5	0.0001	0.0002	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008	0.0009	0.0042	0.0036	0.0030	0.0023	0.0016	0.0010	0.0006	0.0003	0.0001
-12.5	0.0001	0.0001	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008	0.0008	0.0042	0.0036	0.0030	0.0023	0.0016	0.0010	0.0006	0.0003	0.0001
-7.5	0.0001	0.0002	0.0003	0.0004	0.0006	0.0007	0.0008	0.0009	0.0010	0.0045	0.0039	0.0032	0.0025	0.0018	0.0011	0.0007	0.0003	0.0001
-2.5	0.0001	0.0002	0.0003	0.0004	0.0005	0.0007	0.0008	0.0009	0.0010	0.0045	0.0039	0.0032	0.0025	0.0018	0.0011	0.0007	0.0003	0.0001
2.5	0.0001	0.0002	0.0003	0.0004	0.0005	0.0006	0.0007	0.0009	0.0009	0.0045	0.0038	0.0031	0.0024	0.0017	0.0011	0.0006	0.0003	0.0001
7.5	0.0001	0.0002	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008	0.0009	0.0044	0.0037	0.0031	0.0024	0.0017	0.0011	0.0006	0.0003	0.0001
12.5	0.0000	0.0001	0.0003	0.0004	0.0005	0.0006	0.0006	0.0007	0.0008	0.0042	0.0036	0.0029	0.0023	0.0016	0.0010	0.0006	0.0003	0.0001
17.5	0.0001	0.0002	0.0003	0.0004	0.0006	0.0007	0.0008	0.0009	0.0011	0.0044	0.0038	0.0031	0.0024	0.0017	0.0011	0.0006	0.0003	0.0001
22.5	0.0000	0.0002	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008	0.0009	0.0042	0.0035	0.0029	0.0022	0.0016	0.0010	0.0006	0.0003	0.0001
27.5	0.0001	0.0002	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008	0.0045	0.0040	0.0034	0.0027	0.0021	0.0015	0.0010	0.0006	0.0003	0.0001
32.5	0.0001	0.0002	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008	0.0044	0.0039	0.0033	0.0027	0.0020	0.0014	0.0009	0.0006	0.0003	0.0001
37.5	0.0001	0.0001	0.0002	0.0003	0.0004	0.0005	0.0006	0.0007	0.0040	0.0035	0.0029	0.0024	0.0018	0.0013	0.0009	0.0005	0.0003	0.0001
42.5	0.0000	0.0001	0.0002	0.0003	0.0004	0.0005	0.0005	0.0041	0.0037	0.0032	0.0027	0.0022	0.0016	0.0012	0.0008	0.0005	0.0003	0.0001
47.5	0.0052	0.0052	0.0051	0.0050	0.0048	0.0046	0.0043	0.0039	0.0035	0.0031	0.0026	0.0021	0.0016	0.0011	0.0008	0.0005	0.0003	0.0001
52.5	0.0047	0.0047	0.0046	0.0045	0.0043	0.0041	0.0038	0.0034	0.0031	0.0027	0.0022	0.0018	0.0014	0.0010	0.0007	0.0005	0.0002	0.0001
57.5	0.0041	0.0041	0.0041	0.0040	0.0038	0.0036	0.0034	0.0031	0.0027	0.0024	0.0020	0.0016	0.0012	0.0009	0.0007	0.0004	0.0002	0.0001
62.5	0.0035	0.0036	0.0035	0.0034	0.0033	0.0031	0.0029	0.0027	0.0024	0.0020	0.0017	0.0014	0.0011	0.0009	0.0006	0.0004	0.0002	0.0001
67.5	0.0029	0.0029	0.0029	0.0028	0.0027	0.0026	0.0024	0.0022	0.0019	0.0017	0.0014	0.0012	0.0010	0.0008	0.0006	0.0004	0.0002	0.0001
72.5	0.0023	0.0023	0.0023	0.0023	0.0022	0.0021	0.0020	0.0018	0.0017	0.0015	0.0013	0.0011	0.0009	0.0007	0.0006	0.0004	0.0002	0.0001
77.5	0.0017	0.0017	0.0017	0.0017	0.0016	0.0016	0.0015	0.0014	0.0013	0.0012	0.0011	0.0010	0.0008	0.0007	0.0005	0.0003	0.0002	0.0001
82.5	0.0010	0.0011	0.0011	0.0011	0.0011	0.0012	0.0012	0.0011	0.0011	0.0010	0.0009	0.0008	0.0007	0.0006	0.0005	0.0003	0.0002	0.0001
87.5	0.0004	0.0005	0.0006	0.0007	0.0007	0.0008	0.0008	0.0008	0.0008	0.0008	0.0007	0.0007	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001
92.5	0.0001	0.0003	0.0004	0.0005	0.0006	0.0006	0.0007	0.0007	0.0007	0.0007	0.0007	0.0006	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001
97.5	0.0001	0.0003	0.0005	0.0006	0.0007	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	0.0007	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001
102.5	0.0001	0.0002	0.0005	0.0007	0.0008	0.0009	0.0009	0.0009	0.0009	0.0009	0.0008	0.0008	0.0007	0.0006	0.0004	0.0003	0.0002	0.0001
107.5	0.0001	0.0002	0.0004	0.0007	0.0009	0.0010	0.0010	0.0010	0.0010	0.0010	0.0009	0.0008	0.0007	0.0006	0.0005	0.0003	0.0002	0.0001
112.5	0.0001	0.0002	0.0004	0.0006	0.0009	0.0010	0.0011	0.0012	0.0011	0.0011	0.0010	0.0009	0.0008	0.0006	0.0005	0.0003	0.0002	0.0001
117.5	0.0001	0.0002	0.0004	0.0006	0.0008	0.0010	0.0012	0.0013	0.0012	0.0012	0.0011	0.0010	0.0008	0.0007	0.0005	0.0003	0.0002	0.0001
122.5	0.0003	0.0005	0.0006	0.0008	0.0009	0.0011	0.0013	0.0013	0.0013	0.0013	0.0012	0.0010	0.0009	0.0007	0.0005	0.0004	0.0002	0.0001
127.5	0.0007	0.0008	0.0009	0.0011	0.0012	0.0013	0.0014	0.0015	0.0014	0.0014	0.0012	0.0011	0.0009	0.0007	0.0006	0.0004	0.0002	0.0001
132.5	0.0010	0.0011	0.0012	0.0013	0.0014	0.0015	0.0015	0.0016	0.0016	0.0015	0.0013	0.0012	0.0010	0.0008	0.0006	0.0004	0.0002	0.0001
137.5	0.0014	0.0015	0.0016	0.0017	0.0017	0.0018	0.0018	0.0017	0.0017	0.0016	0.0014	0.0012	0.0010	0.0008	0.0006	0.0004	0.0002	0.0001
142.5	0.0019	0.0020	0.0020	0.0021	0.0021	0.0020	0.0020	0.0019	0.0018	0.0017	0.0015	0.0013	0.0011	0.0008	0.0006	0.0004	0.0002	0.0001
147.5	0.0021	0.0022	0.0023	0.0023	0.0023	0.0022	0.0022	0.0020	0.0019	0.0017	0.0015	0.0013	0.0011	0.0009	0.0006	0.0004	0.0002	0.0001
152.5	0.0024	0.0025	0.0025	0.0026	0.0025	0.0024	0.0023	0.0022	0.0020	0.0018	0.0016	0.0014	0.0011	0.0009	0.0006	0.0004	0.0002	0.0001
157.5	0.0027	0.0028	0.0028	0.0028	0.0027	0.0026	0.0025	0.0023	0.0021	0.0019	0.0017	0.0014	0.0012	0.0009	0.0006	0.0004	0.0002	0.0001
162.5	0.0029	0.0030	0.0030	0.0030	0.0029	0.0028	0.0027	0.0025	0.0023	0.0020	0.0017	0.0015	0.0012	0.0009	0.0007	0.0004	0.0002	0.0001
167.5	0.0031	0.0032	0.0032	0.0032	0.0031	0.0030	0.0028	0.0026	0.0023	0.0021	0.0018	0.0015	0.0012	0.0009	0.0007	0.0004	0.0002	0.0001
172.5	0.0032	0.0033	0.0033	0.0032	0.0031	0.0030	0.0028	0.0026	0.0024	0.0021	0.0018	0.0015	0.0012	0.0009	0.0007	0.0004	0.0002	0.0001
177.5	0.0033	0.0034	0.0034	0.0034	0.0033	0.0031	0.0029	0.0027	0.0024	0.0022	0.0019	0.0015	0.0012	0.0009	0.0007	0.0004	0.0002	0.0001

Numerical values of vertical skylight coefficients for SQU50:

(ρ_b = 0.2, ρ_g = 0.2)

ϕ / γ	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5
-177.5	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000	0.0000
-172.5	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
-167.5	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
-162.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-157.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-152.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-147.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-142.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-137.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-132.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-127.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-122.5	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-117.5	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-112.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-107.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-102.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-97.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
-92.5	0.0000	0.0001	0.0002	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
-87.5	0.0000	0.0001	0.0002	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
-82.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000
-77.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000
-72.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000
-67.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
-62.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
-57.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
-52.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
-47.5	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
-42.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0001	0.0001	0.0001	0.0003	0.0001	0.0000
-37.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0003	0.0001	0.0000
-32.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0004	0.0001	0.0000
-27.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0001	0.0026	0.0021	0.0016	0.0011	0.0007	0.0004	0.0002	0.0000
-22.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0022	0.0016	0.0011	0.0007	0.0004	0.0002	0.0000
-17.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0001	0.0022	0.0017	0.0012	0.0007	0.0004	0.0002	0.0000
-12.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0001	0.0001	0.0001	0.0023	0.0017	0.0012	0.0007	0.0004	0.0002	0.0000
-7.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0036	0.0029	0.0023	0.0017	0.0012	0.0008	0.0004	0.0002	0.0000
-2.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0036	0.0029	0.0023	0.0017	0.0012	0.0008	0.0004	0.0002	0.0000
2.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0036	0.0029	0.0023	0.0017	0.0012	0.0008	0.0004	0.0002	0.0000
7.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0035	0.0029	0.0023	0.0017	0.0012	0.0007	0.0004	0.0002	0.0000
12.5	0.0074	0.0073	0.0071	0.0068	0.0064	0.0059	0.0053	0.0047	0.0041	0.0035	0.0028	0.0022	0.0017	0.0012	0.0007	0.0004	0.0002	0.0000
17.5	0.0072	0.0071	0.0069	0.0066	0.0062	0.0058	0.0052	0.0046	0.0040	0.0034	0.0028	0.0022	0.0016	0.0011	0.0007	0.0004	0.0002	0.0000
22.5	0.0070	0.0069	0.0067	0.0064	0.0060	0.0056	0.0051	0.0045	0.0039	0.0033	0.0027	0.0021	0.0016	0.0011	0.0007	0.0004	0.0002	0.0000
27.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0037	0.0031	0.0026	0.0020	0.0015	0.0010	0.0007	0.0004	0.0002	0.0000
32.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0035	0.0030	0.0024	0.0019	0.0014	0.0010	0.0006	0.0004	0.0001	0.0000
37.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0033	0.0028	0.0023	0.0018	0.0013	0.0009	0.0006	0.0003	0.0001	0.0000
42.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0031	0.0026	0.0021	0.0017	0.0012	0.0009	0.0006	0.0003	0.0001	0.0000
47.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0029	0.0024	0.0020	0.0016	0.0012	0.0008	0.0005	0.0003	0.0001	0.0000
52.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0026	0.0022	0.0018	0.0014	0.0011	0.0007	0.0005	0.0003	0.0001	0.0000
57.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0023	0.0019	0.0016	0.0012	0.0009	0.0007	0.0004	0.0002	0.0001	0.0000
62.5	0.0035	0.0035	0.0034	0.0032	0.0030	0.0028	0.0025	0.0023	0.0020	0.0017	0.0014	0.0011	0.0008	0.0006	0.0004	0.0002	0.0001	0.0000
67.5	0.0029	0.0029	0.0028	0.0027	0.0025	0.0023	0.0021	0.0019	0.0016	0.0014	0.0012	0.0009	0.0007	0.0005	0.0003	0.0002	0.0001	0.0000
72.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0010	0.0008	0.0006	0.0004	0.0003	0.0002	0.0001	0.0000
77.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0008	0.0006	0.0005	0.0004	0.0002	0.0001	0.0001	0.0000
82.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0001	0.0000
87.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0003	0.0004	0.0003	0.0003	0.0002	0.0001	0.0001	0.0000	0.0000
92.5	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
97.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
102.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
107.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
112.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
117.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
122.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
127.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
132.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
137.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
142.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
147.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
152.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
157.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
162.5	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
167.5	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
172.5	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
177.5	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000	0.0000

Numerical values of vertical skylight coefficients for SQU50:

(ρ_b = 0.7, ρ_g = 0.7)

φ / γ	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5
-177.5	0.0018	0.0019	0.0019	0.0018	0.0018	0.0017	0.0016	0.0015	0.0014	0.0012	0.0011	0.0009	0.0007	0.0006	0.0004	0.0003	0.0001	0.0000
-172.5	0.0011	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0011	0.0011	0.0010	0.0009	0.0008	0.0006	0.0005	0.0004	0.0003	0.0001	0.0000
-167.5	0.0005	0.0005	0.0006	0.0006	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0006	0.0006	0.0005	0.0004	0.0002	0.0001	0.0000
-162.5	0.0003	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0006	0.0006	0.0006	0.0005	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
-157.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0002	0.0001	0.0000
-152.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
-147.5	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
-142.5	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0001	0.0000
-137.5	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0003	0.0003	0.0003	0.0003	0.0002	0.0001	0.0000
-132.5	0.0000	0.0000	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0001	0.0000
-127.5	0.0000	0.0000	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0001	0.0000
-122.5	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
-117.5	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0002	0.0001	0.0000
-112.5	0.0000	0.0000	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0002	0.0001	0.0000
-107.5	0.0000	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0005	0.0005	0.0004	0.0004	0.0003	0.0002	0.0001	0.0000
-102.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0005	0.0006	0.0005	0.0005	0.0005	0.0004	0.0004	0.0002	0.0001	0.0000
-97.5	0.0000	0.0001	0.0001	0.0002	0.0003	0.0004	0.0006	0.0007	0.0008	0.0008	0.0008	0.0007	0.0006	0.0005	0.0004	0.0002	0.0001	0.0000
-92.5	0.0001	0.0003	0.0008	0.0012	0.0013	0.0014	0.0014	0.0013	0.0012	0.0011	0.0010	0.0008	0.0007	0.0005	0.0004	0.0002	0.0001	0.0000
-87.5	0.0001	0.0004	0.0009	0.0012	0.0014	0.0014	0.0014	0.0013	0.0012	0.0011	0.0010	0.0008	0.0007	0.0005	0.0004	0.0002	0.0001	0.0000
-82.5	0.0000	0.0002	0.0003	0.0004	0.0005	0.0006	0.0008	0.0009	0.0009	0.0009	0.0008	0.0007	0.0006	0.0005	0.0004	0.0002	0.0001	0.0000
-77.5	0.0000	0.0001	0.0002	0.0004	0.0005	0.0006	0.0006	0.0006	0.0007	0.0007	0.0007	0.0007	0.0006	0.0005	0.0004	0.0002	0.0002	0.0000
-72.5	0.0000	0.0001	0.0002	0.0002	0.0004	0.0005	0.0006	0.0007	0.0006	0.0006	0.0006	0.0006	0.0005	0.0005	0.0003	0.0002	0.0002	0.0000
-67.5	0.0000	0.0000	0.0001	0.0002	0.0002	0.0003	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0003	0.0002	0.0002	0.0000
-62.5	0.0000	0.0001	0.0001	0.0001	0.0002	0.0003	0.0003	0.0004	0.0005	0.0006	0.0006	0.0005	0.0005	0.0004	0.0003	0.0002	0.0002	0.0000
-57.5	0.0000	0.0001	0.0001	0.0001	0.0002	0.0003	0.0003	0.0004	0.0005	0.0006	0.0006	0.0005	0.0004	0.0004	0.0003	0.0002	0.0002	0.0000
-52.5	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0005	0.0006	0.0006	0.0005	0.0004	0.0003	0.0002	0.0002	0.0001
-47.5	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0005	0.0006	0.0006	0.0005	0.0004	0.0003	0.0002	0.0002	0.0001
-42.5	0.0001	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0005	0.0006	0.0005	0.0004	0.0003	0.0005	0.0002	0.0001
-37.5	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0005	0.0005	0.0005	0.0004	0.0003	0.0005	0.0002	0.0001
-32.5	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0005	0.0004	0.0004	0.0003	0.0005	0.0002	0.0001
-27.5	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0005	0.0006	0.0005	0.0005	0.0030	0.0024	0.0019	0.0013	0.0009	0.0005	0.0002	0.0001
-22.5	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0005	0.0007	0.0006	0.0006	0.0005	0.0025	0.0019	0.0014	0.0009	0.0005	0.0002	0.0001
-17.5	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0005	0.0006	0.0006	0.0005	0.0005	0.0025	0.0019	0.0014	0.0009	0.0005	0.0002	0.0001
-12.5	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0026	0.0019	0.0014	0.0009	0.0005	0.0002	0.0001
-7.5	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0005	0.0004	0.0039	0.0032	0.0026	0.0019	0.0014	0.0009	0.0005	0.0002	0.0001
-2.5	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0038	0.0031	0.0025	0.0019	0.0014	0.0009	0.0005	0.0002	0.0001
2.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0038	0.0031	0.0025	0.0019	0.0014	0.0009	0.0005	0.0003	0.0001
7.5	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0037	0.0031	0.0025	0.0019	0.0014	0.0009	0.0005	0.0002	0.0001
12.5	0.0074	0.0074	0.0072	0.0069	0.0065	0.0060	0.0055	0.0049	0.0043	0.0036	0.0030	0.0024	0.0018	0.0013	0.0009	0.0005	0.0002	0.0001
17.5	0.0073	0.0072	0.0070	0.0067	0.0064	0.0059	0.0054	0.0048	0.0042	0.0036	0.0030	0.0024	0.0018	0.0013	0.0009	0.0005	0.0002	0.0001
22.5	0.0070	0.0070	0.0068	0.0065	0.0061	0.0057	0.0052	0.0046	0.0040	0.0034	0.0028	0.0023	0.0017	0.0012	0.0008	0.0005	0.0002	0.0001
27.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0039	0.0033	0.0027	0.0022	0.0016	0.0012	0.0008	0.0005	0.0002	0.0001
32.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0037	0.0031	0.0026	0.0021	0.0016	0.0011	0.0008	0.0005	0.0002	0.0001
37.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0035	0.0030	0.0024	0.0019	0.0015	0.0011	0.0007	0.0005	0.0002	0.0001
42.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0032	0.0027	0.0023	0.0018	0.0014	0.0010	0.0007	0.0004	0.0002	0.0001
47.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0030	0.0026	0.0022	0.0017	0.0013	0.0010	0.0007	0.0004	0.0002	0.0001
52.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0027	0.0023	0.0020	0.0016	0.0012	0.0009	0.0006	0.0004	0.0002	0.0001
57.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0024	0.0021	0.0017	0.0014	0.0011	0.0008	0.0006	0.0004	0.0002	0.0000
62.5	0.0035	0.0035	0.0034	0.0033	0.0031	0.0029	0.0027	0.0024	0.0021	0.0018	0.0015	0.0013	0.0010	0.0008	0.0006	0.0004	0.0002	0.0000
67.5	0.0029	0.0029	0.0028	0.0027	0.0026	0.0025	0.0023	0.0020	0.0018	0.0016	0.0013	0.0011	0.0010	0.0008	0.0005	0.0004	0.0002	0.0000
72.5	0.0000	0.0000	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0013	0.0011	0.0009	0.0007	0.0005	0.0003	0.0002	0.0000
77.5	0.0000	0.0000	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0004	0.0005	0.0012	0.0010	0.0009	0.0007	0.0005	0.0003	0.0002	0.0000
82.5	0.0000	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0004	0.0005	0.0007	0.0011	0.0010	0.0008	0.0006	0.0004	0.0003	0.0001	0.0000
87.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0006	0.0009	0.0010	0.0009	0.0007	0.0005	0.0004	0.0003	0.0001	0.0000
92.5	0.0001	0.0003	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0007	0.0009	0.0009	0.0008	0.0006	0.0005	0.0004	0.0002	0.0001	0.0000
97.5	0.0000	0.0001	0.0003	0.0004	0.0004	0.0005	0.0005	0.0005	0.0006	0.0006	0.0007	0.0007	0.0006	0.0005	0.0004	0.0002	0.0001	0.0000
102.5	0.0000	0.0001	0.0002	0.0003	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
107.5	0.0000	0.0001	0.0002	0.0003	0.0003	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
112.5	0.0000	0.0001	0.0001	0.0002	0.0003	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
117.5	0.0000	0.0001	0.0001	0.0002	0.0003	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
122.5	0.0000	0.0001	0.0001	0.0002	0.0003	0.0003	0.0004	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
127.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0005	0.0005	0.0004	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
132.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0005	0.0005	0.0004	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
137.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0005	0.0005	0.0004	0.0004	0.0004	0.0003	0.0002	0.0001	0.0000
142.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
147.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0002	0.0001	0.0000
152.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0002	0.0001	0.0000
157.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0002	0.0001	0.0000
162.5	0.0001	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0005	0.0005	0.0006	0.0006	0.0005	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
167.5	0.0003	0.0004	0.0004	0.0005	0.0006	0.0006	0.0006	0.0007	0.0007	0.0007	0.0007	0.0006	0.0006	0.0005	0.0004	0.0003	0.0001	0.0000
172.5	0.0010	0.0010	0.0011	0.0011	0.0011	0.0011	0.0011	0.0010	0.0010	0.0009	0.0008	0.0008	0.0006	0.0005	0.0004	0.0003	0.0001	0.0000
177.5	0.0018	0.0019	0.0019	0.0019	0.0018	0.0017	0.0016	0.0015	0.0014	0.0012	0.0011	0.0009	0.0007	0.0006	0.0004	0.0003	0.0001	0.0000

Numerical values of vertical skylight coefficients for STA50:

(ρ_b = 0.2, ρ_g = 0.2)

ϕ / γ	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5
-177.5	0.0006	0.0006	0.0006	0.0006	0.0005	0.0005	0.0005	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000	0.0000
-172.5	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
-167.5	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
-162.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-157.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-152.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-147.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-142.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-137.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-132.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-127.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-122.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-117.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-112.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-107.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-102.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
-97.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
-92.5	0.0000	0.0000	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
-87.5	0.0000	0.0000	0.0001	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
-82.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
-77.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
-72.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
-67.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
-62.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
-57.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
-52.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
-47.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000
-42.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0003	0.0001	0.0000
-37.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0003	0.0001	0.0000
-32.5	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0004	0.0001	0.0000
-27.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0038	0.0033	0.0027	0.0021	0.0016	0.0011	0.0007	0.0004	0.0002	0.0000
-22.5	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0045	0.0039	0.0034	0.0028	0.0022	0.0016	0.0011	0.0007	0.0004	0.0002	0.0000
-17.5	0.0073	0.0072	0.0070	0.0067	0.0063	0.0058	0.0053	0.0047	0.0041	0.0035	0.0029	0.0023	0.0017	0.0012	0.0007	0.0004	0.0002	0.0000
-12.5	0.0076	0.0075	0.0073	0.0070	0.0065	0.0061	0.0055	0.0049	0.0042	0.0036	0.0029	0.0023	0.0017	0.0012	0.0008	0.0004	0.0002	0.0000
-7.5	0.0077	0.0076	0.0074	0.0070	0.0066	0.0061	0.0055	0.0049	0.0043	0.0036	0.0030	0.0023	0.0017	0.0012	0.0008	0.0004	0.0002	0.0000
-2.5	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0036	0.0030	0.0023	0.0017	0.0012	0.0008	0.0004	0.0002	0.0000
2.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0035	0.0029	0.0023	0.0017	0.0012	0.0007	0.0004	0.0002	0.0000
7.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0035	0.0029	0.0023	0.0017	0.0012	0.0007	0.0004	0.0002	0.0000
12.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0028	0.0022	0.0017	0.0012	0.0007	0.0004	0.0002	0.0000
17.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0022	0.0016	0.0011	0.0007	0.0004	0.0002	0.0000
22.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0021	0.0016	0.0011	0.0007	0.0004	0.0002	0.0000
27.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0026	0.0020	0.0015	0.0011	0.0007	0.0004	0.0002	0.0000
32.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0024	0.0019	0.0014	0.0010	0.0006	0.0003	0.0001	0.0000
37.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0033	0.0028	0.0023	0.0018	0.0013	0.0009	0.0006	0.0003	0.0001	0.0000
42.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0040	0.0036	0.0031	0.0026	0.0021	0.0017	0.0012	0.0009	0.0006	0.0003	0.0001	0.0000
47.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0037	0.0033	0.0028	0.0024	0.0019	0.0015	0.0011	0.0008	0.0005	0.0003	0.0001	0.0000
52.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0033	0.0029	0.0026	0.0022	0.0018	0.0014	0.0010	0.0007	0.0005	0.0003	0.0001	0.0000
57.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0029	0.0026	0.0023	0.0019	0.0016	0.0012	0.0009	0.0007	0.0004	0.0002	0.0001	0.0000
62.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0025	0.0023	0.0020	0.0017	0.0013	0.0011	0.0008	0.0006	0.0004	0.0002	0.0001	0.0000
67.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0021	0.0019	0.0016	0.0014	0.0011	0.0009	0.0007	0.0005	0.0003	0.0002	0.0001	0.0000
72.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0009	0.0007	0.0006	0.0004	0.0003	0.0002	0.0001	0.0000
77.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0007	0.0006	0.0005	0.0003	0.0002	0.0001	0.0001	0.0000
82.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0005	0.0004	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000
87.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000	0.0000
92.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
97.5	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
102.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
107.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
112.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
117.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
122.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
127.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
132.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
137.5	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
142.5	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
147.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
152.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
157.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
162.5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
167.5	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
172.5	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000
177.5	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0002	0.0001	0.0001	0.0000	0.0000

Numerical values of vertical skylight coefficients for STA50:

(ρ_b = 0.7, ρ_g = 0.7)

ϕ / γ	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5
-177.5	0.0020	0.0020	0.0020	0.0020	0.0019	0.0018	0.0017	0.0016	0.0014	0.0012	0.0011	0.0009	0.0007	0.0005	0.0004	0.0003	0.0001	0.0000
-172.5	0.0013	0.0013	0.0013	0.0014	0.0013	0.0013	0.0012	0.0012	0.0011	0.0010	0.0009	0.0008	0.0006	0.0005	0.0004	0.0003	0.0001	0.0000
-167.5	0.0006	0.0007	0.0007	0.0007	0.0007	0.0008	0.0008	0.0008	0.0008	0.0007	0.0007	0.0006	0.0006	0.0005	0.0004	0.0003	0.0001	0.0000
-162.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0003	0.0003	0.0001	0.0000
-157.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0004	0.0003	0.0003	0.0001	0.0000
-152.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
-147.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
-142.5	0.0000	0.0001	0.0001	0.0002	0.0003	0.0003	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
-137.5	0.0000	0.0001	0.0001	0.0002	0.0003	0.0003	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0002	0.0001	0.0000
-132.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0004	0.0004	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
-127.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0004	0.0004	0.0004	0.0005	0.0004	0.0004	0.0004	0.0004	0.0003	0.0002	0.0001	0.0000
-122.5	0.0000	0.0001	0.0001	0.0002	0.0002	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
-117.5	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0004	0.0003	0.0002	0.0001	0.0000
-112.5	0.0003	0.0004	0.0004	0.0005	0.0005	0.0005	0.0006	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0002	0.0001	0.0000
-107.5	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0005	0.0005	0.0004	0.0004	0.0003	0.0002	0.0001	0.0000
-102.5	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
-97.5	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0005	0.0006	0.0007	0.0007	0.0007	0.0007	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
-92.5	0.0001	0.0001	0.0003	0.0007	0.0009	0.0010	0.0010	0.0010	0.0009	0.0009	0.0008	0.0007	0.0006	0.0004	0.0003	0.0002	0.0001	0.0000
-87.5	0.0001	0.0001	0.0003	0.0007	0.0009	0.0010	0.0010	0.0010	0.0009	0.0009	0.0008	0.0007	0.0006	0.0004	0.0003	0.0002	0.0001	0.0000
-82.5	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0004	0.0005	0.0006	0.0007	0.0006	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
-77.5	0.0004	0.0004	0.0004	0.0004	0.0004	0.0005	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0003	0.0002	0.0002	0.0000
-72.5	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0004	0.0004	0.0003	0.0002	0.0002	0.0000
-67.5	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0004	0.0004	0.0003	0.0002	0.0002	0.0000
-62.5	0.0003	0.0004	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0006	0.0005	0.0005	0.0004	0.0004	0.0003	0.0002	0.0002	0.0000
-57.5	0.0000	0.0000	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0004	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0002	0.0002	0.0000
-52.5	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0004	0.0005	0.0006	0.0005	0.0005	0.0004	0.0003	0.0002	0.0002	0.0001
-47.5	0.0000	0.0000	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0004	0.0005	0.0006	0.0006	0.0005	0.0004	0.0003	0.0002	0.0002	0.0001
-42.5	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0006	0.0006	0.0006	0.0005	0.0004	0.0003	0.0005	0.0002	0.0001
-37.5	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0005	0.0007	0.0007	0.0006	0.0005	0.0004	0.0003	0.0005	0.0002	0.0001
-32.5	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0005	0.0007	0.0006	0.0006	0.0005	0.0004	0.0003	0.0005	0.0002	0.0001
-27.5	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0041	0.0037	0.0031	0.0025	0.0019	0.0014	0.0009	0.0005	0.0002	0.0001
-22.5	0.0001	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0048	0.0043	0.0038	0.0032	0.0026	0.0020	0.0014	0.0009	0.0005	0.0002	0.0001
-17.5	0.0075	0.0074	0.0072	0.0069	0.0065	0.0061	0.0055	0.0050	0.0046	0.0040	0.0033	0.0026	0.0020	0.0015	0.0010	0.0006	0.0003	0.0001
-12.5	0.0081	0.0080	0.0078	0.0075	0.0071	0.0066	0.0060	0.0054	0.0047	0.0040	0.0033	0.0027	0.0020	0.0015	0.0009	0.0005	0.0003	0.0001
-7.5	0.0081	0.0080	0.0078	0.0075	0.0071	0.0066	0.0060	0.0054	0.0047	0.0040	0.0034	0.0027	0.0021	0.0015	0.0010	0.0006	0.0003	0.0001
-2.5	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0040	0.0033	0.0027	0.0020	0.0015	0.0009	0.0006	0.0003	0.0001
2.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0037	0.0031	0.0024	0.0019	0.0013	0.0009	0.0005	0.0003	0.0001
7.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0037	0.0031	0.0024	0.0019	0.0013	0.0009	0.0005	0.0002	0.0001
12.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0030	0.0024	0.0018	0.0013	0.0008	0.0005	0.0002	0.0001
17.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0023	0.0018	0.0013	0.0008	0.0005	0.0002	0.0001
22.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0022	0.0017	0.0012	0.0008	0.0005	0.0002	0.0001
27.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0027	0.0022	0.0017	0.0012	0.0008	0.0005	0.0002	0.0001
32.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0026	0.0021	0.0016	0.0011	0.0008	0.0005	0.0002	0.0001
37.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0034	0.0029	0.0024	0.0019	0.0015	0.0011	0.0007	0.0004	0.0002	0.0001
42.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0041	0.0036	0.0032	0.0027	0.0022	0.0018	0.0014	0.0010	0.0007	0.0004	0.0002	0.0001
47.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0037	0.0033	0.0029	0.0025	0.0021	0.0017	0.0013	0.0009	0.0006	0.0004	0.0002	0.0001
52.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0034	0.0030	0.0026	0.0023	0.0019	0.0015	0.0012	0.0008	0.0006	0.0004	0.0002	0.0000
57.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0030	0.0027	0.0024	0.0020	0.0017	0.0014	0.0011	0.0008	0.0006	0.0004	0.0002	0.0000
62.5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0026	0.0024	0.0021	0.0018	0.0015	0.0012	0.0009	0.0007	0.0005	0.0003	0.0002	0.0000
67.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0022	0.0020	0.0017	0.0015	0.0012	0.0010	0.0009	0.0007	0.0005	0.0003	0.0002	0.0000
72.5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0011	0.0009	0.0008	0.0006	0.0005	0.0003	0.0002	0.0000
77.5	0.0000	0.0000	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0010	0.0009	0.0007	0.0006	0.0004	0.0003	0.0001	0.0000
82.5	0.0000	0.0001	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0004	0.0005	0.0009	0.0008	0.0006	0.0005	0.0004	0.0002	0.0001	0.0000
87.5	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0005	0.0006	0.0008	0.0007	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
92.5	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0005	0.0006	0.0007	0.0007	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
97.5	0.0002	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0005	0.0005	0.0006	0.0006	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
102.5	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0005	0.0004	0.0004	0.0003	0.0002	0.0001	0.0000
107.5	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
112.5	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0003	0.0002	0.0001	0.0000
117.5	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
122.5	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
127.5	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
132.5	0.0001	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
137.5	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0001	0.0000
142.5	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
147.5	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
152.5	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0005	0.0004	0.0004	0.0004	0.0003	0.0002	0.0001	0.0000
157.5	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
162.5	0.0003	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0006	0.0006	0.0006	0.0005	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
167.5	0.0005	0.0006	0.0006	0.0006	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0006	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
172.5	0.0009	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0009	0.0009	0.0008	0.0007	0.0006	0.0005	0.0004	0.0003	0.0001	0.0000
177.5	0.0018	0.0018	0.0018	0.0018	0.0018	0.0017	0.0016	0.0015	0.0013	0.0012	0.0010	0.0009	0.0007	0.0006	0.0004	0.0003	0.0001	0.0000

Appendix F3: VDF results by calculation and RADIANCE simulation

Numerical values of VDF for layout SQU50:

Height of reference point above ground (m)	VDF results (%)	
	RADIANCE	Vertical skylight coefficients method
10	12.9	12.1
20	13.4	12.8
30	14.3	13.6
40	15.5	14.8
50	17.1	16.6
60	19.7	19.1
70	22.9	22.5
80	27.3	27.0
90	33.7	33.5

Numerical values of VDF for layout SQU70:

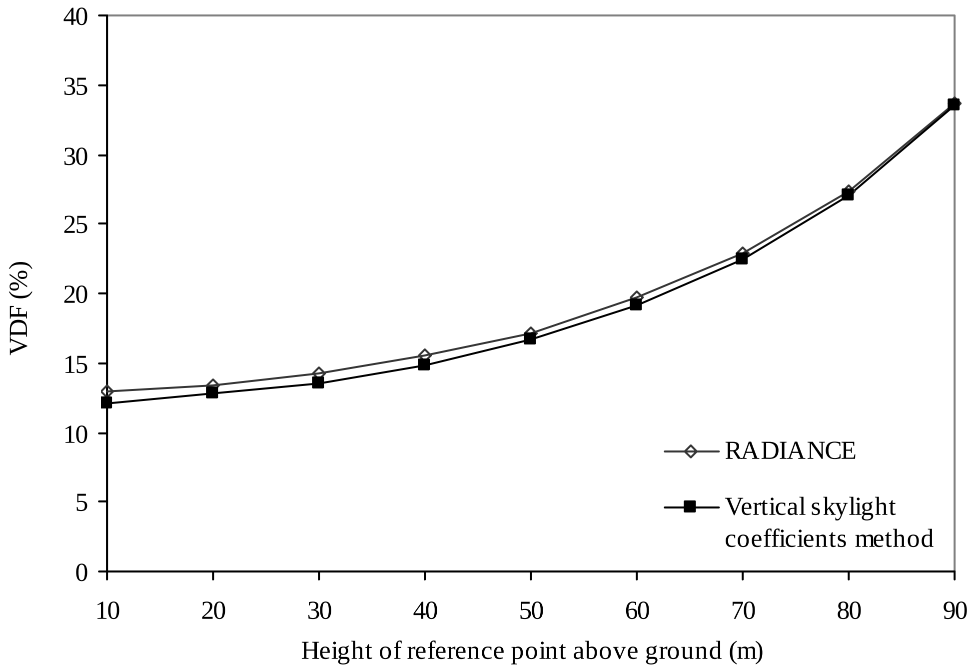
Height of reference point above ground (m)	VDF results (%)	
	RADIANCE	Vertical skylight coefficients method
10	20.2	20.3
20	21.0	21.2
30	22.2	22.2
40	23.3	23.4
50	24.9	25.0
60	26.9	27.0
70	29.0	29.3
80	31.9	32.2
90	36.5	36.5

Numerical values of VDF for layout STA50:

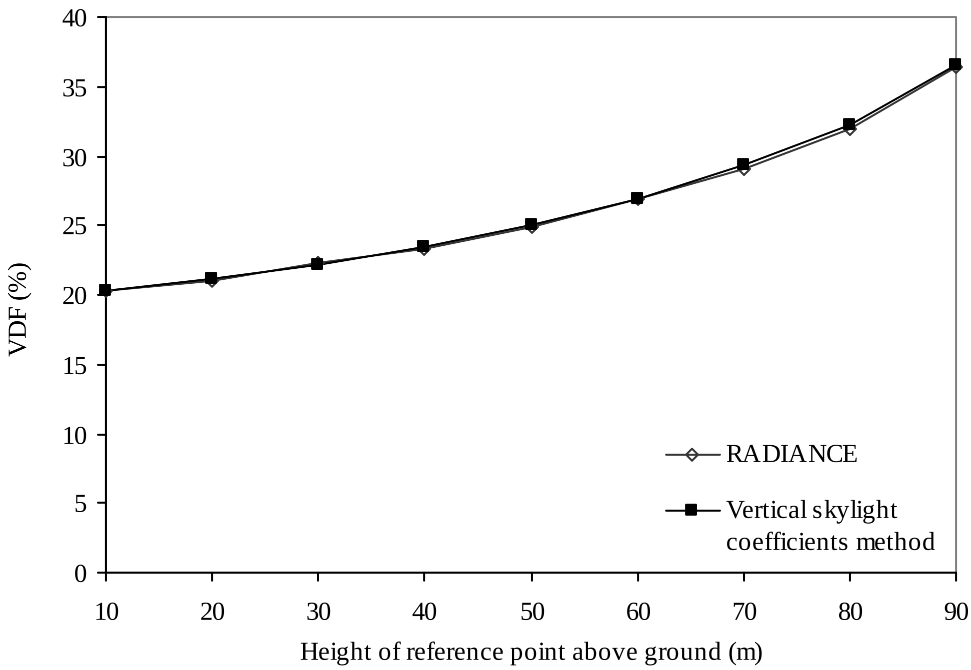
Height of reference point above ground (m)	VDF results (%)	
	RADIANCE	Vertical skylight coefficients method
10	12.7	11.5
20	13.6	12.3
30	14.5	13.3
40	15.9	14.7
50	17.7	16.6
60	19.9	19.2
70	23.2	22.6
80	27.6	27.1
90	33.9	33.4

Numerical values of VDF for layout STA70:

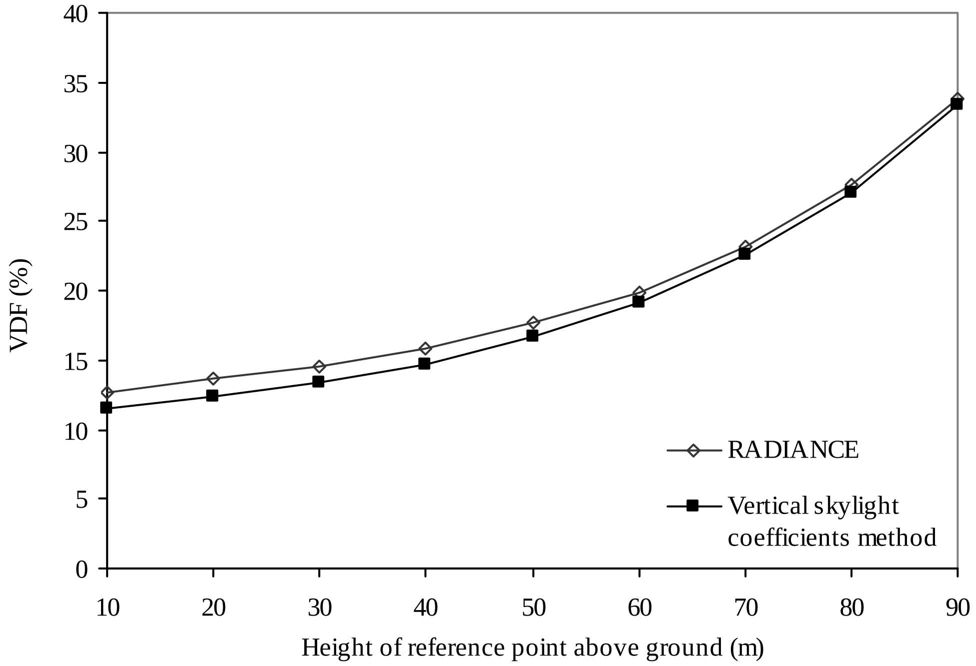
Height of reference point above ground (m)	VDF results (%)	
	RADIANCE	Vertical skylight coefficients method
10	22.2	22.9
20	23.0	23.9
30	24.2	24.9
40	25.3	26.0
50	26.7	27.4
60	28.3	29.1
70	30.3	31.0
80	32.7	33.4
90	36.9	37.4



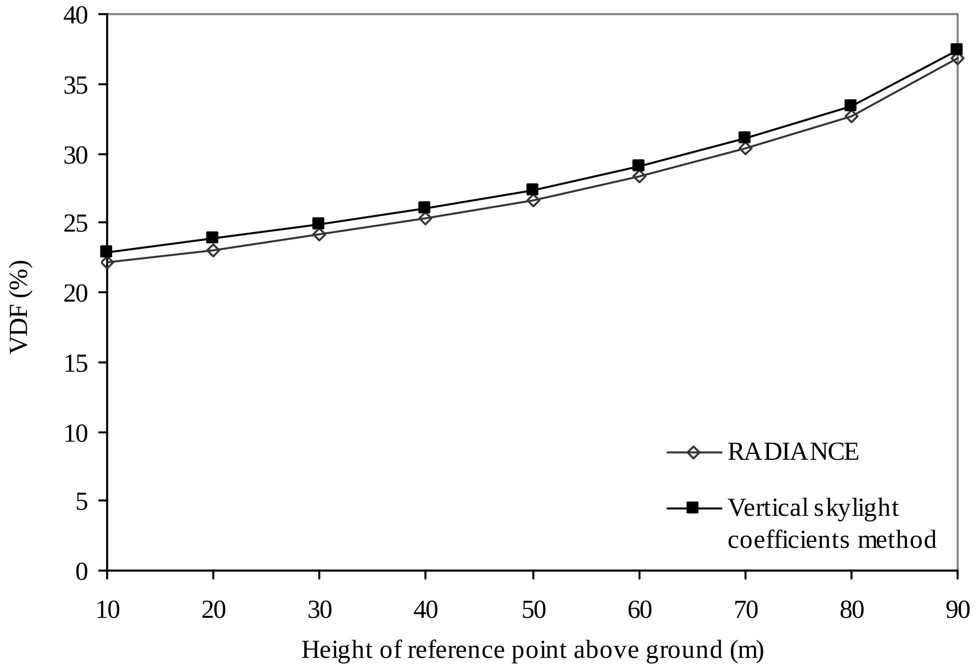
Comparison of VDF results for layout SQU50



Comparison of VDF results for layout SQU70



Comparison of VDF results for layout STA50



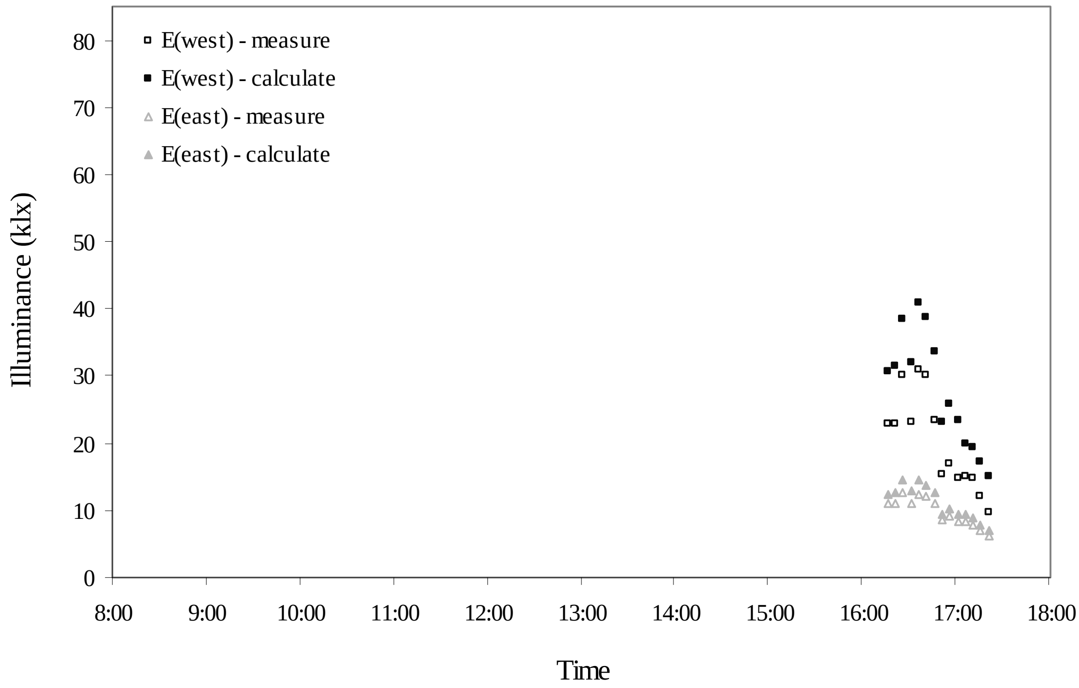
Comparison of VDF results for layout STA70

Appendix F4: Numerical values of vertical skylight coefficients for the reference points of experiment

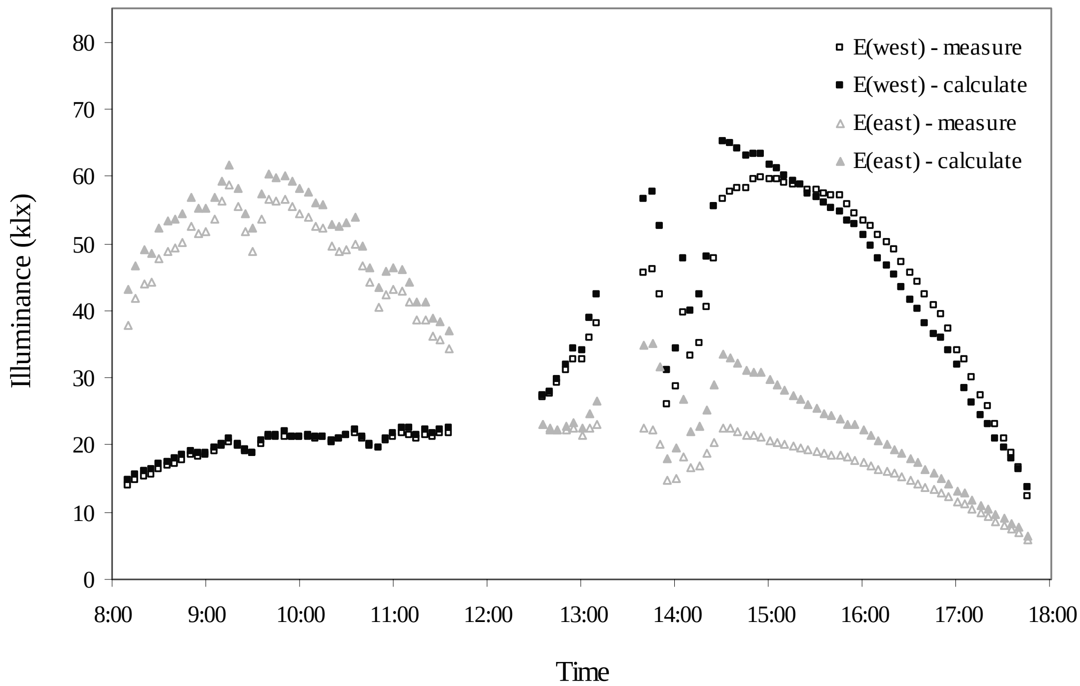
Vertical skylight coefficients for all sky patches in the whole sky hemisphere:

ϕ / γ	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5
-177.5	0.0014	0.0014	0.0014	0.0014	0.0014	0.0013	0.0012	0.0011	0.0010	0.0009	0.0008	0.0007	0.0006	0.0004	0.0003	0.0002	0.0001	0.0000
-172.5	0.0012	0.0013	0.0013	0.0013	0.0013	0.0012	0.0012	0.0011	0.0010	0.0009	0.0008	0.0007	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
-167.5	0.0011	0.0011	0.0012	0.0012	0.0012	0.0012	0.0011	0.0011	0.0010	0.0009	0.0008	0.0007	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
-162.5	0.0009	0.0010	0.0010	0.0011	0.0011	0.0011	0.0011	0.0010	0.0010	0.0009	0.0008	0.0007	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
-157.5	0.0008	0.0008	0.0009	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0009	0.0008	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
-152.5	0.0006	0.0007	0.0008	0.0008	0.0009	0.0010	0.0010	0.0010	0.0009	0.0008	0.0007	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
-147.5	0.0004	0.0005	0.0006	0.0007	0.0008	0.0008	0.0009	0.0009	0.0009	0.0008	0.0007	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
-142.5	0.0002	0.0003	0.0005	0.0006	0.0007	0.0008	0.0009	0.0009	0.0008	0.0008	0.0007	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
-137.5	0.0000	0.0002	0.0004	0.0005	0.0007	0.0007	0.0008	0.0008	0.0008	0.0007	0.0006	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
-132.5	0.0000	0.0002	0.0003	0.0005	0.0006	0.0007	0.0008	0.0008	0.0007	0.0007	0.0006	0.0005	0.0004	0.0004	0.0003	0.0002	0.0001	0.0000
-127.5	0.0000	0.0002	0.0003	0.0005	0.0006	0.0007	0.0008	0.0007	0.0007	0.0006	0.0006	0.0005	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
-122.5	0.0001	0.0002	0.0003	0.0005	0.0006	0.0007	0.0007	0.0007	0.0006	0.0006	0.0005	0.0005	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
-117.5	0.0001	0.0002	0.0004	0.0005	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0005	0.0005	0.0004	0.0003	0.0002	0.0002	0.0001	0.0000
-112.5	0.0001	0.0002	0.0004	0.0005	0.0006	0.0006	0.0006	0.0006	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0002	0.0002	0.0001	0.0000
-107.5	0.0001	0.0002	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-102.5	0.0001	0.0002	0.0003	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-97.5	0.0001	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0001	0.0001	0.0000
-92.5	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000
-87.5	0.0003	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
-82.5	0.0010	0.0010	0.0010	0.0011	0.0010	0.0010	0.0010	0.0009	0.0009	0.0008	0.0007	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
-77.5	0.0017	0.0017	0.0017	0.0016	0.0016	0.0015	0.0014	0.0013	0.0012	0.0011	0.0009	0.0008	0.0006	0.0005	0.0003	0.0002	0.0001	0.0000
-72.5	0.0023	0.0023	0.0022	0.0022	0.0021	0.0020	0.0018	0.0017	0.0015	0.0013	0.0011	0.0009	0.0007	0.0006	0.0004	0.0002	0.0001	0.0000
-67.5	0.0029	0.0029	0.0028	0.0027	0.0026	0.0024	0.0022	0.0020	0.0018	0.0016	0.0013	0.0011	0.0009	0.0006	0.0004	0.0003	0.0001	0.0000
-62.5	0.0035	0.0035	0.0034	0.0033	0.0032	0.0029	0.0027	0.0024	0.0021	0.0018	0.0016	0.0013	0.0010	0.0007	0.0005	0.0003	0.0001	0.0000
-57.5	0.0041	0.0041	0.0040	0.0039	0.0037	0.0035	0.0032	0.0029	0.0025	0.0022	0.0018	0.0015	0.0011	0.0008	0.0006	0.0003	0.0002	0.0000
-52.5	0.0046	0.0046	0.0045	0.0043	0.0041	0.0038	0.0035	0.0031	0.0027	0.0023	0.0019	0.0016	0.0012	0.0009	0.0006	0.0004	0.0002	0.0000
-47.5	0.0052	0.0052	0.0051	0.0049	0.0047	0.0044	0.0040	0.0036	0.0031	0.0027	0.0022	0.0018	0.0014	0.0010	0.0007	0.0004	0.0002	0.0000
-42.5	0.0056	0.0056	0.0055	0.0053	0.0050	0.0046	0.0042	0.0038	0.0033	0.0028	0.0023	0.0018	0.0014	0.0010	0.0007	0.0004	0.0002	0.0000
-37.5	0.0060	0.0060	0.0059	0.0057	0.0054	0.0050	0.0046	0.0041	0.0036	0.0031	0.0025	0.0020	0.0015	0.0011	0.0007	0.0004	0.0002	0.0000
-32.5	0.0064	0.0064	0.0063	0.0061	0.0058	0.0054	0.0050	0.0044	0.0039	0.0033	0.0027	0.0021	0.0016	0.0012	0.0008	0.0004	0.0002	0.0000
-27.5	0.0067	0.0067	0.0066	0.0063	0.0061	0.0057	0.0052	0.0047	0.0041	0.0034	0.0028	0.0022	0.0017	0.0012	0.0008	0.0005	0.0002	0.0000
-22.5	0.0000	0.0001	0.0002	0.0002	0.0003	0.0059	0.0054	0.0049	0.0043	0.0036	0.0030	0.0024	0.0018	0.0013	0.0008	0.0005	0.0002	0.0000
-17.5	0.0000	0.0001	0.0002	0.0003	0.0004	0.0062	0.0057	0.0051	0.0045	0.0038	0.0031	0.0025	0.0018	0.0013	0.0009	0.0005	0.0002	0.0000
-12.5	0.0000	0.0001	0.0002	0.0003	0.0003	0.0062	0.0058	0.0052	0.0045	0.0038	0.0031	0.0025	0.0019	0.0013	0.0009	0.0005	0.0002	0.0000
-7.5	0.0000	0.0001	0.0003	0.0004	0.0005	0.0065	0.0060	0.0054	0.0048	0.0041	0.0033	0.0026	0.0020	0.0014	0.0009	0.0005	0.0002	0.0001
-2.5	0.0000	0.0002	0.0003	0.0004	0.0006	0.0066	0.0062	0.0056	0.0050	0.0042	0.0035	0.0027	0.0020	0.0015	0.0010	0.0005	0.0002	0.0001
2.5	0.0000	0.0001	0.0002	0.0003	0.0004	0.0065	0.0060	0.0054	0.0048	0.0041	0.0033	0.0026	0.0020	0.0014	0.0009	0.0005	0.0002	0.0000
7.5	0.0000	0.0001	0.0002	0.0003	0.0004	0.0064	0.0060	0.0054	0.0047	0.0040	0.0033	0.0026	0.0019	0.0014	0.0009	0.0005	0.0002	0.0000
12.5	0.0000	0.0001	0.0002	0.0002	0.0003	0.0062	0.0057	0.0051	0.0045	0.0038	0.0031	0.0024	0.0018	0.0013	0.0009	0.0005	0.0002	0.0000
17.5	0.0000	0.0001	0.0002	0.0004	0.0005	0.0063	0.0058	0.0052	0.0047	0.0039	0.0032	0.0025	0.0019	0.0014	0.0009	0.0005	0.0002	0.0000
22.5	0.0000	0.0001	0.0002	0.0003	0.0004	0.0060	0.0055	0.0050	0.0044	0.0037	0.0030	0.0024	0.0018	0.0013	0.0009	0.0005	0.0002	0.0000
27.5	0.0067	0.0067	0.0066	0.0064	0.0061	0.0057	0.0052	0.0047	0.0041	0.0035	0.0029	0.0023	0.0017	0.0012	0.0008	0.0005	0.0002	0.0000
32.5	0.0064	0.0064	0.0063	0.0061	0.0058	0.0054	0.0050	0.0045	0.0039	0.0033	0.0027	0.0022	0.0016	0.0012	0.0008	0.0005	0.0002	0.0000
37.5	0.0061	0.0060	0.0059	0.0057	0.0054	0.0051	0.0047	0.0042	0.0037	0.0031	0.0025	0.0020	0.0015	0.0011	0.0007	0.0004	0.0002	0.0000
42.5	0.0056	0.0056	0.0055	0.0053	0.0050	0.0047	0.0043	0.0039	0.0034	0.0028	0.0023	0.0019	0.0014	0.0010	0.0007	0.0004	0.0002	0.0000
47.5	0.0052	0.0052	0.0051	0.0049	0.0047	0.0044	0.0040	0.0036	0.0031	0.0027	0.0022	0.0018	0.0014	0.0010	0.0007	0.0004	0.0002	0.0000
52.5	0.0046	0.0046	0.0045	0.0043	0.0041	0.0038	0.0034	0.0031	0.0027	0.0023	0.0019	0.0015	0.0012	0.0009	0.0006	0.0003	0.0002	0.0000
57.5	0.0041	0.0041	0.0040	0.0038	0.0036	0.0034	0.0031	0.0028	0.0024	0.0021	0.0018	0.0014	0.0011	0.0008	0.0005	0.0003	0.0002	0.0000
62.5	0.0035	0.0035	0.0034	0.0033	0.0031	0.0029	0.0027	0.0024	0.0021	0.0018	0.0016	0.0013	0.0010	0.0007	0.0005	0.0003	0.0001	0.0000
67.5	0.0029	0.0029	0.0028	0.0027	0.0026	0.0024	0.0022	0.0020	0.0018	0.0016	0.0013	0.0011	0.0009	0.0006	0.0004	0.0003	0.0001	0.0000
72.5	0.0023	0.0023	0.0022	0.0022	0.0021	0.0020	0.0018	0.0017	0.0015	0.0013	0.0011	0.0009	0.0007	0.0006	0.0004	0.0002	0.0001	0.0000
77.5	0.0017	0.0017	0.0016	0.0016	0.0016	0.0015	0.0014	0.0013	0.0012	0.0010	0.0009	0.0008	0.0006	0.0005	0.0003	0.0002	0.0001	0.0000
82.5	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0009	0.0008	0.0008	0.0007	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
87.5	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
92.5	0.0001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000
97.5	0.0001	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0002	0.0001	0.0001	0.0000
102.5	0.0001	0.0002	0.0003	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0004	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
107.5	0.0001	0.0002	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0003	0.0002	0.0002	0.0001	0.0000
112.5	0.0001	0.0002	0.0004	0.0005	0.0006	0.0006	0.0006	0.0006	0.0005	0.0005	0.0005	0.0004	0.0004	0.0003	0.0002	0.0002	0.0001	0.0000
117.5	0.0001	0.0002	0.0004	0.0005	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0005	0.0005	0.0004	0.0003	0.0002	0.0002	0.0001	0.0000
122.5	0.0001	0.0002	0.0003	0.0005	0.0006	0.0007	0.0007	0.0007	0.0006	0.0006	0.0005	0.0005	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
127.5	0.0000	0.0002	0.0003	0.0005	0.0006	0.0007	0.0008	0.0007	0.0007	0.0006	0.0006	0.0005	0.0004	0.0003	0.0003	0.0002	0.0001	0.0000
132.5	0.0000	0.0002	0.0003	0.0005	0.0006	0.0007	0.0008	0.0008	0.0007	0.0007	0.0006	0.0005	0.0004	0.0004	0.0003	0.0002	0.0001	0.0000
137.5	0.0000	0.0002	0.0004	0.0005	0.0007	0.0007	0.0008	0.0008	0.0008	0.0007	0.0006	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
142.5	0.0002	0.0003	0.0005	0.0006	0.0007	0.0008	0.0009	0.0009	0.0008	0.0008	0.0007	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
147.5	0.0004	0.0005	0.0006	0.0007	0.0008	0.0008	0.0009	0.0009	0.0009	0.0008	0.0007	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
152.5	0.0006	0.0007	0.0008	0.0008	0.0009	0.0010	0.0010	0.0010	0.0009	0.0008	0.0007	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
157.5	0.0008	0.0008	0.0009	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0009	0.0008	0.0006	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
162.5	0.0009	0.0010	0.0010	0.0011	0.0011	0.0011	0.0011	0.0010	0.0010	0.0009	0.0008	0.0007	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
167.5	0.0011	0.0011	0.0012	0.0012	0.0012	0.0012	0.0011	0.0011	0.0010	0.0009	0.0008	0.0007	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
172.5	0.0012	0.0013	0.0013	0.0013	0.0013	0.0012	0.0012	0.0011	0.0010	0.0009	0.0008	0.0007	0.0005	0.0004	0.0003	0.0002	0.0001	0.0000
177.5	0.0014	0.0014	0.0014	0.0014	0.0014	0.0013	0.0012	0.0011	0.0010	0.0009	0.0008	0.0007	0.0006	0.0004	0.0003	0.0002	0.0001	0.0000

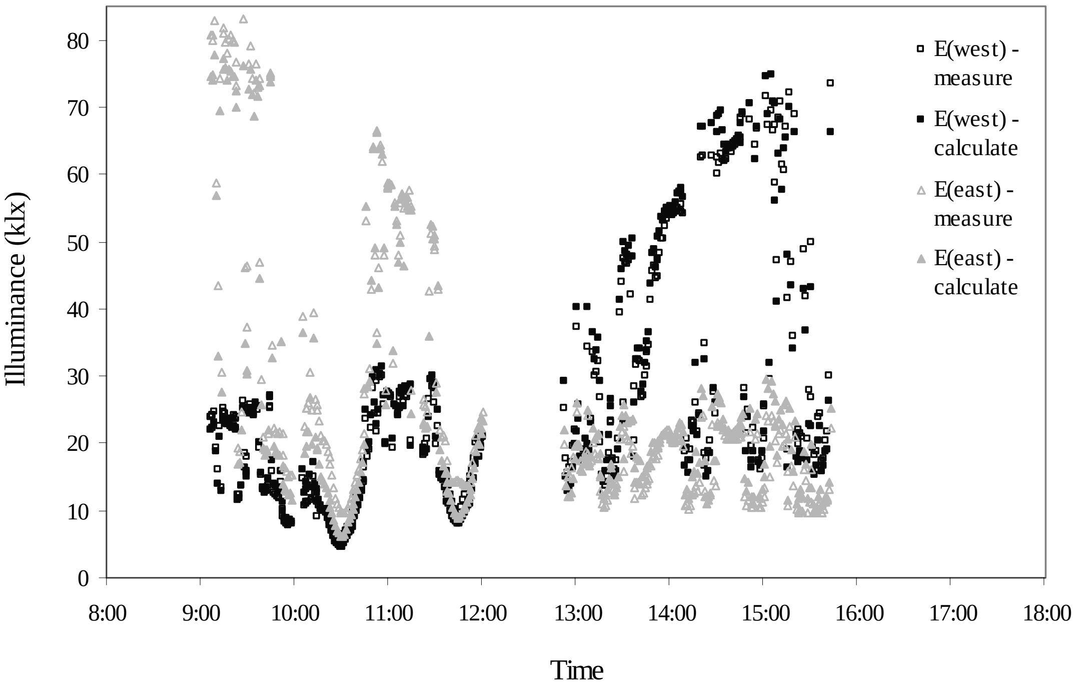
Appendix F5: Vertical illuminance results by calculation and measurement under real skies



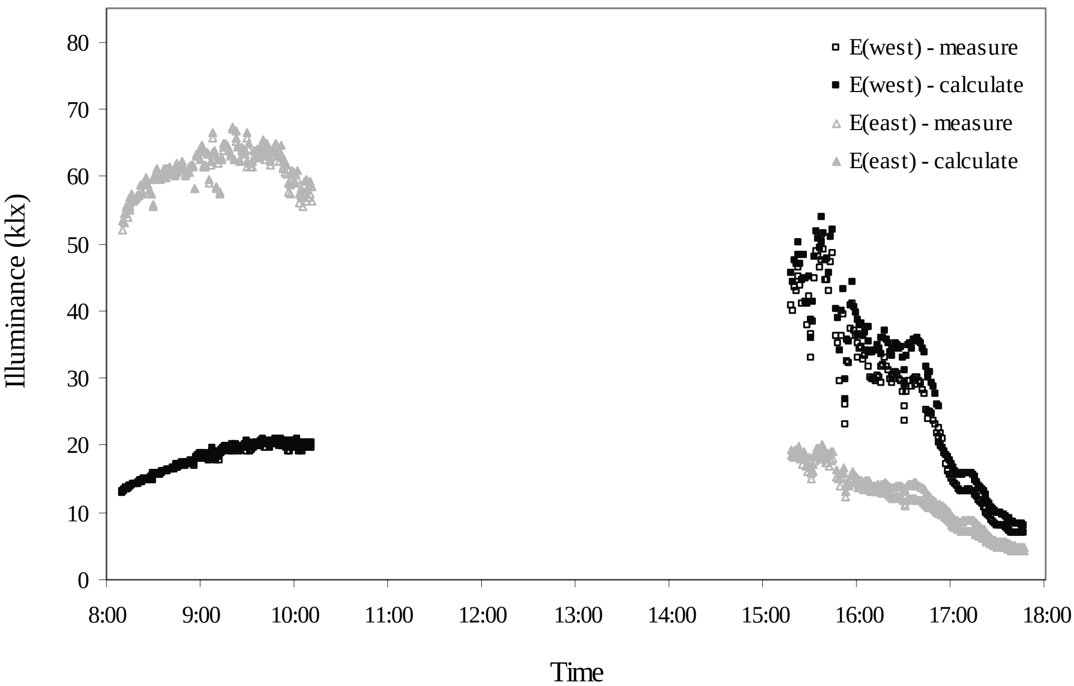
Measurement and calculation results on 10 June 2004



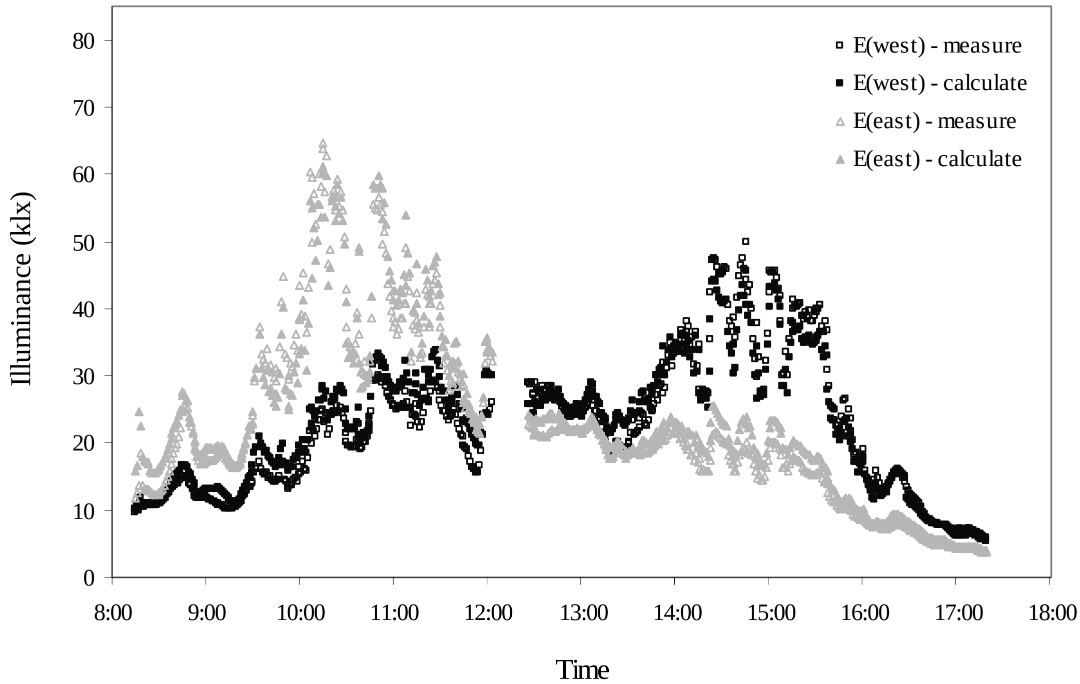
Measurement and calculation results on 11 June 2004



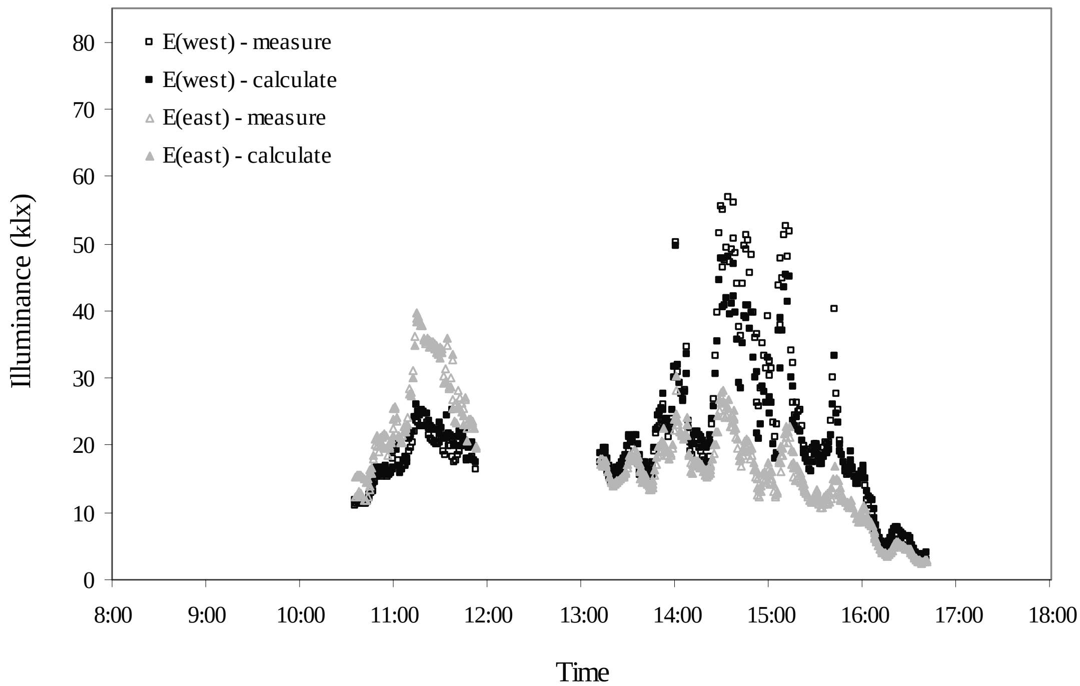
Measurement and calculation results on 25 June 2004



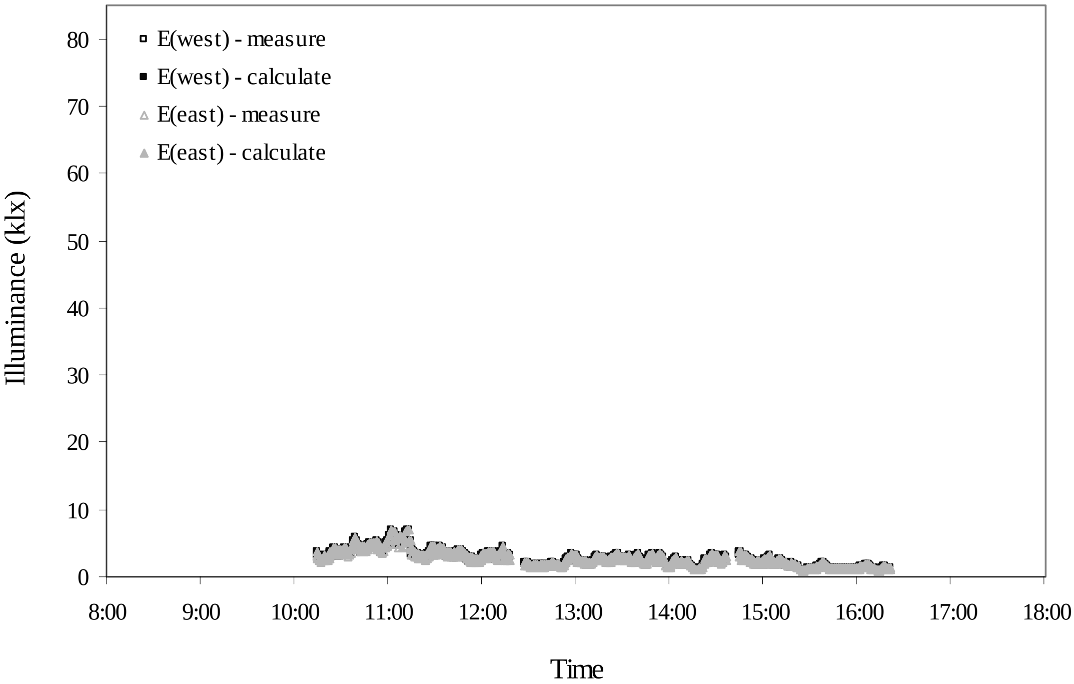
Measurement and calculation results on 17 August 2004



Measurement and calculation results on 15 September 2004



Measurement and calculation results on 21 January 2005



Measurement and calculation results on 25 February 2005

Appendix F6: Annual cumulative sky

Annual cumulative luminance of every sky patch ($\sum_{\text{annual}} H_{sky(\phi,\gamma)}$) for the annual cumulative sky:

(unit = 10^6 lm·hr/m^2·sr)

φ / γ	87.5	82.5	77.5	72.5	67.5	62.5	57.5	52.5	47.5	42.5	37.5	32.5	27.5	22.5	17.5	12.5	7.5	2.5
-177.5	4.37	4.78	5.20	5.62	6.03	6.44	6.83	7.22	7.60	7.96	8.30	8.63	8.93	9.21	9.47	9.69	9.89	10.04
-172.5	4.36	4.77	5.19	5.61	6.02	6.42	6.82	7.21	7.58	7.94	8.29	8.61	8.92	9.20	9.46	9.68	9.88	10.04
-167.5	4.36	4.77	5.18	5.60	6.01	6.41	6.81	7.20	7.57	7.93	8.28	8.60	8.91	9.19	9.45	9.68	9.88	10.04
-162.5	4.35	4.77	5.18	5.59	6.00	6.41	6.80	7.19	7.56	7.92	8.27	8.59	8.90	9.18	9.44	9.68	9.88	10.04
-157.5	4.35	4.76	5.18	5.59	6.00	6.40	6.80	7.19	7.56	7.92	8.27	8.59	8.90	9.18	9.44	9.67	9.88	10.04
-152.5	4.35	4.77	5.18	5.59	6.00	6.40	6.80	7.19	7.56	7.92	8.27	8.59	8.90	9.18	9.44	9.67	9.88	10.04
-147.5	4.36	4.77	5.18	5.59	6.00	6.41	6.80	7.19	7.56	7.93	8.27	8.60	8.90	9.19	9.45	9.68	9.88	10.04
-142.5	4.36	4.77	5.19	5.60	6.01	6.41	6.81	7.20	7.57	7.93	8.28	8.60	8.91	9.19	9.45	9.68	9.88	10.04
-137.5	4.37	4.78	5.19	5.61	6.02	6.42	6.82	7.21	7.58	7.94	8.29	8.61	8.92	9.20	9.46	9.69	9.88	10.04
-132.5	4.37	4.79	5.20	5.62	6.03	6.43	6.83	7.22	7.60	7.96	8.30	8.63	8.93	9.22	9.47	9.70	9.89	10.04
-127.5	4.38	4.79	5.21	5.63	6.04	6.45	6.85	7.23	7.61	7.97	8.32	8.65	8.95	9.23	9.48	9.71	9.90	10.04
-122.5	4.39	4.80	5.22	5.64	6.05	6.46	6.86	7.25	7.63	7.99	8.34	8.67	8.97	9.25	9.50	9.72	9.90	10.05
-117.5	4.40	4.82	5.23	5.65	6.07	6.48	6.88	7.27	7.65	8.02	8.37	8.69	9.00	9.27	9.52	9.73	9.91	10.05
-112.5	4.41	4.83	5.25	5.67	6.09	6.50	6.90	7.30	7.68	8.04	8.39	8.72	9.02	9.30	9.54	9.75	9.92	10.05
-107.5	4.42	4.84	5.26	5.68	6.10	6.52	6.92	7.32	7.71	8.07	8.42	8.75	9.05	9.32	9.56	9.76	9.93	10.06
-102.5	4.43	4.85	5.28	5.70	6.12	6.54	6.95	7.35	7.74	8.10	8.46	8.78	9.08	9.35	9.59	9.78	9.94	10.06
-97.5	4.44	4.87	5.29	5.72	6.14	6.56	6.97	7.38	7.77	8.14	8.49	8.82	9.11	9.38	9.61	9.80	9.96	10.06
-92.5	4.45	4.88	5.31	5.74	6.17	6.59	7.00	7.41	7.80	8.17	8.52	8.85	9.14	9.41	9.64	9.82	9.97	10.07
-87.5	4.46	4.89	5.33	5.76	6.19	6.61	7.03	7.44	7.83	8.20	8.56	8.88	9.18	9.44	9.66	9.84	9.98	10.07
-82.5	4.48	4.91	5.34	5.78	6.21	6.64	7.06	7.47	7.86	8.24	8.59	8.92	9.21	9.47	9.68	9.86	9.99	10.08
-77.5	4.49	4.92	5.36	5.80	6.24	6.67	7.09	7.50	7.90	8.27	8.63	8.95	9.24	9.50	9.71	9.88	10.01	10.08
-72.5	4.50	4.94	5.38	5.82	6.26	6.70	7.12	7.53	7.93	8.31	8.66	8.99	9.27	9.53	9.73	9.90	10.02	10.08
-67.5	4.52	4.96	5.40	5.85	6.29	6.73	7.15	7.57	7.97	8.35	8.70	9.02	9.31	9.56	9.76	9.92	10.03	10.09
-62.5	4.53	4.98	5.42	5.87	6.32	6.76	7.19	7.61	8.01	8.39	8.74	9.06	9.34	9.59	9.78	9.94	10.04	10.09
-57.5	4.55	4.99	5.44	5.90	6.35	6.79	7.23	7.65	8.05	8.43	8.78	9.10	9.38	9.62	9.81	9.96	10.06	10.10
-52.5	4.56	5.01	5.47	5.92	6.38	6.82	7.26	7.69	8.10	8.48	8.83	9.14	9.42	9.65	9.83	9.98	10.07	10.10
-47.5	4.58	5.03	5.49	5.95	6.41	6.86	7.30	7.73	8.14	8.52	8.87	9.18	9.46	9.68	9.86	10.00	10.08	10.11
-42.5	4.59	5.05	5.51	5.98	6.44	6.89	7.34	7.77	8.19	8.57	8.92	9.23	9.49	9.71	9.89	10.02	10.09	10.11
-37.5	4.61	5.07	5.54	6.00	6.47	6.93	7.38	7.82	8.23	8.61	8.96	9.27	9.53	9.74	9.91	10.04	10.11	10.12
-32.5	4.63	5.09	5.56	6.03	6.50	6.96	7.42	7.86	8.27	8.66	9.01	9.31	9.57	9.78	9.94	10.06	10.12	10.12
-27.5	4.65	5.12	5.59	6.06	6.53	6.99	7.45	7.90	8.32	8.71	9.05	9.35	9.60	9.81	9.97	10.07	10.13	10.12
-22.5	4.67	5.14	5.61	6.09	6.56	7.03	7.49	7.94	8.36	8.75	9.09	9.39	9.64	9.84	9.99	10.09	10.14	10.13
-17.5	4.69	5.16	5.64	6.11	6.59	7.06	7.53	7.97	8.40	8.79	9.14	9.43	9.68	9.87	10.01	10.11	10.15	10.13
-12.5	4.71	5.18	5.66	6.14	6.62	7.10	7.56	8.01	8.44	8.84	9.18	9.47	9.71	9.90	10.04	10.12	10.16	10.13
-7.5	4.73	5.21	5.69	6.17	6.66	7.13	7.60	8.05	8.48	8.88	9.22	9.51	9.74	9.92	10.06	10.14	10.16	10.14
-2.5	4.76	5.24	5.72	6.21	6.69	7.17	7.64	8.09	8.52	8.92	9.26	9.54	9.77	9.95	10.07	10.15	10.17	10.14
2.5	4.78	5.26	5.75	6.24	6.72	7.20	7.67	8.13	8.56	8.95	9.29	9.57	9.80	9.97	10.09	10.16	10.18	10.14
7.5	4.80	5.29	5.78	6.27	6.76	7.24	7.71	8.17	8.60	8.99	9.33	9.60	9.82	9.99	10.11	10.17	10.19	10.14
12.5	4.83	5.32	5.81	6.30	6.79	7.28	7.75	8.21	8.64	9.03	9.36	9.63	9.85	10.01	10.12	10.18	10.19	10.14
17.5	4.86	5.35	5.84	6.34	6.83	7.32	7.79	8.25	8.68	9.06	9.39	9.65	9.87	10.03	10.13	10.19	10.20	10.15
22.5	4.88	5.38	5.87	6.37	6.87	7.36	7.83	8.29	8.71	9.09	9.41	9.67	9.88	10.04	10.14	10.20	10.20	10.15
27.5	4.91	5.41	5.91	6.41	6.91	7.40	7.87	8.33	8.75	9.11	9.43	9.69	9.89	10.05	10.15	10.20	10.20	10.15
32.5	4.93	5.43	5.94	6.44	6.94	7.43	7.91	8.36	8.77	9.13	9.44	9.70	9.90	10.06	10.16	10.21	10.20	10.15
37.5	4.96	5.46	5.97	6.47	6.98	7.47	7.94	8.39	8.79	9.15	9.45	9.71	9.91	10.06	10.16	10.21	10.21	10.15
42.5	4.98	5.49	5.99	6.50	7.01	7.50	7.97	8.41	8.80	9.16	9.46	9.71	9.91	10.06	10.16	10.21	10.20	10.15
47.5	5.00	5.51	6.02	6.53	7.03	7.52	7.99	8.42	8.81	9.16	9.46	9.71	9.90	10.05	10.15	10.21	10.20	10.15
52.5	5.02	5.53	6.04	6.55	7.05	7.54	8.00	8.42	8.81	9.15	9.45	9.70	9.90	10.05	10.15	10.20	10.20	10.14
57.5	5.03	5.54	6.05	6.56	7.06	7.54	7.99	8.41	8.80	9.14	9.43	9.69	9.89	10.04	10.14	10.19	10.20	10.14
62.5	5.03	5.55	6.06	6.56	7.06	7.53	7.98	8.40	8.78	9.12	9.42	9.67	9.87	10.03	10.13	10.18	10.19	10.14
67.5	5.03	5.54	6.05	6.55	7.05	7.52	7.96	8.38	8.76	9.10	9.40	9.65	9.86	10.01	10.11	10.17	10.18	10.14
72.5	5.03	5.53	6.04	6.54	7.03	7.49	7.94	8.35	8.73	9.08	9.37	9.62	9.83	9.99	10.10	10.16	10.18	10.13
77.5	5.01	5.51	6.02	6.52	7.00	7.47	7.91	8.32	8.70	9.04	9.34	9.60	9.81	9.97	10.08	10.14	10.17	10.13
82.5	4.99	5.49	5.99	6.49	6.97	7.43	7.87	8.29	8.66	9.01	9.31	9.57	9.78	9.95	10.06	10.13	10.16	10.13
87.5	4.97	5.47	5.96	6.45	6.93	7.39	7.83	8.25	8.62	8.97	9.27	9.53	9.74	9.91	10.03	10.11	10.14	10.12
92.5	4.94	5.44	5.93	6.41	6.89	7.35	7.79	8.20	8.58	8.92	9.23	9.48	9.70	9.88	10.00	10.08	10.13	10.12
97.5	4.91	5.40	5.89	6.37	6.85	7.30	7.73	8.15	8.52	8.86	9.17	9.43	9.65	9.84	9.97	10.06	10.12	10.11
102.5	4.87	5.36	5.84	6.32	6.79	7.24	7.67	8.08	8.45	8.79	9.10	9.37	9.60	9.79	9.93	10.04	10.10	10.11
107.5	4.83	5.31	5.79	6.26	6.72	7.17	7.60	8.00	8.37	8.72	9.03	9.31	9.54	9.74	9.90	10.01	10.08	10.10
112.5	4.79	5.26	5.73	6.20	6.65	7.09	7.51	7.92	8.29	8.64	8.96	9.24	9.48	9.69	9.86	9.98	10.07	10.10
117.5	4.74	5.21	5.67	6.13	6.58	7.01	7.43	7.83	8.21	8.56	8.88	9.17	9.43	9.64	9.82	9.96	10.05	10.09
122.5	4.70	5.15	5.61	6.06	6.51	6.94	7.36	7.76	8.14	8.49	8.81	9.11	9.37	9.59	9.78	9.93	10.03	10.09
127.5	4.65	5.10	5.55	6.00	6.44	6.87	7.29	7.68	8.06	8.42	8.75	9.05	9.31	9.55	9.74	9.90	10.02	10.08
132.5	4.61	5.05	5.50	5.94	6.38	6.80	7.22	7.62	8.00	8.35	8.68	8.99	9.26	9.50	9.71	9.88	10.00	10.08
137.5	4.57	5.01	5.45	5.89	6.32	6.74	7.16	7.55	7.93	8.29	8.63	8.93	9.21	9.46	9.67	9.85	9.99	10.07
142.5	4.53	4.97	5.41	5.84	6.27	6.69	7.10	7.50	7.88	8.23	8.57	8.88	9.17	9.42	9.64	9.83	9.97	10.07
147.5	4.50	4.93	5.37	5.80	6.22	6.64	7.05	7.44	7.82	8.18	8.52	8.84	9.13	9.38	9.61	9.80	9.96	10.06
152.5	4.47	4.90	5.33	5.76	6.18	6.60	7.00	7.40	7.78	8.14	8.48	8.79	9.09	9.35	9.58	9.78	9.94	10.06
157.5	4.45	4.87	5.30	5.73	6.15	6.56	6.96	7.36	7.74	8.10	8.44	8.76	9.05	9.32	9.56	9.76	9.93	10.06
162.5	4.43	4.85	5.27	5.70	6.11	6.53	6.93	7.32	7.70	8.06	8.40	8.72	9.02	9.29	9.53	9.75	9.92	10.05
167.5	4.41	4.83	5.25	5.67	6.09	6.50	6.90	7.29	7.67	8.03	8.37	8.69	8.99	9.27	9.51	9.73	9.91	10.05
172.5	4.39	4.81	5.23	5.65	6.06	6.47	6.87	7.26	7.64	8.00	8.34	8.67	8.97	9.24	9.49	9.72	9.90	10.05
177.5	4.38	4.79	5.21	5.63	6.04	6.45	6.85	7.24	7.62	7.98	8.32	8.64	8.95	9.23	9.48	9.70	9.89	10.04

Appendix F7: Annual cumulative sun

Annual cumulative solar normal illumination energy density of every sky patch ($\sum_{\text{annual}} G_p$) for the annual cumulative sun:

(unit = 10^5 lm·hr/m^2)

ϕ / γ	87.5	82.5	77.5	72.5	67.5	62.5	57.5	52.5	47.5	42.5	37.5	32.5	27.5	22.5	17.5	12.5	7.5	2.5
-177.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-172.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-167.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-162.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-157.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-152.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-147.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-142.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-137.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-132.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-127.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-122.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-117.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.28
-112.5	0.00	0.01	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15
-107.5	0	0	0.01	0.08	0.08	0.10	0	0	0	0	0	0	0	0	0	0	0	0.14
-102.5	0	0	0.01	0.03	0.08	0.13	0.27	0.42	0.32	0.32	0.04	0	0	0	0	0	0.35	0.18
-97.5	0	0	0.01	0.04	0.04	0.07	0.14	0.13	0.27	0.49	0.79	1.06	0.96	0.94	0.90	0.53	0.94	0.16
-92.5	0	0.00	0.01	0.02	0.02	0.07	0.09	0.15	0.23	0.17	0.25	0.30	0.40	0.68	0.64	0.59	0.64	0.18
-87.5	0	0.00	0.02	0.02	0.04	0.07	0.04	0.10	0.20	0.23	0.34	0.17	0.25	0.40	0.30	0.34	0.22	0.07
-82.5	0.00	0.00	0.01	0.02	0.05	0.07	0.08	0.17	0.08	0.13	0.37	0.28	0.36	0.16	0.19	0.33	0.14	0.15
-77.5	0	0.00	0.01	0.02	0.04	0.06	0.09	0.17	0.13	0.21	0.17	0.18	0.45	0.27	0.26	0.18	0.08	0.10
-72.5	0	0.00	0.02	0.04	0.04	0.06	0.12	0.11	0.18	0.22	0.14	0.13	0.29	0.30	0.29	0.18	0.07	0.09
-67.5	0	0.00	0.01	0.03	0.08	0.11	0.09	0.13	0.19	0.27	0.18	0.27	0.09	0.19	0.40	0.16	0.15	0.01
-62.5	0	0	0.01	0.03	0.05	0.11	0.23	0.15	0.21	0.16	0.33	0.24	0.15	0.09	0.34	0.18	0.09	0.08
-57.5	0	0	0.02	0.09	0.13	0.12	0.15	0.23	0.30	0.29	0.19	0.29	0.21	0.18	0.18	0.22	0.14	0.11
-52.5	0	0	0	0.05	0.16	0.27	0.21	0.29	0.36	0.29	0.26	0.22	0.41	0.13	0.09	0.20	0.14	0.03
-47.5	0	0	0	0	0.06	0.25	0.40	0.27	0.30	0.32	0.35	0.22	0.26	0.14	0.06	0.24	0.18	0.09
-42.5	0	0	0	0	0	0.14	0.50	0.45	0.36	0.54	0.37	0.24	0.29	0.28	0.21	0.15	0.12	0.00
-37.5	0	0	0	0	0	0	0.30	0.91	0.47	0.59	0.41	0.37	0.19	0.35	0.08	0.19	0.16	0.04
-32.5	0	0	0	0	0	0	0	0.63	0.61	0.44	0.47	0.43	0.30	0.21	0.21	0.10	0.13	0.01
-27.5	0	0	0	0	0	0	0	0.36	0.82	0.52	0.81	0.32	0.41	0.28	0.20	0.13	0.18	0.01
-22.5	0	0	0	0	0	0	0	0	1.04	0.60	0.76	0.44	0.16	0.35	0.15	0.07	0.14	0.00
-17.5	0	0	0	0	0	0	0	0	0.99	0.93	0.51	0.82	0.42	0.20	0.29	0.07	0.12	0.08
-12.5	0	0	0	0	0	0	0	0	0.90	0.92	0.36	0.64	0.54	0.21	0.15	0.05	0.18	0.09
-7.5	0	0	0	0	0	0	0	0	0.76	1.09	0.87	0.24	0.19	0.24	0.29	0.27	0.10	0
-2.5	0	0	0	0	0	0	0	0	0.55	1.23	0.98	0.92	0.44	0.18	0.33	0	0	0
2.5	0	0	0	0	0	0	0	0	0.59	1.30	1.03	0.94	0.35	0.29	0.14	0	0.54	0.24
7.5	0	0	0	0	0	0	0	0	0.73	1.31	1.00	0.19	0.33	0.31	0.48	0.30	0	0.09
12.5	0	0	0	0	0	0	0	0	0.92	1.29	0.47	0.79	0.57	0.22	0.08	0.06	0.03	0.05
17.5	0	0	0	0	0	0	0	0	1.45	1.24	0.55	0.99	0.46	0.30	0.16	0	0.08	0.05
22.5	0	0	0	0	0	0	0	0	1.79	0.88	1.10	0.67	0.36	0.24	0.44	0.16	0.17	0.04
27.5	0	0	0	0	0	0	0	0.78	1.41	0.84	1.24	0.31	0.40	0.31	0.01	0.09	0.29	0
32.5	0	0	0	0	0	0	0	1.64	1.33	0.85	0.87	0.63	0.36	0.37	0.45	0.07	0.28	0.06
37.5	0	0	0	0	0	0	1.25	1.77	1.11	1.16	0.62	0.72	0.23	0.43	0.02	0.09	0.09	0.09
42.5	0	0	0	0	0	0.76	1.63	1.02	1.05	1.06	0.69	0.42	0.31	0.21	0.29	0.30	0.11	0.00
47.5	0	0	0	0	0.53	1.67	1.43	1.10	1.10	0.77	0.81	0.37	0.33	0.34	0.08	0.21	0.13	0.09
52.5	0	0	0	0.87	1.77	1.29	1.09	1.13	0.93	0.76	0.61	0.31	0.53	0.23	0.13	0.18	0.29	0.08
57.5	0	0	1.45	1.84	1.16	0.91	1.02	1.02	0.80	0.80	0.30	0.43	0.23	0.31	0.16	0.29	0.05	0.04
62.5	0	1.01	1.51	0.83	0.83	1.10	1.06	0.90	0.73	0.40	0.55	0.40	0.35	0.08	0.36	0.38	0.16	0.14
67.5	0	0.46	0.45	1.06	1.15	0.88	0.81	0.83	0.42	0.33	0.38	0.54	0.08	0.40	0.39	0.26	0.09	0.10
72.5	0	0.13	0.48	0.88	0.75	0.91	0.63	0.40	0.46	0.66	0.49	0.21	0.38	0.38	0.56	0.21	0.19	0.04
77.5	0	0.12	0.49	0.89	0.61	0.42	0.47	0.64	0.60	0.58	0.24	0.51	0.48	0.63	0.27	0.36	0.17	0.10
82.5	0.01	0.93	0.56	0.44	0.63	0.57	0.63	0.69	0.26	0.36	0.76	0.68	0.87	0.46	0.28	0.35	0.17	0.11
87.5	0.41	0.58	0.77	0.58	0.65	0.64	0.39	0.43	0.84	0.98	0.90	0.74	0.44	0.68	0.36	0.52	0.27	0.06
92.5	0.03	0.53	0.53	0.49	0.42	0.53	0.87	1.06	0.89	0.77	0.88	0.86	0.61	1.07	0.84	0.92	0.44	0.22
97.5	0	0.30	0.51	0.67	0.94	1.01	1.00	0.94	1.41	1.55	2.80	1.77	1.89	1.32	1.11	1.01	0.89	0.20
102.5	0	0.10	0.99	0.92	1.23	1.49	3.03	1.80	2.21	0.75	0.32	0	0	0	0	0	0.15	0.51
107.5	0	0	1.73	1.93	2.18	0.78	0	0	0	0	0	0	0	0	0	0	0	0.05
112.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.08
117.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.11
122.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05
127.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.17
132.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.13
137.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.30
142.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
147.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
152.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
157.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
162.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
167.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
172.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
177.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Azimuth angle of averaged sun position ($\overline{\phi_{s,sky(\phi,\gamma)}}$) of every sky patch for the annual cumulative sun:

(unit = degree)

φ / γ	87.5	82.5	77.5	72.5	67.5	62.5	57.5	52.5	47.5	42.5	37.5	32.5	27.5	22.5	17.5	12.5	7.5	2.5
-177.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-172.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-167.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-162.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-157.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-152.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-147.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-142.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-137.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-132.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-127.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-122.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-117.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-117.1
-112.5	-113.4	-111.9	-110.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-112.6
-107.5	0	0	-107.8	-107.6	-106.4	-105.6	0	0	0	0	0	0	0	0	0	0	0	-107.6
-102.5	0	0	-102.2	-102.8	-102.7	-103.0	-102.7	-102.3	-101.2	-100.6	-100.2	0	0	0	0	0	-101.8	-102.6
-97.5	0	0	-97.6	-97.6	-97.4	-97.8	-97.6	-97.4	-97.7	-98.0	-98.1	-97.6	-97.3	-96.6	-96.8	-96.9	-97.8	-97.6
-92.5	0	-90.8	-92.3	-92.9	-92.7	-92.5	-92.3	-92.8	-92.6	-92.4	-92.6	-93.0	-92.7	-92.7	-92.7	-92.5	-93.0	-92.1
-87.5	0	-88.0	-87.4	-87.3	-87.5	-87.7	-87.6	-87.3	-87.6	-87.7	-87.7	-87.6	-87.6	-87.7	-87.6	-87.6	-87.5	-87.7
-82.5	-83.6	-82.4	-82.4	-82.6	-82.4	-82.4	-82.5	-82.7	-82.6	-82.5	-82.5	-82.4	-82.5	-82.9	-82.7	-82.6	-82.4	-82.3
-77.5	0	-77.4	-78.0	-77.4	-77.7	-77.4	-77.3	-77.6	-77.3	-77.4	-77.8	-77.6	-77.5	-77.5	-77.5	-77.5	-77.2	-77.6
-72.5	0	-72.6	-72.0	-72.7	-72.5	-72.3	-72.7	-72.4	-72.4	-72.7	-72.5	-72.3	-72.4	-72.4	-72.6	-72.7	-72.3	-73.1
-67.5	0	-69.7	-67.8	-67.2	-67.3	-67.7	-67.4	-67.2	-67.6	-67.6	-67.5	-67.6	-67.7	-67.4	-67.4	-67.7	-67.5	-68.1
-62.5	0	0	-62.1	-62.5	-62.3	-62.2	-62.3	-62.7	-62.3	-62.7	-62.4	-62.7	-62.5	-62.4	-62.4	-62.4	-62.7	-61.9
-57.5	0	0	-58.3	-57.2	-57.5	-57.4	-57.4	-57.4	-57.2	-57.7	-57.5	-57.2	-57.1	-57.6	-57.5	-57.5	-58.0	-56.6
-52.5	0	0	0	-54.1	-52.3	-52.2	-52.6	-52.6	-52.3	-52.5	-52.6	-52.4	-52.6	-52.4	-52.5	-52.7	-52.8	-51.6
-47.5	0	0	0	0	-49.6	-47.5	-47.1	-47.5	-47.4	-47.7	-47.8	-47.3	-47.1	-48.0	-47.6	-47.6	-47.5	-47.0
-42.5	0	0	0	0	0	-44.3	-42.5	-42.4	-42.7	-42.5	-42.0	-42.5	-42.6	-42.0	-43.2	-42.3	-42.5	-42.7
-37.5	0	0	0	0	0	0	-38.3	-36.9	-37.6	-37.0	-37.2	-37.9	-36.9	-38.0	-37.1	-38.0	-37.1	-36.6
-32.5	0	0	0	0	0	0	0	-32.3	-32.4	-32.1	-33.3	-32.1	-33.1	-31.7	-33.0	-31.9	-32.6	-33.0
-27.5	0	0	0	0	0	0	0	-27.8	-27.4	-27.8	-27.7	-27.1	-26.8	-28.6	-27.9	-27.3	-27.5	-28.5
-22.5	0	0	0	0	0	0	0	0	-22.7	-23.6	-21.4	-23.7	-22.4	-21.6	-21.8	-24.1	-22.2	-22.7
-17.5	0	0	0	0	0	0	0	0	-17.8	-18.3	-16.2	-17.4	-17.7	-19.1	-17.5	-16.1	-18.3	-17.3
-12.5	0	0	0	0	0	0	0	0	-12.9	-12.8	-14.4	-10.6	-11.7	-10.8	-14.2	-12.4	-11.0	-13.5
-7.5	0	0	0	0	0	0	0	0	-7.7	-7.7	-8.8	-9.8	-6.2	-9.0	-8.6	-8.8	-9.3	0
-2.5	0	0	0	0	0	0	0	0	-2.4	-2.7	-2.9	-3.4	-2.7	-0.8	-3.2	0	0	0
2.5	0	0	0	0	0	0	0	0	2.6	2.5	3.1	3.5	2.6	0.5	2.9	0	3.7	2.9
7.5	0	0	0	0	0	0	0	0	7.7	7.7	9.0	9.8	6.4	9.1	8.2	6.7	0	6.9
12.5	0	0	0	0	0	0	0	0	12.6	13.1	14.6	10.5	11.7	11.0	13.5	11.0	13.6	12.9
17.5	0	0	0	0	0	0	0	0	17.7	18.6	15.8	17.4	17.6	18.8	17.9	0	17.4	18.6
22.5	0	0	0	0	0	0	0	0	22.8	23.7	21.5	24.0	22.3	22.1	20.9	22.8	22.2	24.5
27.5	0	0	0	0	0	0	0	27.7	27.7	27.8	27.7	27.4	26.4	28.5	27.6	26.8	27.4	0
32.5	0	0	0	0	0	0	0	32.5	32.5	32.0	33.3	31.9	33.1	31.7	32.5	32.3	32.4	32.2
37.5	0	0	0	0	0	0	38.3	37.0	37.7	37.0	37.3	37.8	36.7	37.8	37.0	38.0	37.8	37.2
42.5	0	0	0	0	0	44.4	42.3	42.3	42.8	42.7	42.1	42.8	42.5	41.9	42.8	42.3	42.3	42.3
47.5	0	0	0	0	49.5	47.4	47.1	47.5	47.5	47.8	47.8	47.3	47.6	47.6	47.4	47.3	47.1	47.0
52.5	0	0	0	54.2	52.1	52.3	52.5	52.5	52.4	52.5	52.7	52.6	52.3	52.5	52.4	53.2	52.2	52.2
57.5	0	0	58.4	57.2	57.5	57.3	57.4	57.3	57.3	57.4	57.6	57.3	57.5	57.4	57.6	57.7	57.3	57.4
62.5	0	61.6	62.2	62.4	62.3	62.1	62.4	62.7	62.6	62.6	62.3	62.7	62.5	62.3	62.0	63.0	62.3	61.8
67.5	0	67.5	67.5	67.1	67.4	67.7	67.4	67.3	67.7	67.4	67.4	67.2	67.8	67.5	67.5	67.5	67.2	67.2
72.5	0	70.7	72.4	72.7	72.6	72.4	72.7	72.5	72.5	72.4	72.4	72.4	72.5	72.5	72.5	72.0	72.7	72.3
77.5	0	78.8	77.4	77.4	77.8	77.4	77.3	77.6	77.4	77.3	77.5	77.8	77.4	77.5	77.3	77.4	77.7	78.1
82.5	84.1	82.7	82.9	82.5	82.1	82.6	82.4	82.3	82.9	82.5	82.5	82.6	82.5	82.5	82.5	82.6	82.6	82.6
87.5	87.7	87.5	87.4	87.5	87.5	87.5	87.7	87.6	87.6	87.2	87.8	87.6	87.5	87.5	87.9	87.5	87.6	87.6
92.5	90.3	92.3	92.5	92.5	92.8	92.4	92.6	92.3	92.6	92.8	92.6	92.6	92.8	92.7	92.8	92.7	92.7	93.1
97.5	0	97.1	97.8	97.4	97.8	97.3	97.7	97.9	97.7	97.6	98.3	97.5	97.3	96.7	96.7	97.0	98.1	97.7
102.5	0	100.8	102.8	102.4	102.7	103.0	103.1	101.9	101.4	100.6	100.1	0	0	0	0	0	101.6	103.6
107.5	0	0	108.2	107.3	106.6	105.5	0	0	0	0	0	0	0	0	0	0	0	108.0
112.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	111.6
117.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	118.3
122.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	122.4
127.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	127.0
132.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	132.4
137.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	137.4
142.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
147.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
152.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
157.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
162.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
167.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
172.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
177.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Altitude angle of averaged sun position ($\overline{\gamma_{s,sky(\phi,\gamma)}}$) of every sky patch for the annual cumulative sun:

(unit = degree)

ϕ / γ	87.5	82.5	77.5	72.5	67.5	62.5	57.5	52.5	47.5	42.5	37.5	32.5	27.5	22.5	17.5	12.5	7.5	2.5
-177.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-172.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-167.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-162.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-157.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-152.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-147.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-142.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-137.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-132.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-127.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-122.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-117.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	87.6
-112.5	3.6	7.5	11.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	87.6
-107.5	0	0	13.9	17.6	22.2	27.0	0	0	0	0	0	0	0	0	0	0	0	87.6
-102.5	0	0	13.5	17.5	22.7	27.9	32.4	37.4	42.2	47.4	50.1	0	0	0	0	0	84.2	87.4
-97.5	0	0	12.7	17.6	22.6	27.3	32.5	37.5	42.4	47.4	52.4	57.4	62.4	67.4	72.3	77.3	81.9	87.8
-92.5	0	9.2	12.5	17.7	22.6	27.6	32.6	37.4	42.6	47.5	52.3	57.3	62.5	67.7	72.9	77.5	81.8	86.5
-87.5	0	7.3	12.5	17.7	22.4	27.5	32.8	37.4	42.3	47.5	52.9	57.5	62.1	67.4	72.9	78.0	82.5	86.3
-82.5	4.4	8.8	12.5	17.2	22.4	27.7	32.3	37.7	43.0	47.2	52.0	57.5	62.7	67.4	72.6	77.8	82.5	86.3
-77.5	0	8.5	12.8	17.6	22.7	27.3	32.1	37.2	42.2	47.5	52.9	57.7	62.5	67.4	72.2	77.5	82.2	85.9
-72.5	0	7.4	12.7	17.7	22.6	27.7	32.8	37.8	42.4	47.4	52.4	56.8	62.0	67.5	72.3	77.1	82.1	86.4
-67.5	0	9.6	12.6	17.2	22.3	27.5	32.5	37.3	42.6	47.9	52.3	57.8	63.5	67.9	72.9	77.8	82.6	86.6
-62.5	0	0	12.2	17.7	22.2	27.0	32.2	37.5	42.4	46.9	52.0	57.2	62.1	66.7	72.1	77.2	82.1	87.0
-57.5	0	0	13.0	17.3	22.5	27.7	32.3	37.0	42.1	47.7	53.2	58.0	62.5	67.4	72.2	76.9	81.9	86.8
-52.5	0	0	0	18.8	22.4	27.1	32.7	37.9	42.9	47.6	52.1	56.7	62.4	68.3	73.4	78.2	82.5	86.6
-47.5	0	0	0	0	24.4	27.3	32.2	37.6	42.5	47.2	52.4	58.3	63.2	66.7	72.0	77.3	82.2	86.4
-42.5	0	0	0	0	0	29.4	32.0	37.0	41.7	46.8	52.3	56.8	61.6	67.6	71.1	76.9	82.8	86.7
-37.5	0	0	0	0	0	0	34.0	37.2	42.4	48.0	53.2	57.7	63.7	67.6	74.0	77.8	83.1	88.0
-32.5	0	0	0	0	0	0	0	38.0	42.6	47.7	51.7	57.2	61.6	68.0	72.0	78.3	82.0	87.9
-27.5	0	0	0	0	0	0	0	39.2	42.0	47.2	52.3	58.2	62.8	66.5	70.9	77.7	82.9	87.6
-22.5	0	0	0	0	0	0	0	0	42.1	46.7	52.7	57.0	61.7	68.7	73.0	75.8	81.7	87.2
-17.5	0	0	0	0	0	0	0	0	43.1	47.3	53.1	57.3	62.9	66.3	72.6	79.8	80.6	86.4
-12.5	0	0	0	0	0	0	0	0	43.8	47.2	51.3	58.2	62.1	67.9	70.7	78.2	84.1	85.4
-7.5	0	0	0	0	0	0	0	0	44.3	47.3	52.4	55.8	62.9	66.7	72.9	77.1	81.6	0
-2.5	0	0	0	0	0	0	0	0	44.5	47.1	52.4	57.5	62.2	67.5	71.6	0	0	0
2.5	0	0	0	0	0	0	0	0	44.5	47.1	52.4	57.5	62.2	67.5	72.6	0	82.7	86.6
7.5	0	0	0	0	0	0	0	0	44.3	47.2	52.4	55.6	63.1	67.1	72.6	77.3	0	88.4
12.5	0	0	0	0	0	0	0	0	43.8	47.2	51.1	58.1	62.1	69.0	71.0	79.2	80.5	88.9
17.5	0	0	0	0	0	0	0	0	43.1	47.3	53.3	57.4	62.9	67.0	72.5	0	82.0	89.1
22.5	0	0	0	0	0	0	0	0	42.1	46.8	52.6	57.0	61.8	68.7	73.0	76.8	83.4	89.3
27.5	0	0	0	0	0	0	0	39.2	42.1	47.2	52.3	58.0	62.6	66.7	71.5	78.2	82.3	0
32.5	0	0	0	0	0	0	0	37.9	42.5	47.8	51.7	57.3	61.9	68.1	72.6	79.0	82.6	86.3
37.5	0	0	0	0	0	0	34.0	37.1	42.2	47.8	52.9	57.6	63.5	67.4	73.5	76.3	82.0	85.9
42.5	0	0	0	0	0	29.4	32.2	37.2	42.0	46.9	52.5	56.7	61.9	67.2	71.0	77.2	82.5	86.3
47.5	0	0	0	0	24.3	27.4	32.1	37.5	42.5	47.3	52.4	58.2	62.9	67.0	72.8	78.2	83.0	87.0
52.5	0	0	0	18.8	22.6	27.2	32.7	38.0	42.9	47.6	51.9	56.6	62.5	68.6	73.5	76.9	81.3	86.2
57.5	0	0	13.0	17.4	22.5	27.6	32.2	37.0	42.2	47.7	53.1	57.9	61.8	66.5	72.1	77.4	81.9	86.4
62.5	0	8.1	12.3	17.6	22.1	26.9	32.2	37.5	42.5	46.8	51.9	57.5	62.8	67.4	72.3	77.4	82.5	87.2
67.5	0	8.3	12.2	17.0	22.3	27.6	32.7	37.4	42.6	47.9	52.4	57.2	62.5	67.9	72.6	77.6	82.8	86.8
72.5	0	9.7	12.4	17.8	22.6	27.5	32.7	38.0	42.6	47.6	52.9	57.2	62.5	67.4	72.4	77.9	82.7	86.6
77.5	0	7.8	13.1	17.6	22.7	27.6	32.1	37.2	42.2	46.9	52.3	58.0	62.5	67.2	72.1	76.8	82.0	87.5
82.5	4.9	7.7	12.8	17.4	22.4	27.4	32.3	37.5	42.7	47.7	52.6	57.4	62.3	67.8	72.6	77.2	82.3	86.7
87.5	3.0	7.2	12.4	17.6	22.2	27.6	33.1	37.5	42.4	47.5	52.2	57.3	62.4	67.2	72.2	77.2	82.5	86.6
92.5	4.8	7.6	12.1	17.4	22.9	27.4	32.2	37.4	42.5	47.4	52.8	58.0	62.5	67.0	72.3	77.3	82.3	86.8
97.5	0	9.1	12.8	17.5	22.3	27.4	32.5	37.5	42.7	47.8	52.9	57.4	62.4	67.4	72.5	77.4	82.3	87.1
102.5	0	9.8	12.6	17.5	22.5	27.6	32.4	37.5	42.4	47.4	50.9	0	0	0	0	0	84.9	85.7
107.5	0	0	13.4	17.4	22.3	27.1	0	0	0	0	0	0	0	0	0	0	0	88.1
112.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	88.6
117.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	88.6
122.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	88.2
127.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	88.5
132.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	88.6
137.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	88.7
142.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
147.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
152.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
157.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
162.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
167.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
172.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
177.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix G1: Numerical values of VDF and OPA for correlation analysis

	Height of reference point above ground	OPA	VDF (%)					
			$\rho_b = 0.1$	$\rho_b = 0.2$	$\rho_b = 0.3$	$\rho_b = 0.4$	$\rho_b = 0.5$	$\rho_b = 0.6$
SQU 50	5	1.3	10.2	11.0	11.8	12.9	14.0	15.3
	10	1.3	10.2	11.0	12.0	13.2	14.5	16.1
	15	1.3	10.3	11.2	12.3	13.5	14.9	16.5
	20	1.3	10.3	11.3	12.4	13.7	15.2	17.0
	25	1.3	10.5	11.4	12.7	14.0	15.6	17.5
	30	1.3	10.5	11.6	12.8	14.3	15.9	17.9
	35	1.3	10.5	11.6	12.9	14.4	16.2	18.2
	40	1.3	10.7	11.7	13.1	14.7	16.5	18.6
	45	1.3	10.9	12.0	13.4	15.0	16.9	19.1
	50	1.3	11.2	12.4	13.8	15.5	17.4	19.7
	55	1.3	11.5	12.7	14.1	15.8	17.8	20.1
	60	1.3	11.8	13.0	14.5	16.2	18.3	20.7
	65	1.2	12.0	13.3	14.9	16.6	18.7	21.3
	70	1.2	12.4	13.8	15.4	17.2	19.4	22.0
	75	1.2	12.8	14.2	15.9	17.8	20.1	22.7
	80	1.2	13.4	14.8	16.5	18.5	20.8	23.5
	85	1.2	14.0	15.5	17.2	19.3	21.7	24.4
	90	1.2	14.9	16.4	18.2	20.3	22.7	25.6
	95	1.1	15.6	17.2	19.0	21.2	23.7	26.6
	100	1.1	16.8	18.4	20.3	22.4	25.1	28.0
	105	1.1	18.1	19.7	21.7	24.0	26.5	29.6
	110	1.0	19.4	21.1	23.1	25.4	28.1	31.2
	115	1.0	21.2	23.0	25.0	27.4	30.0	33.1
	120	0.9	23.1	24.9	27.0	29.4	32.1	35.2
	125	0.8	25.5	27.4	29.4	31.8	34.5	37.5
	130	0.7	28.2	30.0	32.1	34.5	37.1	40.1
	135	0.5	31.9	33.6	35.7	37.9	40.5	43.3

SQU 70

Height of reference point above ground	OPA	VDF (%) $\rho_b = 0.1$	$\rho_b = 0.2$	$\rho_b = 0.3$	$\rho_b = 0.4$	$\rho_b = 0.5$	$\rho_b = 0.6$
5	1.1	16.0	17.2	18.4	19.8	21.3	23.1
10	1.1	16.6	17.8	19.2	20.7	22.3	24.3
15	1.1	16.7	18.0	19.5	21.1	22.9	25.0
20	1.1	16.9	18.3	19.8	21.5	23.4	25.5
25	1.1	17.0	18.3	19.9	21.7	23.7	25.9
30	1.1	17.1	18.6	20.2	22.0	24.1	26.4
35	1.1	17.2	18.7	20.4	22.3	24.4	26.8
40	1.1	17.4	18.9	20.7	22.7	24.9	27.3
45	1.1	17.7	19.3	21.1	23.1	25.4	27.9
50	1.0	18.0	19.6	21.4	23.4	25.8	28.3
55	1.0	18.4	20.0	21.8	23.9	26.3	28.9
60	1.0	18.7	20.3	22.2	24.4	26.8	29.5
65	1.0	19.0	20.7	22.6	24.8	27.2	29.9
70	1.0	19.5	21.2	23.2	25.4	27.9	30.7
75	1.0	20.2	21.9	23.9	26.1	28.6	31.4
80	1.0	20.7	22.5	24.5	26.8	29.3	32.1
85	0.9	21.3	23.1	25.1	27.4	30.0	32.8
90	0.9	22.0	23.9	25.9	28.2	30.8	33.7
95	0.9	22.9	24.8	26.9	29.2	31.8	34.7
100	0.9	23.8	25.7	27.8	30.1	32.7	35.7
105	0.8	25.0	26.8	29.0	31.3	33.9	36.8
110	0.8	26.1	27.9	30.0	32.3	34.9	37.8
115	0.7	27.1	29.0	31.1	33.4	36.0	38.9
120	0.7	28.5	30.4	32.4	34.8	37.3	40.2
125	0.6	30.0	31.9	33.9	36.2	38.7	41.5
130	0.5	31.8	33.7	35.7	37.9	40.4	43.1
135	0.4	34.7	36.5	38.4	40.5	42.9	45.5

STA 50

Height of reference point above ground	OPA	VDF (%) $\rho_b = 0.1$	$\rho_b = 0.2$	$\rho_b = 0.3$	$\rho_b = 0.4$	$\rho_b = 0.5$	$\rho_b = 0.6$
5	1.3	9.6	10.3	11.3	12.3	13.5	14.7
10	1.3	9.9	10.7	11.7	12.8	14.1	15.6
15	1.3	10.0	10.9	12.0	13.2	14.5	16.2
20	1.3	10.1	11.1	12.2	13.5	14.9	16.7
25	1.3	10.3	11.3	12.4	13.8	15.3	17.2
30	1.3	10.4	11.4	12.7	14.0	15.7	17.7
35	1.3	10.5	11.6	12.8	14.3	16.0	18.0
40	1.3	10.6	11.8	13.0	14.6	16.3	18.4
45	1.3	10.9	12.1	13.4	14.9	16.8	19.0
50	1.3	11.2	12.5	13.8	15.4	17.3	19.6
55	1.3	11.4	12.7	14.0	15.7	17.8	20.0
60	1.3	11.9	13.2	14.6	16.4	18.4	20.7
65	1.3	12.2	13.5	15.0	16.8	18.9	21.3
70	1.3	12.6	14.0	15.5	17.3	19.5	22.0
75	1.2	13.2	14.5	16.2	18.0	20.2	22.8
80	1.2	13.7	15.1	16.8	18.7	20.9	23.6
85	1.2	14.4	15.9	17.6	19.6	21.9	24.6
90	1.2	15.1	16.6	18.3	20.4	22.8	25.6
95	1.2	16.2	17.7	19.4	21.6	24.0	26.9
100	1.1	17.1	18.8	20.7	22.8	25.3	28.3
105	1.1	18.4	20.0	21.9	24.1	26.7	29.7
110	1.0	19.7	21.4	23.4	25.7	28.3	31.3
115	1.0	21.6	23.2	25.2	27.5	30.2	33.2
120	0.9	23.4	25.2	27.3	29.6	32.3	35.3
125	0.8	25.8	27.7	29.7	32.0	34.7	37.7
130	0.7	28.5	30.2	32.3	34.6	37.3	40.3
135	0.5	32.1	33.9	35.8	38.1	40.6	43.5

	Height of reference point above ground	OPA	VDF (%) ρ_b = 0.1	ρ_b = 0.2	ρ_b = 0.3	ρ_b = 0.4	ρ_b = 0.5	ρ_b = 0.6
STA 70	5	1.0	18.2	19.2	20.3	21.5	22.9	24.5
	10	1.0	18.7	19.8	21.0	22.3	23.9	25.7
	15	1.0	18.9	20.1	21.3	22.8	24.4	26.3
	20	1.0	19.2	20.4	21.7	23.3	24.9	26.9
	25	1.0	19.3	20.6	22.0	23.5	25.3	27.3
	30	1.0	19.5	20.8	22.2	23.8	25.6	27.8
	35	1.0	19.6	21.0	22.5	24.2	26.0	28.2
	40	0.9	19.9	21.2	22.8	24.5	26.4	28.7
	45	0.9	20.2	21.6	23.2	24.9	26.9	29.2
	50	0.9	20.4	21.8	23.4	25.2	27.3	29.6
	55	0.9	20.7	22.2	23.8	25.7	27.8	30.2
	60	0.9	21.0	22.5	24.2	26.1	28.3	30.7
	65	0.9	21.4	22.8	24.5	26.5	28.7	31.2
	70	0.9	21.9	23.5	25.2	27.2	29.4	31.9
	75	0.9	22.5	24.0	25.8	27.8	30.0	32.6
	80	0.9	22.9	24.4	26.2	28.3	30.6	33.2
	85	0.8	23.6	25.2	27.0	29.0	31.4	34.0
	90	0.8	24.2	25.9	27.7	29.8	32.1	34.8
	95	0.8	24.9	26.6	28.5	30.6	32.9	35.6
	100	0.8	25.8	27.4	29.3	31.4	33.8	36.5
	105	0.7	26.5	28.2	30.2	32.3	34.7	37.4
	110	0.7	27.5	29.2	31.1	33.2	35.7	38.3
	115	0.7	28.6	30.3	32.2	34.3	36.7	39.4
	120	0.6	29.7	31.4	33.3	35.4	37.8	40.5
	125	0.6	31.0	32.7	34.6	36.7	39.1	41.7
	130	0.5	32.7	34.4	36.3	38.4	40.7	43.2
	135	0.4	35.3	36.9	38.7	40.7	42.9	45.4

	Height of reference point above ground	OPA	VDF (%) ρ_b = 0.1	ρ_b = 0.2	ρ_b = 0.3	ρ_b = 0.4	ρ_b = 0.5	ρ_b = 0.6
SQU 40	5	1.6	1.6	1.9	2.2	2.7	3.2	3.8
	10	1.5	1.7	2.0	2.4	2.9	3.5	4.1
	15	1.5	1.7	2.0	2.5	3.0	3.6	4.4
	20	1.5	1.7	2.0	2.5	3.1	3.8	4.6
	25	1.5	1.8	2.1	2.7	3.3	4.0	4.9
	30	1.5	1.9	2.3	2.8	3.5	4.3	5.2
	35	1.5	1.9	2.4	3.0	3.6	4.5	5.5
	40	1.5	2.1	2.6	3.2	4.0	4.8	5.9
	45	1.5	2.3	2.8	3.4	4.2	5.1	6.3
	50	1.5	2.5	3.0	3.7	4.5	5.5	6.7
	55	1.5	2.6	3.2	3.9	4.8	5.9	7.2
	60	1.5	3.0	3.6	4.4	5.3	6.4	7.8
	65	1.5	3.4	4.1	4.9	5.9	7.1	8.6
	70	1.5	3.7	4.4	5.3	6.3	7.7	9.2
	75	1.5	4.3	5.0	6.0	7.1	8.5	10.2
	80	1.5	4.9	5.8	6.8	8.0	9.5	11.3
	85	1.4	5.6	6.5	7.5	8.9	10.5	12.4
	90	1.4	6.4	7.4	8.6	10.0	11.7	13.7
	95	1.4	7.3	8.4	9.7	11.2	13.0	15.3
	100	1.4	8.7	9.8	11.2	12.8	14.8	17.1
	105	1.3	10.0	11.2	12.7	14.5	16.6	19.1
	110	1.3	11.8	13.1	14.7	16.6	18.9	21.5
	115	1.2	14.1	15.5	17.2	19.2	21.6	24.3
	120	1.1	16.5	18.0	19.8	22.0	24.5	27.3
	125	1.0	19.7	21.3	23.2	25.4	27.9	30.9
	130	0.9	23.4	25.1	27.0	29.2	31.8	34.8
	135	0.7	28.1	29.8	31.8	34.0	36.6	39.5

Appendix G2: Numerical values of VDF simulated by RADIANCE and calculated by UVA and OPA method

	a	b	VDF (%) RADIANCE	VDF (%) UVA method	VDF (%) OPA method
Point 1	1	9	16.5	12.0	12.8
H = 9	1	8	18.1	12.0	13.0
	1	7	20.3	12.0	19.6
	1	6	22.0	12.0	19.7
	1	5	23.5	12.0	20.7
	1	4	25.7	12.0	23.3
	1	3	28.1	12.0	27.0
	1	2	30.6	12.0	31.1
	1	1	33.2	12.0	31.1
	2	8	16.9	11.3	11.4
	2	7	18.8	11.3	18.1
	2	6	20.1	11.3	18.2
	2	5	21.7	11.3	19.2
	2	4	23.1	11.3	21.8
	2	3	25.3	11.3	25.4
	2	2	27.5	11.3	28.9
	2	1	29.9	11.3	28.9
	3	7	17.2	10.5	14.4
	3	6	18.5	10.5	14.4
	3	5	19.4	10.5	15.3
	3	4	20.3	10.5	15.3
	3	3	22.1	10.5	16.3
	3	2	24.4	10.5	20.2
	3	1	26.9	10.5	20.2
	4	6	15.2	9.5	10.0
	4	5	16.1	9.5	11.0
	4	4	17.2	9.5	11.0
	4	3	18.4	9.5	11.9
	4	2	20.7	9.5	15.9
	4	1	23.3	9.5	15.9
	5	5	13.9	8.5	10.2
	5	4	15.0	8.5	10.2
	5	3	16.3	8.5	11.1
	5	2	18.1	8.5	15.2
	5	1	20.6	8.5	15.2
	6	4	13.1	7.4	8.2
	6	3	14.3	7.4	9.2
	6	2	15.7	7.4	10.2
	6	1	18.3	7.4	10.2
	7	3	12.3	6.3	7.3
	7	2	13.7	6.3	8.3
	7	1	15.8	6.3	8.3
	8	2	11.7	5.1	6.3
	8	1	13.6	5.1	6.3
	9	1	11.9	3.9	4.3

			VDF (%)		
	a	b	RADIANCE	UVA method	OPA method
Point 2	1	9	25.6	12.8	24.9
H = 9	1	8	28.3	12.8	25.0
	1	7	30.0	12.8	29.6
	1	6	31.4	12.8	29.6
	1	5	32.8	12.8	31.7
	1	4	33.7	12.8	32.8
	1	3	35.8	12.8	36.1
	1	2	38.4	12.8	39.5
	1	1	41.1	12.8	39.5
	2	8	27.6	12.4	24.3
	2	7	29.4	12.4	28.9
	2	6	30.4	12.4	28.9
	2	5	31.9	12.4	31.0
	2	4	32.8	12.4	32.2
	2	3	34.4	12.4	35.4
	2	2	36.7	12.4	38.5
	2	1	38.7	12.4	38.5
	3	7	28.5	12.0	27.2
	3	6	29.7	12.0	27.2
	3	5	30.8	12.0	29.3
	3	4	31.3	12.0	29.3
	3	3	32.8	12.0	31.4
	3	2	35.2	12.0	34.7
	3	1	37.3	12.0	34.7
	4	6	28.1	11.5	25.3
	4	5	29.3	11.5	27.4
	4	4	29.6	11.5	27.4
	4	3	31.1	11.5	29.5
	4	2	33.5	11.5	32.9
	4	1	35.4	11.5	32.9
	5	5	28.3	11.0	27.0
	5	4	28.7	11.0	27.0
	5	3	30.1	11.0	29.2
	5	2	32.2	11.0	32.6
	5	1	34.4	11.0	32.6
	6	4	27.7	10.5	26.2
	6	3	29.1	10.5	28.4
	6	2	30.7	10.5	30.5
	6	1	33.4	10.5	30.5
	7	3	28.2	9.9	27.6
	7	2	29.7	9.9	29.7
	7	1	32.2	9.9	29.7
	8	2	29.0	9.4	28.9
	8	1	31.1	9.4	28.9
	9	1	30.1	8.8	28.1

	a	b	VDF (%) RADIANCE	UVA method	OPA method
Point 3	1	9	16.7	12.0	12.8
H = 9	1	8	18.2	12.0	13.0
	1	7	20.6	12.0	19.6
	1	6	22.7	12.0	19.7
	1	5	25.1	12.0	23.4
	1	4	28.4	12.0	25.9
	1	3	30.1	12.0	29.5
	1	2	32.5	12.0	33.5
	1	1	34.8	12.0	33.5
	2	8	17.0	11.3	11.4
	2	7	19.3	11.3	18.1
	2	6	21.3	11.3	18.2
	2	5	23.6	11.3	21.9
	2	4	26.1	11.3	24.5
	2	3	28.0	11.3	27.9
	2	2	29.9	11.3	31.4
	2	1	32.2	11.3	31.4
	3	7	17.7	10.5	17.0
	3	6	19.6	10.5	17.0
	3	5	21.3	10.5	20.7
	3	4	23.1	10.5	20.7
	3	3	25.0	10.5	24.3
	3	2	27.0	10.5	27.9
	3	1	29.4	10.5	27.9
	4	6	17.1	9.5	12.8
	4	5	18.8	9.5	16.5
	4	4	20.6	9.5	16.5
	4	3	22.6	9.5	20.3
	4	2	24.4	9.5	24.0
	4	1	26.8	9.5	24.0
	5	5	15.9	8.5	15.8
	5	4	17.7	8.5	15.8
	5	3	19.7	8.5	19.6
	5	2	21.7	8.5	23.3
	5	1	24.0	8.5	23.3
	6	4	14.3	7.4	11.2
	6	3	16.3	7.4	15.1
	6	2	18.2	7.4	19.0
	6	1	20.7	7.4	19.0
	7	3	12.9	6.3	10.4
	7	2	15.1	6.3	14.4
	7	1	17.4	6.3	14.4
	8	2	11.3	5.1	9.5
	8	1	18.4	5.1	9.5
	9	1	10.2	3.9	4.3

	a	b	VDF (%) RADIANCE	UVA method	OPA method
Point 4	1	9	25.8	12.8	24.9
H = 9	1	8	27.1	12.8	25.0
	1	7	29.0	12.8	29.6
	1	6	30.8	12.8	29.6
	1	5	34.9	12.8	32.9
	1	4	36.7	12.8	34.0
	1	3	38.1	12.8	37.2
	1	2	39.8	12.8	40.5
	1	1	42.0	12.8	40.6
	2	8	26.6	12.4	24.3
	2	7	28.5	12.4	28.9
	2	6	30.2	12.4	28.9
	2	5	34.3	12.4	32.2
	2	4	36.1	12.4	33.3
	2	3	35.6	12.4	36.5
	2	2	37.7	12.4	39.6
	2	1	41.0	12.4	39.6
	3	7	27.6	12.0	28.4
	3	6	29.3	12.0	28.4
	3	5	33.3	12.0	31.6
	3	4	34.7	12.0	31.6
	3	3	34.3	12.0	34.9
	3	2	37.5	12.0	38.0
	3	1	39.2	12.0	38.0
	4	6	28.2	11.5	26.5
	4	5	32.1	11.5	29.8
	4	4	33.6	11.5	29.8
	4	3	34.8	11.5	33.1
	4	2	35.0	11.5	36.3
	4	1	38.2	11.5	36.3
	5	5	30.7	11.0	29.5
	5	4	32.1	11.0	29.5
	5	3	33.0	11.0	32.8
	5	2	34.9	11.0	36.0
	5	1	36.8	11.0	36.0
	6	4	30.7	10.5	27.5
	6	3	31.6	10.5	30.9
	6	2	33.3	10.5	34.2
	6	1	34.3	10.5	34.2
	7	3	28.4	9.9	28.9
	7	2	30.5	9.9	32.3
	7	1	32.7	9.9	32.3
	8	2	30.1	9.4	30.2
	8	1	30.8	9.4	30.2
	9	1	29.1	8.8	28.1

	a	b	VDF (%)		
			RADIANCE	UVA method	OPA method
Point 5	1	9	34.9	12.0	37.6
H = 9	1	8	38.7	12.0	37.6
	1	7	36.4	12.0	37.6
	1	6	35.1	12.0	37.6
	1	5	39.0	12.0	37.6
	1	4	38.9	12.0	37.6
	1	3	35.9	12.0	37.6
	1	2	36.3	12.0	37.6
	1	1	39.2	12.0	37.6
	2	8	36.3	11.3	34.7
	2	7	36.3	11.3	34.7
	2	6	36.2	11.3	34.7
	2	5	36.4	11.3	34.7
	2	4	33.0	11.3	34.7
	2	3	33.9	11.3	34.7
	2	2	36.7	11.3	34.7
	2	1	37.0	11.3	34.7
	3	7	33.9	10.5	31.4
	3	6	33.9	10.5	31.4
	3	5	34.0	10.5	31.4
	3	4	34.2	10.5	31.4
	3	3	34.3	10.5	31.4
	3	2	34.2	10.5	31.4
	3	1	34.5	10.5	31.4
	4	6	27.5	9.5	27.6
	4	5	27.4	9.5	27.6
	4	4	31.6	9.5	27.6
	4	3	27.9	9.5	27.6
	4	2	31.8	9.5	27.6
	4	1	29.2	9.5	27.6
	5	5	28.8	8.5	27.0
	5	4	24.7	8.5	27.0
	5	3	29.0	8.5	27.0
	5	2	26.3	8.5	27.0
	5	1	29.4	8.5	27.0
	6	4	25.7	7.4	22.8
	6	3	23.8	7.4	22.8
	6	2	22.2	7.4	22.8
	6	1	22.8	7.4	22.8
	7	3	18.3	6.3	18.4
	7	2	18.5	6.3	18.4
	7	1	22.8	6.3	18.4
	8	2	15.0	5.1	13.6
	8	1	19.4	5.1	13.6
	9	1	11.6	3.9	8.5

	a	b	VDF (%) RADIANCE	UVA method	OPA method
Point 6	1	9	44.1	12.8	43.9
H = 9	1	8	41.3	12.8	43.9
	1	7	44.3	12.8	43.9
	1	6	41.3	12.8	43.9
	1	5	44.3	12.8	43.9
	1	4	41.8	12.8	43.9
	1	3	42.0	12.8	43.9
	1	2	43.6	12.8	43.9
	1	1	43.0	12.8	43.9
	2	8	40.7	12.4	42.6
	2	7	39.9	12.4	42.6
	2	6	40.1	12.4	42.6
	2	5	42.8	12.4	42.6
	2	4	43.0	12.4	42.6
	2	3	42.7	12.4	42.6
	2	2	41.1	12.4	42.6
	2	1	42.2	12.4	42.6
	3	7	38.6	12.0	41.1
	3	6	41.7	12.0	41.1
	3	5	39.0	12.0	41.1
	3	4	39.1	12.0	41.1
	3	3	39.9	12.0	41.1
	3	2	42.0	12.0	41.1
	3	1	40.5	12.0	41.1
	4	6	37.8	11.5	39.5
	4	5	40.6	11.5	39.5
	4	4	40.7	11.5	39.5
	4	3	40.8	11.5	39.5
	4	2	40.8	11.5	39.5
	4	1	39.2	11.5	39.5
	5	5	36.7	11.0	39.2
	5	4	36.5	11.0	39.2
	5	3	39.5	11.0	39.2
	5	2	39.5	11.0	39.2
	5	1	39.7	11.0	39.2
	6	4	37.8	10.5	37.4
	6	3	35.4	10.5	37.4
	6	2	36.3	10.5	37.4
	6	1	38.2	10.5	37.4
	7	3	33.6	9.9	35.6
	7	2	33.9	9.9	35.6
	7	1	36.6	9.9	35.6
	8	2	34.7	9.4	33.6
	8	1	32.7	9.4	33.6
	9	1	30.7	8.8	31.5

	a	b	VDF (%)		
			RADIANCE	UVA method	OPA method
Point 1	1	9	11.5	7.1	8.3
H = 12	1	8	13.5	7.2	8.5
	1	7	15.9	7.4	16.2
	1	6	18.0	7.5	16.3
	1	5	19.4	7.7	17.1
	1	4	21.7	7.9	20.2
	1	3	25.0	8.1	24.4
	1	2	27.9	8.3	29.1
	1	1	30.8	8.5	29.1
	2	8	12.5	6.7	7.1
	2	7	14.6	6.9	14.9
	2	6	16.1	7.0	15.0
	2	5	17.6	7.2	15.9
	2	4	19.3	7.4	19.0
	2	3	21.7	7.6	23.0
	2	2	24.4	7.8	27.0
	2	1	27.3	8.1	27.0
	3	7	13.0	6.3	10.9
	3	6	14.6	6.5	10.9
	3	5	15.4	6.7	11.7
	3	4	16.3	6.9	11.7
	3	3	18.3	7.1	12.5
	3	2	20.7	7.3	16.9
	3	1	23.9	7.5	16.9
	4	6	11.2	5.9	6.3
	4	5	12.1	6.1	7.1
	4	4	13.0	6.3	7.1
	4	3	14.4	6.5	7.9
	4	2	16.9	6.7	12.4
	4	1	20.0	6.9	12.4
	5	5	9.9	5.4	6.6
	5	4	10.9	5.6	6.6
	5	3	12.1	5.8	7.4
	5	2	14.0	6.1	11.9
	5	1	17.2	6.3	11.9
	6	4	9.4	5.0	5.2
	6	3	10.7	5.2	6.0
	6	2	12.0	5.4	6.8
	6	1	15.1	5.6	6.8
	7	3	9.4	4.5	4.6
	7	2	10.5	4.7	5.4
	7	1	13.0	4.9	5.4
	8	2	9.1	3.9	4.0
	8	1	10.8	4.1	4.0
	9	1	9.6	3.4	2.5

	a	b	VDF (%)		
			RADIANCE	UVA method	OPA method
Point 2	1	9	23.4	7.8	22.0
H = 12	1	8	23.9	7.9	22.1
	1	7	25.9	8.1	27.3
	1	6	27.6	8.3	27.4
	1	5	30.2	8.4	29.6
	1	4	31.8	8.6	31.0
	1	3	33.9	8.8	34.6
	1	2	36.8	9.1	38.4
	1	1	39.8	9.3	38.4
	2	8	23.4	7.7	21.5
	2	7	26.4	7.9	26.8
	2	6	26.7	8.0	26.8
	2	5	28.3	8.2	29.0
	2	4	30.2	8.4	30.4
	2	3	32.5	8.6	34.0
	2	2	35.0	8.8	37.5
	2	1	37.4	9.0	37.5
	3	7	24.6	7.6	25.0
	3	6	26.0	7.7	25.0
	3	5	27.3	7.9	27.2
	3	4	29.1	8.1	27.2
	3	3	30.9	8.3	29.4
	3	2	33.5	8.5	33.1
	3	1	36.0	8.8	33.1
	4	6	25.6	7.5	23.0
	4	5	25.7	7.6	25.2
	4	4	27.3	7.8	25.2
	4	3	29.0	8.0	27.5
	4	2	31.6	8.2	31.3
	4	1	34.2	8.5	31.3
	5	5	25.8	7.3	25.0
	5	4	26.3	7.5	25.0
	5	3	28.0	7.7	27.3
	5	2	30.5	7.9	31.1
	5	1	32.8	8.2	31.1
	6	4	25.6	7.2	24.4
	6	3	27.3	7.4	26.7
	6	2	28.8	7.6	28.9
	6	1	32.0	7.8	28.9
	7	3	26.4	7.0	26.1
	7	2	28.0	7.2	28.4
	7	1	30.7	7.5	28.4
	8	2	27.3	6.9	27.8
	8	1	29.7	7.1	27.8
	9	1	29.2	6.7	27.2

	a	b	VDF (%)		
			RADIANCE	UVA method	OPA method
Point 3	1	9	11.7	7.1	8.3
H = 12	1	8	13.5	7.2	8.5
	1	7	16.3	7.4	16.2
	1	6	18.6	7.5	16.3
	1	5	21.5	7.7	20.4
	1	4	24.2	7.9	23.4
	1	3	27.4	8.1	27.5
	1	2	30.0	8.3	32.0
	1	1	32.8	8.5	32.0
	2	8	12.3	6.7	7.1
	2	7	15.0	6.9	14.9
	2	6	17.5	7.0	15.0
	2	5	20.4	7.2	19.2
	2	4	23.0	7.4	22.2
	2	3	25.2	7.6	26.1
	2	2	27.5	7.8	30.0
	2	1	30.1	8.1	30.0
	3	7	13.9	6.3	14.2
	3	6	16.2	6.5	14.2
	3	5	18.1	6.7	18.3
	3	4	20.2	6.9	18.3
	3	3	22.6	7.1	22.3
	3	2	24.7	7.3	26.3
	3	1	27.3	7.5	26.3
	4	6	13.6	5.9	9.7
	4	5	15.6	6.1	13.9
	4	4	17.6	6.3	13.9
	4	3	20.1	6.5	18.2
	4	2	22.2	6.7	22.3
	4	1	24.7	6.9	22.3
	5	5	12.5	5.4	13.4
	5	4	14.6	5.6	13.4
	5	3	16.9	5.8	17.7
	5	2	19.2	6.1	21.9
	5	1	21.7	6.3	21.9
	6	4	11.2	5.0	8.8
	6	3	13.6	5.2	13.2
	6	2	15.8	5.4	17.5
	6	1	18.4	5.6	17.5
	7	3	10.1	4.5	8.3
	7	2	12.4	4.7	12.8
	7	1	14.9	4.9	12.8
	8	2	8.9	3.9	7.8
	8	1	11.4	4.1	7.8
	9	1	7.7	3.4	2.5

	a	b	VDF (%) RADIANCE	VDF (%) UVA method	VDF (%) OPA method
Point 4	1	9	22.4	7.8	22.0
H = 12	1	8	24.0	7.9	22.1
	1	7	26.1	8.1	27.3
	1	6	28.1	8.3	27.4
	1	5	32.9	8.4	31.0
	1	4	34.9	8.6	32.4
	1	3	35.1	8.8	36.0
	1	2	37.7	9.1	39.7
	1	1	40.1	9.3	39.7
	2	8	23.5	7.7	21.5
	2	7	25.6	7.9	26.8
	2	6	27.6	8.0	26.8
	2	5	32.4	8.2	30.5
	2	4	34.3	8.4	31.8
	2	3	34.1	8.6	35.4
	2	2	37.3	8.8	38.8
	2	1	39.0	9.0	38.8
	3	7	25.1	7.6	26.4
	3	6	27.0	7.7	26.4
	3	5	31.3	7.9	30.1
	3	4	33.1	8.1	30.1
	3	3	34.3	8.3	33.7
	3	2	34.9	8.5	37.2
	3	1	37.7	8.8	37.2
	4	6	25.8	7.5	24.5
	4	5	30.3	7.6	28.2
	4	4	32.0	7.8	28.2
	4	3	31.6	8.0	31.9
	4	2	35.0	8.2	35.5
	4	1	36.3	8.5	35.5
	5	5	28.7	7.3	28.0
	5	4	30.5	7.5	28.0
	5	3	30.1	7.7	31.6
	5	2	33.5	7.9	35.3
	5	1	35.9	8.2	35.3
	6	4	29.1	7.2	25.9
	6	3	28.5	7.4	29.7
	6	2	30.8	7.6	33.4
	6	1	33.1	7.8	33.4
	7	3	28.5	7.0	27.6
	7	2	28.9	7.2	31.4
	7	1	31.4	7.5	31.4
	8	2	28.8	6.9	29.4
	8	1	29.6	7.1	29.4
	9	1	29.0	6.7	27.2

	a	b	VDF (%) RADIANCE	VDF (%) UVA method	VDF (%) OPA method
Point 5	1	9	33.4	8.8	36.7
H = 12	1	8	37.1	8.8	36.7
	1	7	37.2	8.8	36.7
	1	6	37.3	8.8	36.7
	1	5	33.7	8.8	36.7
	1	4	37.4	8.8	36.7
	1	3	37.4	8.8	36.7
	1	2	37.6	8.8	36.7
	1	1	37.7	8.8	36.7
	2	8	34.6	8.3	33.7
	2	7	30.6	8.3	33.7
	2	6	30.8	8.3	33.7
	2	5	31.2	8.3	33.7
	2	4	31.1	8.3	33.7
	2	3	31.5	8.3	33.7
	2	2	35.3	8.3	33.7
	2	1	32.7	8.3	33.7
	3	7	32.3	7.7	30.2
	3	6	28.2	7.7	30.2
	3	5	32.4	7.7	30.2
	3	4	32.5	7.7	30.2
	3	3	32.6	7.7	30.2
	3	2	29.7	7.7	30.2
	3	1	30.1	7.7	30.2
	4	6	28.3	7.1	26.4
	4	5	29.8	7.1	26.4
	4	4	28.0	7.1	26.4
	4	3	26.1	7.1	26.4
	4	2	27.6	7.1	26.4
	4	1	27.2	7.1	26.4
	5	5	22.9	6.5	25.9
	5	4	26.8	6.5	25.9
	5	3	27.0	6.5	25.9
	5	2	27.0	6.5	25.9
	5	1	24.5	6.5	25.9
	6	4	19.7	5.8	21.7
	6	3	20.3	5.8	21.7
	6	2	20.5	5.8	21.7
	6	1	20.9	5.8	21.7
	7	3	15.9	5.1	17.2
	7	2	16.3	5.1	17.2
	7	1	20.9	5.1	17.2
	8	2	13.4	4.4	12.4
	8	1	13.2	4.4	12.4
	9	1	9.6	3.6	7.3

	a	b	VDF (%) RADIANCE	VDF (%) UVA method	VDF (%) OPA method
Point 6	1	9	40.2	9.5	43.5
H = 12	1	8	43.4	9.5	43.5
	1	7	40.6	9.5	43.5
	1	6	43.5	9.5	43.5
	1	5	43.5	9.5	43.5
	1	4	41.4	9.5	43.5
	1	3	43.7	9.5	43.5
	1	2	43.8	9.5	43.5
	1	1	43.0	9.5	43.5
	2	8	39.2	9.3	42.1
	2	7	42.0	9.3	42.1
	2	6	39.2	9.3	42.1
	2	5	42.3	9.3	42.1
	2	4	42.2	9.3	42.1
	2	3	39.7	9.3	42.1
	2	2	40.6	9.3	42.1
	2	1	42.5	9.3	42.1
	3	7	37.8	9.0	40.6
	3	6	37.9	9.0	40.6
	3	5	38.5	9.0	40.6
	3	4	41.1	9.0	40.6
	3	3	41.2	9.0	40.6
	3	2	41.4	9.0	40.6
	3	1	41.5	9.0	40.6
	4	6	36.6	8.7	38.9
	4	5	37.5	8.7	38.9
	4	4	39.9	8.7	38.9
	4	3	40.0	8.7	38.9
	4	2	40.1	8.7	38.9
	4	1	40.3	8.7	38.9
	5	5	38.4	8.4	38.7
	5	4	38.4	8.4	38.7
	5	3	38.6	8.4	38.7
	5	2	36.1	8.4	38.7
	5	1	38.8	8.4	38.7
	6	4	37.1	8.0	37.0
	6	3	34.2	8.0	37.0
	6	2	34.8	8.0	37.0
	6	1	37.4	8.0	37.0
	7	3	35.5	7.7	35.1
	7	2	32.9	7.7	35.1
	7	1	33.4	7.7	35.1
	8	2	33.8	7.3	33.1
	8	1	31.6	7.3	33.1
	9	1	32.2	6.9	31.0

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