ABSTRACT

CARRINGTON, K. DARYL. A Photometric Characterization Methodology for Daylighting Fixtures. (Under the direction of Wayne Place.)

This dissertation conceptualizes and computationally demonstrates a photometric characterization methodology for daylighting fixtures. The methodology is based upon applying far-field photometric evaluation techniques. The photometric characterization methodologies use computer simulations to characterize visible light and thermal performance of daylighting fixtures. A daylighting fixture is defined to include the boundary and all the components that exist between the admittance plane and exit plane of a daylighting aperture. The fixture concept allows the characterization data to be applied to daylighting fixtures in any setting.

The lack of comprehensive daylighting performance evaluation protocols and basic daylighting component research indicate the need to develop this characterization methodology. This dissertation articulates key weaknesses in current daylighting indicators and performance characterization research, which support the need for additional protocols to characterize daylight, including angular intensity distribution at the point it is admitted into a building and associated thermal gains.

The characterization methodology is demonstrated using four lighting software programs to assess louver control components for toplighting. Visible light characterizations addressed in this dissertation study include angular intensity distribution, illuminance distribution and visual effect. Thermal characterizations addressed include irradiance transmittance through the

aperture and heat gain associated with irradiance absorbed by the louver control component. Simulations are limited to using currently available computer tools. Where simulation tools do not exist to properly support the characterization, a description is given of the software capabilities that need to be developed. The characterization data provided by this methodology is fully compatible with electric lighting and glazing performance data currently used by designers.

The proposed methodology will support architects and lighting designers in selecting daylighting components and/or systems on a performance basis comparable to the selection of other building products. Given the huge potential for daylighting, the lack of well daylighted buildings indicates the potential for this research. Daylighting in buildings has implications for renewable energy, and the health and well-being of human occupants. It is envisioned that the proposed photometric characterization data will be used by architects and lighting designers to develop daylighting strategies incorporating performance, experiential, and aesthetic criteria.

A PHOTOMETRIC CHARACTERIZATION METHODOLOGY FOR DAYLIGHTING FIXTURES

by

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North Carolina State University
in partial fulfillment of the requirements for the Degree of
Doctor of Philosophy

DESIGN

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DEDICATION

Undertakings with the scope and time of a dissertation, while in the name an individual, require the formal and informal support and assistance from many people. This dissertation is dedicated to all those who have helped directly and indirectly to make this document possible. I thank my wife, Dr. Mary Myers, and my children, Jaspar and Ian Carrington; Dr. Wayne Place and my dissertation committee, including Dr. Larry Silverberg, Dr. Perver Baran, and Associate Dean James Tomlinson; and, my research assistants, James Sweeney at North Carolina State University and Greg Wilson at Philadelphia University. I also thank Ph.D. Program Director, Professor Meredith Davis; the Ph.D. faculty at the College of Design; my academic and professional colleagues; and Pamela Christie-Tabron for their support, criticism and guidance through the process.

BIOGRAPHY

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1.0 INTRODUCTION

1.1. Description of Problem Area

> *Light is one of the most universal and all-pervasive elements in our world. In the form of the Sun, it is the well-spring of all life and drives all our known biological processes, starting with photosynthesis in plants. But it is also the principal 'maker' of the world in another sense, in that it is the medium by which we directly experience our surroundings – without it we would be completely unable to comprehend and appreciate color, depth, space or volume. Even more fundamentally light can determine our deepest emotions and moods. Yet despite its essential nature and universal presence, light is also one of life's greatest mysteries' (Gardner and Molony).*

Daylighting in buildings has implications for renewable energy and the health and well-being of human occupants. The lack of substantially daylighted buildings in the last quarter of the 20th century (Selkowitz, 1998) indicates daylighting research has failed the design fields. It appears little has changed since 1990 when the state of daylighting research was described to be like 'the field of structural engineering before the advent of analytic tools, before the properties of most materials were known, and before performance indicators such as the modulus of elasticity had been formulated' (Love, 1990). The problem is a lack of daylighting design methodologies that facilitate the creative design process in a flexible, efficient manner while providing legitimate performance indicators.

This dissertation proposes a means of characterizing daylighting devices that will facilitate the design process in a manner that takes maximum advantage of existing design processes. Creating a new analytic tool in the form of a characterization methodology for daylighting fixtures will address several systemic problems of daylighting research. They are as follows:

Lack of comprehensive performance data: Generally applied daylighting indicators fail to account for the spatial and temporal variability of light. Daylighting indicators frequently compromise the data by simplifying either the portion of the resource characterized, or the setting of the characterization. Failure to account for the 3-dimensional nature of light is perhaps the worst shortcoming (Love, 1990). Self-imposed limitations are no longer necessary, as laptop computers now have the capability to easily store and process an entire year worth of hourly solar performance data.

Lack of available performance data: Basic performance knowledge comparing daylighting systems is lacking and/or unavailable to designers. Curatorial interviews and photometric readings taken in a pilot study performed by the author measuring daylighting performance in six museums designed by world-renowned architects indicated actual performance may be quite different than presumed performance. In addition, daylighting system flaws, such as over-lighting, which has resulted in the need to occasionally put aluminum lids on the glass roof of Renzo Piano's Menil Collection, are not general knowledge. Performance data should not only be made available to daylighting designers, but made available in a form that may be measured against previous examples or benchmarks. A consistent methodological tool for the evaluation and characterization of both the lighting and thermal performance of daylighting apertures is necessary.

Lack of typological classification: Professionals require knowledge about daylighting components and systems that 'can be classified with respect to luminous behavior' (Baker, Fanchiotti & Steemers, Eds., 1993). Insufficient classification or comparative analysis of research results means little progress has been made toward building theoretical principles of daylighting. There is, consequently, no theory of daylighting suggesting, for example, how to deploy daylighting openings. There are only rules of thumb, such as the effective daylighting distance for a window is 2.5 times the height of the window (Ander, 1995). Rules of thumb are not dependable predictors of performance. The European Union (EU) has proposed typological classification of openings and other daylighting components, which may be linked to general performance characterizations, to inform a 'typological design process' (Baker, Fanchiotti & Steemers, Eds., 1993). Daylighting research should inform the typological design process by classifying component and/or system performance.

Failure to maintain the role of the designer: System based daylighting research (Place, 1986, Hu, 2003) limits the designer by establishing all the parameters of a space. If the space is not replicated as constructed in the test, it will not have the predicted performance. Typically the room volume, ceiling height, area of fenestration, interior partitions, mechanical distribution, and, possibly, structure are part of the tested system and cannot be modified. Whereas, all the issues need to be considered when designing a daylighting system, daylighting research needs to make provision for and support the creative role of the designer. A new methodology is required to build daylighting knowledge independent from system constraints by identifying, characterizing and classifying daylighting component rather than system performance.

Lack of daylighting design evolution: The core idea of Darwin's conceptualization of evolution is 'cumulative evolution by nonrandom survival of random heredity traits'. (Dawkins, 2003) If daylighting is to evolve in terms of performance, designers need to have performance information to 'non-randomly' select the best performing systems and advance the next application from that starting point. A review of daylighting literature indicated that current research methodologies do not provide the relevant performance data to enable designers to advance the performance of daylighting systems or components. Thus, the nonrandom 'survival of the fittest' leg of evolution is not occurring in architectural daylighting, as it has with other building systems. The rapid development of glazing performance, which is characterized as a component, indicates the potential of this approach. This research seeks to create a daylighting characterization methodology that will enable daylighting application and performance evolution if it becomes available to daylighting designers.

1.2 Research Hypothesis and Purpose

This research proposes and demonstrates a daylighting characterization methodology based upon far-field photometry techniques. Photometry techniques are used in the standardized characterization of electric lighting fixtures, and certain aspects of standardized glazing characterization. The intent is to adapt these techniques to the unique problems of assessing architectural daylighting to develop a more comprehensive and useful performance characterization for daylighting apertures. It will not be until daylighting designs are evaluated as *standard* building products that they will be effectively and efficiently used by designers.

Hypothesis:

A daylighting component characterization methodology adapted from existing far field photometric protocols will provide a more comprehensive daylighting performance characterization that is more integral to standard design practice than existing daylighting indicators.

1.3 Demonstrating the Characterization Methodology

The second part of this research will illustrate the proposed characterization methodology with four light simulation software programs. None of the available lighting programs can implement the full methodology. The use of four lighting programs permits comparison of the capabilities of each program for implementing the methodology. Comparison and evaluation may be used to discern needs and possibilities for future lighting software development.

The characterization methodology will provide photometric and thermal irradiance information in a form that can be integrated by the designer to optimize system performance. A toplighting component is tested independent of setting, allowing the characterization data to be integrated into daylighting systems in a range of settings. This strategy responds to a perceived weakness in daylighting system research, where the range of applicability of the research findings is limited by the specificity of the setting of the research. This is significant because no test-bed design can adequately fit the design possibilities of the full range of substantially daylighted spaces.

1.4 Delimitation

This research assesses computer simulation software that is readily available to architects and engineers, and compatible with widely used programs, such as AutoCad and photo-effect software commonly used by lighting designers. It is not in the scope of this research to analyze all the capabilities of the software, but to focus on how they may be applied to implement the stated characterization methodology. In addition, it is not in the scope of this research to write or modify available simulation software.

This research is limited by financial resources and time. The proposed characterization methodology is based upon procedures that are normally conducted by testing laboratories. Full implementation of the characterization methodology requires numerous tests generating substantial data for each daylighting component. Doing this effectively requires developing software macros that are outside the scope of the research. Sufficient characterization will be provided with the lighting software, evaluated to illustrate the potential and effectiveness of the photometric characterization.

There is a wide range of programs available, many of which might be useful in the specific aspects of the research. Three of the programs are specifically targeted at daylighting. They are Desktop Radiance, AGI32, and Lumen Designer. In addition to the three daylighting programs, I have chosen one optical design program, TracePro, that is compatible with AutoCad. TracePro was not intended to be integrated into an architectural design office, but has computational tools that fit the goals of the characterization. Computational fluid dynamics programs, although they might be used to provide a more detailed thermal performance analysis, are seen to be outside the purview of this research. Validation of the programs used has been done by others. It is not in the scope of this research to validate or compare the accuracy of outputs from the programs selected.

1.5 Significance of the Study:

The majority of daylighting research has inadequately addressed the needs of designers and the construction industry. The areas of concern include the following:

- Variety of research approaches makes output data inconsistent and limits the ability of researchers and designers to make performance comparisons.
- Application research frequently requires reproducing a specific physical setting to be transferable.
- Research data is not typically provided in a form that is easily incorporated into the design process with tools that are easily accessible to daylighting designers.
- Daylighting research is not sufficiently integrated with artificial lighting performance.
- Daylighting researchers have given little consideration to the design domain of the architect.
- Computer simulation protocols have not been sufficiently developed by daylighting researchers.

This research proposes a comprehensive performance characterization methodology that has the potential to address all these concerns. Photometric analysis of flux distribution at the source as daylight is admitted to the building is a critical component of the methodology. This characterization may be applied to any daylighting aperture, component or system in any geographic location in any architectural setting. Illuminance distribution, visual effect, visible light transmission, and thermal transmission complete the characterization methodology. The methodology shifts daylighting from being a specialty to being a product that may be 'transported' from one building context to another.

It is envisioned that the characterization methodology will provide data to be used by architects and lighting designers to predict daylighting performance and develop daylighting strategies. Accessible and meaningful data may eventually lead to a 'functional optimization' of daylighting systems, where daylighting is used to its best potential. Functional optimization incorporates aesthetic and experiential criteria with performance criteria, and will lead to buildings that respond to the changing needs of their users.

2.0 LITERATURE REVIEW

2.1 Scope of Literature Review

This literature review outlines salient literature in areas of daylighting and related fields that have informed this research. The headings have been organized to follow the development of the research from understanding the problem to demonstrating the proposed assessment tool. The areas of interest are as follows:

- Resource Measurement & Behavior
- Daylighting Performance Indicators
- Photometric Methodologies
- Glazing Performance Characterization Methodologies
- Toplighting Research
- Daylighting Performance Evaluation Using Computer Simulation

2.2 Resource Measurement and Behavior

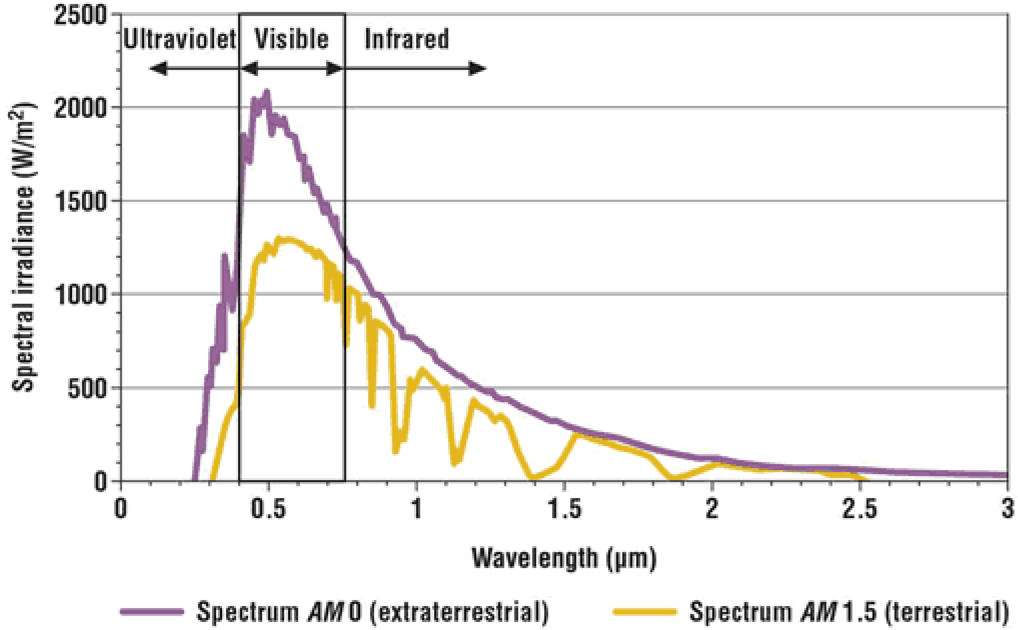

Figure 2.1: Extraterrestrial and terrestrial spectrum of sunlight

(www. volker_quaschning.de.com)

2.2.1 The Solar Resource

Daylighting goals have been linked to, and driven by resource characterization and behavior. The quantity of solar energy is vast; the annual mean solar irradiance reaching to earth's atmosphere is 1,367W/m^2 (Kreider & Kreith, 1977), but it is highly variable at ground level. The energy emitted by the sun varies with surface effects, such as solar flares; the relationship between the earth and the sun varies in time and space through annual and diurnal cycles, and weather and atmospheric turbidity on earth is constantly changing (Place, et al, 1992; Brown and DeKay, 2001; Daniels 1997). This creates a situation in daylighting research where a measurement must either capture an instantaneous condition, or be presented as an average or ratio. Variability may range over several thousand lux within minutes as a cloud passes in front of the sun. Resource variability has caused architectural daylighting to be practiced as an art as much as a science. Daylighting research generally focuses on predicted ranges using, for example, winter solstice, summer solstice and equinox measurements to bracket the possible annual conditions, rather than absolute performance values.

A further concern in architectural daylighting is that visible light is only part of the solar resource. The electromagnetic spectrum includes ultraviolet and infrared radiation, which often conflict with daylighting goals by damaging materials and/or causing thermal gain (Figure 2.1). Illuminance (lumen/m^2) and irradiance (W/ m^2) are measures of visible light energy and thermal energy respectively. Visible light has a fixed range of wavelengths. Thermal energy, although exceeding visible light in the infrared spectrum, may come from any part of the spectrum. Approximately 50% of the thermal energy in daylight is contained in the visible light spectrum. This indicates the thermal importance of not over-lighting spaces with daylight.

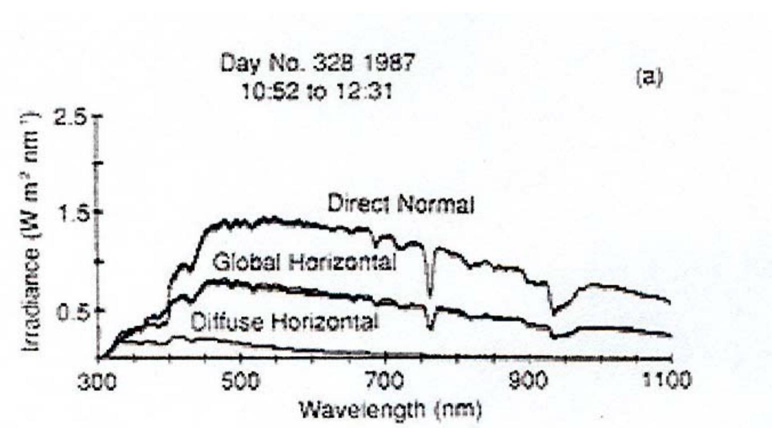

Figure 2.2: Spectral Irradiance

(McQuiston, F. & Parker, J, 1994)

There are two types of visible light arriving at buildings. They are normal incident radiation (beam sunlight) and diffuse radiation (diffuse skylight). Solar irradiance on a horizontal surface may be characterized as total global horizontal irradiance, which is the sum of direct normal (beam) horizontal irradiance and diffuse horizontal irradiance (Figure 2.2). The type of light used has a significant effect on perceived quality in architectural daylighting. Beam sunlight is 'constantly changing in direction' and 'highly variable in intensity', whereas diffuse light from the sky is 'essentially omni-directional' and 'quite steady in its omni-directionality' (Place, Howard & Howard, 1992). Diffuse light is 'a well-behaved source of light that almost never glares and it is a steady source of illumination that is adequate to fully illuminate…almost all daytime hours' (Place, Howard & Howard, 1992). William Lam on the other hand has utilized redirection of beam sunlight in several of his designs (Lam, 1986). Place, Howard & Howard were describing the resource arriving on a presumed aperture surface, whereas Lam proposed to increase daylight quantity by managing beam sunlight with diffusing or other distribution means to control quantity and quality.

2.2.2 Standardized Sky Measurement and Mathematical Models

The International Commission on Illumination (C.I.E., abbreviated as CIE from its French title Commission Internationale de l'Eclairage) has undertaken 'to develop basic standards and procedures of metrology in the fields of light and lighting, and to provide guidance in the application of principles and procedures in the development of international and national standards in the fields of light and lighting' (http://www.cie.co.at). The CIE International Daylight Measurement Programme (IDMP), which began in the early 1990's has developed standard sky models (Figure 2.3), where physical measurements of the 145 sky patches

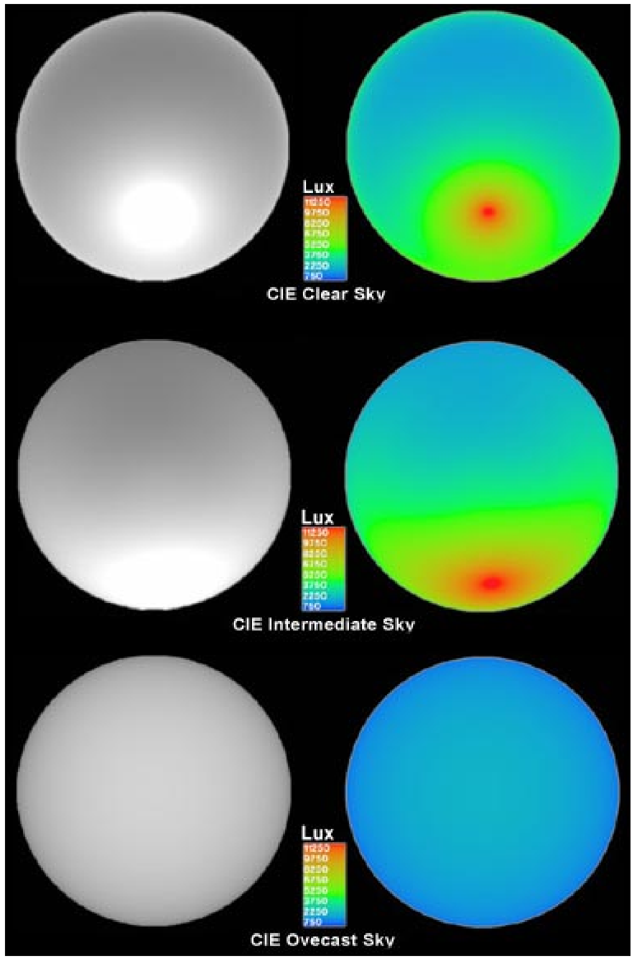

Figure 2.3: Gray Scale and False Color Images of C.I.E. Standard Skies

(www.squareone.com)

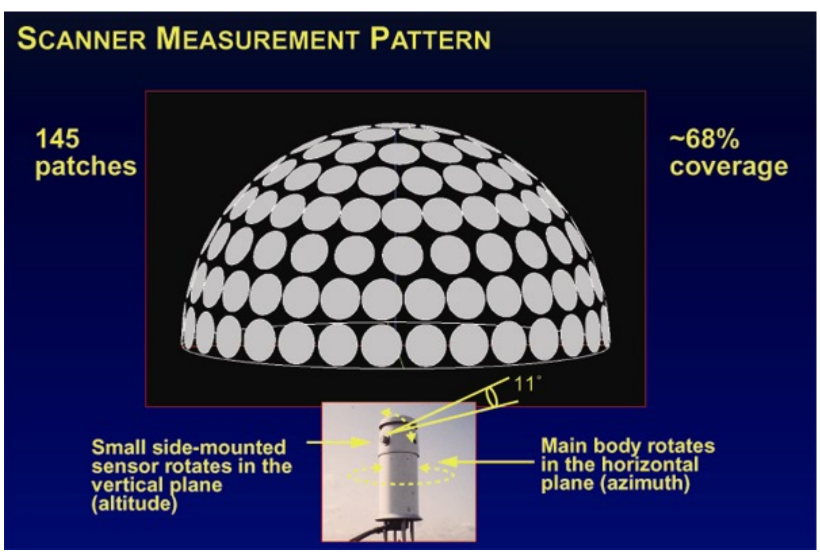

Figure 2.4: Sky Measurement Pattern (Mardaljevic, jm@dmu.ac.uk)

(Figure 2.4) are taken in different locations around the globe, and mathematical models of the sky are derived.

*The CIE mathematically defines fifteen sky types in CIE Publication S 011/E:2003, Spatial Distributions of Daylight - CIE Standard General Skies. The relative sky luminance distributions are described in the (***Figure 2.5):***

Gradation Group - indicates the gradation between horizon and zenith. Indicatrix Group - indicates the scattering function which relates the luminance of a sky element to its angular distance to the sun.

These models provide mean data averaged over a variety of time, location and measurement conditions. The IES Handbook states that the traditional sky models (Clear, Partly Cloudy and Overcast) should not be compared to instantaneous sky conditions (especially for a partly cloudy sky, where the sky luminance distribution can change rapidly and in large amounts as the sun is revealed, partially obstructed or fully obstructed). It is not unusual for the instantaneous measured sky luminance to differ from the average mean value by 2x from measurement to measurement. The CIE states that the Standard General Sky Models (1 - 15) give an approximation to clear, overcast and skies of broken clouds that are sufficiently accurate for most daylight calculations.

Absolute Zenith Luminance Factor…allows you to calibrate the chosen sky models to local conditions by prorating the zenith luminance values based on measured horizontal Illuminance values. It is best applied to overcast skies, as one factor is applied to every patch in the sky dome uniformly. (Excerpted from www.AGI32/Help)

Type	Gradation Group	Indicatrix Group	Description of luminance distribution
1	I	1	CIE Standard Overcast Sky Steep luminance gradation towards zenith, azimuthal uniformity.
2	I	2	Overcast, with steep luminance gradation and slight brightening towards the sun.
3	II	1	Overcast, moderately graded with azimuthal uniformity.
4	II	2	Overcast, moderately graded and slight brightening towards the sun.
5	II	1	Sky of uniform luminance.
6	III	2	Partly cloudy sky, no gradation towards zenith, slight brightening towards the sun.
7	III	3	Partly cloudy sky, no gradation towards zenith, brighter circumsolar region.
8	III	4	Partly cloudy sky, no gradation towards zenith, distinct solar corona.
9	III	2	Partly cloudy, with obscured sun.
10	IV	3	Partly cloudy, with brighter circumsolar region.
11	IV	4	White-blue sky with distinct solar corona.
12	V	4	CIE Standard Clear Sky low luminance turbidity.
13	V	5	CIE Standard Clear Sky polluted atmosphere.
14	VI	5	Cloudless turbid sky with broad solar corona.
15	VI	6	White-blue turbid sky with broad solar corona.

Figure 2.5: C.I.E. Sky Types (www.AGI32/help)

Standard skies (Figure 2.5) have aided 'the development of computer based calculation and simulation; however, there are deficiencies in all areas. Data collection, especially, is still limited geographically and some variables, such as cloud cover and distribution, have proved difficult to measure and have, consequently, largely been ignored. Furthermore, data that has been collected has limitations on its accuracy that does not appear to have been factored into much analysis and model building' (Hayman, 2003). The measurement advisory standard, *Guide to recommended practice of daylight measurement*, demands an overall tolerance of +/- 5% (Tregenza, et al, 1994). 'Derived quantities from daylighting measurements, such as ratios, will be subject to the compound effect of tolerances associated with each individual component', (Hayman, 2003). Commonly used ratios include the diffuse ratio, a measure of sky cloudiness; luminance ratios, used in sky models; and daylight factors, the ratio of internal to external illuminance. 'If these are based on good daylighting data (+/- 10% tolerance) the resulting ratio will be of the order of +/- 20% (actually – 18.2% +22.2%)' (Hayman, 2003).

2.2.3 Interior Lighting Standards

Variability of light levels has a complex impact on human perception that can not be ignored by architects in practice. IESNA interior lighting standards recommend interior lighting quantity and quality defined by human needs (Figure 2.6). They call for relatively uniform levels of illuminance on the task surface, and provide standards for acceptable levels of lighting contrast within the work space. Defining and meeting lighting needs is part of the architect's overall responsibility. Meeting these standards is a significant problem for daylighting because the solar source is variable on a diurnal basis and an intermittent basis as the sun is blocked by clouds and weather phenomena (Robbins, 1986). Architects are challenged to design predictable performance into their buildings, and few programmatic areas can tolerate continued variability that daylighted spaces may have. It has been argued that standard levels for daylighting should be higher than electric lighting levels, because people physically need and can visually adapt to higher levels (Koster, 2004). Arguing for higher levels than IESNA standards is problematic, because solar energy quickly changes from a lighting boon to a thermal burden.

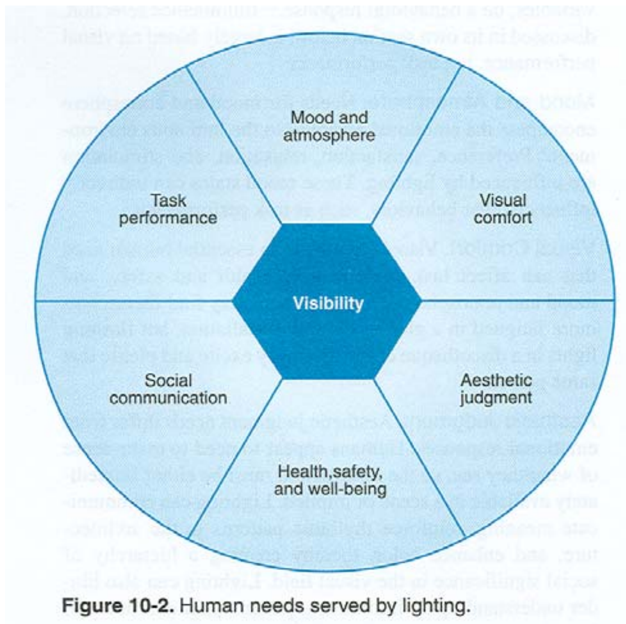

Figure 2.6: Human Needs Served by Lighting, <u>IESNA Handbook</u>

Daylight is managed though its optical characteristics. 'The solar radiation that falls on a surface is subject to absorption and reflection, as well as transmission through transparent bodies. Energy falling on a surface must be subject to one (or more) of these three actions (Figure 2.7): '*therefore:*

$\alpha + \rho + \tau = 1$

where

> α = *the absorptance, the fraction of the total incident radiation absorbed*
>
> ρ = *the reflectance, the fraction of the total incident radiation reflected*

τ = *the transmittance, the fraction of the total incident radiation transmitted through the body.*' (McQuiston & Parker, 1994).

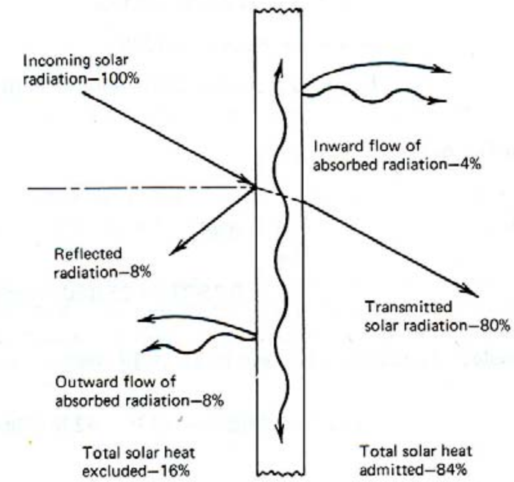

Figure 6-10 Distribution of solar radiation falling on clear plate glass.

Figure 2.7: Distribution of solar radiation falling on clear plate glass

Obstructing bodies, such as the louver control used in the demonstration section, exhibit only absorptance and reflectance. The percentage and type of reflectance is a function of material characteristics and the angle of incidence. Irradiance that is not reflected when striking an opaque object is absorbed by the object. The absorbed portion is either re-radiated, conducted or convectively transported away until thermal equilibrium is reached. Irradiance may be reflected by an object into the atmosphere or toward other objects, which will in turn absorb part and reflect part if they are not translucent. This type of 'bounce' occurs in louver control components. Irradiance may be admitted through control components by passing without striking the louvers or being reflected with one or more bounces between the proposed louver elements.

2.3 Daylighting Performance Indicators

'An important aspect of daylighting research is the development of techniques for estimating quantity and quality of illumination provided by daylighting systems' (Love, 1990). Techniques must account for the light source, quantity of illuminance including variability, and quality factors of illuminance, including distribution, glare and contrast. Since light sources must be integrated into the building envelop, architects are concerned with physical factors, such as, size, location, thermal gain and energy implications, and aesthetic factors, such as form and view. The daylight factor recommended by CIE for use with overcast skies and the lumen method recommended by IESNA are two widely used daylight performance indicators.

The daylight factor method is 'a low precision procedure for determining the illuminance at any point in an interior space produced by a sky of known luminance distribution" to estimate daylighting performance for over 60 years (IESNA, 2000). The *daylight factor* (DF) is the sum of the proportions *skylight component* (SC), *externally reflected component* (ERC) and *internally reflected componen*t (IRC) of light reaching a point on a horizontal plane (Figure 2.8). Therefore, DF = SC + ERC + IRC (IESNA, 2000). A method is included in The IESNA Lighting Handbook to calculate each of the daylight factor light components.

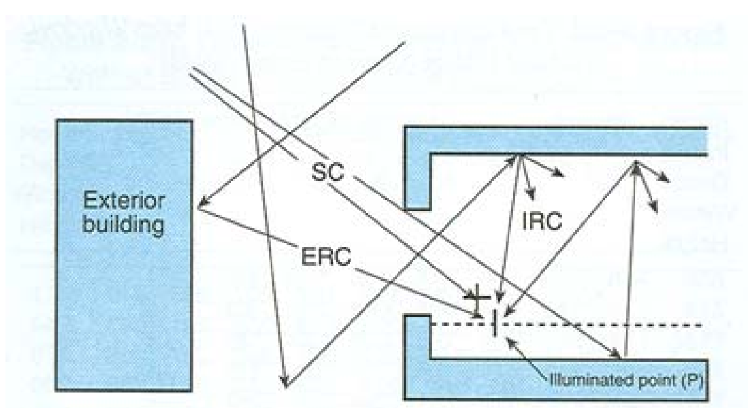

Figure 2.8: Daylight Factor Components (IESNA Handbook, 2000)

‘The daylight factor is widely used on the assumption that it reflects only differences in architectural features because variations due to changing sky luminance are eliminated’ (Love, 1990). The sky luminance varies continually and many locals, such as North Carolina, have predominantly clear skies, which makes the daylight factor a weak indicator of real world conditions. Several shortcoming of the daylight factor, described by Love (1990), are listed below:

- *Limitations to horizontal illuminance as a measure of illuminance performance, because it “obscure(s) the essentially three-dimensional nature of the lighting process, and of many visual task”. (Love, 1990 quoted from Lynes, Burt, Jackson & Cuttle)*
- *It does not provide information on important qualities of illumination, including contrast and glare.*
- *It does not provide thermal gain or loss information.*
- *It does not account for direct normal radiation.*

The IESNA standard method for calculation of interior illuminances is the Lumen Method. This method ‘is similar to the zonal cavity method for electric lighting and is simple enough to permit manual computation. It provides a simple way to predict interior daylight illumination through skylights and windows’ (IESNA, 2000). *‘The basic equation for the illuminance at a prescribed point using the lumen method is the simple formula*

$$E_i = E_x \, NT \, CU$$

where

Ei = *interior illuminance in lx,*

E_x = *exterior illuminance in lx,*

NT = net transmittance,

CU = coefficient of utilization. (IESNA Handbook, 2000)

The lumen method has four steps as put forth in The IESNA Lighting Handbook (2000);

1. Determining exterior illuminance at the opening. This may be calculated or measured with a photosensor.

2. Calculating net transmittance of the fenestration system, which may be determined from glazing data for simple systems or through testing for more complex systems.

3. Determining coefficients of utilization based on ratios of interior to exterior horizontal illuminance.

4. 'The interior illuminance is calculated by taking the product of the factors determined in the first three steps'.

'For the lumen method for toplighting the coefficients provide the average daylight illuminance on the workplane' (IESNA Handbook, 2000). The lumen method for toplighting 'can be used to determine the average workplane illuminance, if the total skylight area and the horizontal exterior illuminance are known. Conversely, the required skylight area can be determined if the required average workplane illuminance and horizontal exterior illuminance are known' (IESNA, 2000). When used for skylights it assumes 'that the skylights are positioned uniformly across the ceiling' (IESNA Handbook, 2000).

Several interrelated inadequacies of this method are as follows:

1. Focus on an instantaneous look at the daylighting condition.

This approach fails to relate skylight performance to the spatial and temporal variability of the solar resource. Solar variability spans the entire year. Meaningful performance analysis needs to include calculations made at the solstices and the equinox for clear and overcast conditions, and at different times of day, which can be used to project annualized performance (Atif, Love & Littlefair, 1997).

2. Doesn't account for variable angles of incidence and resulting reflective losses and system inter-reflections.

The net transmission of any glazing systems varies based upon the position of the sun and sky conditions. As the angle of incident increases a greater proportion of the light is reflected. Changes to the angle of incidence also effect transmission by increasing or reducing system inter-reflections. Daylighting transmission is also affected by the type of sunlight arriving at the skylight. The parallel rays of beam sunlight may be transmitted with fewer system reflections than diffuse skylight.

3. Lacks specific energy performance data.

'Indoor illuminance is an easy parameter to measure, but it is not the only parameter to assess the daylighting performance in buildings' (Atif, Love & Littlefair, 1997). The lumen method fails to account for the proportion of available illuminance that can be used to replace electric light and the thermal gain associated with admitted daylight.

Thus, the lumen method is a useful reference tool, but not a comprehensive performance indicator.

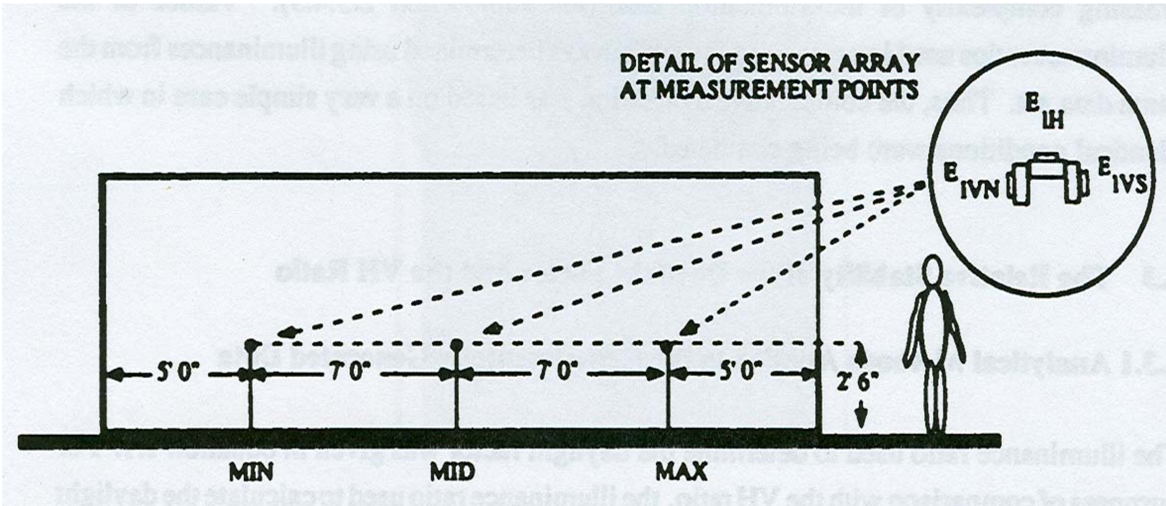

Figure 2.9: The Illuminance Determination Points in the Test Space (Love, 1990)

Love's (1990) dissertation research built upon these and related observations to put forth the vertical-to-horizontal illuminance ratio as a new daylighting performance indicator. The hypothesis tested was 'that the ratio of the illuminances on a pair of vertical and horizontal planes passing through a single point in a laterally daylit space (the VH ratio) is considerably superior to the daylight factor as an indicator of daylighting performance' (Love, 1990). The critical difference was the addition of a vertical component, which acknowledged the three-dimensional nature of sunlight. Testing was performed on full size mockups with two vertical sensors, located facing and away from the opening, and one horizontal sensor to verify predictive calculations. Several sensors were spaced across the rooms (Figure 2.9). Love concluded 'the VH ratio not only seems immune to sun and sky variations that render the daylight factor unusable, it also provides information not captured by the daylight factor', and 'provide(s) useful information on illuminance effects created by systems such as Venetian blinds and light shelves' (Love, 1990). Love did not compare the VH ratio to the

Lumen Method, which may have been more robust for the reasons noted above.

Although the VH ratio is an improved measure of the spatial distribution of light, it has the following shortcomings:

- Does not readily integrate daylighting and artificial lighting performance.
- Does not address toplighting
- Does not provide thermal characterization of daylighting

The goal for accurate characterization of toplighting performance should be to develop a more integrated approach. Atif, Love & Littlefair (1997) state indicators of daylighting performance (may be) limited to:

- *Daylighting contribution to illuminance*
- *Reduction of electric lighting consumption*
- *Reduction of thermal loads associated with daylighting, or contribution to heating needs.*

Atif, Love & Littlefair (1997) state further that three levels of assessment should be:

1. *Measured performance.*
2. *Measurements of performance control parameters.*
3. *Predicted annual performance based on short-term measurements.*

It is at this point that daylighting research fails to support the practical needs of architects. The above analysis of indicators and measurement goals leads to the conclusion that daylighting research is best done on full size mockups using natural sunlight. This technique is too expensive for all but special projects. Consequently, daylighting design and performance testing is limited to high budget architectural projects. The situation is exacerbated further because this data is generally proprietary and unavailable to most practitioners. This is why museums have more sophisticated daylighting than elementary schools, which would benefit in terms of student health and performance, and energy cost. Daylighting researchers need a more comprehensive and affordable assessment tool to provide useful information to all daylighting designers.

2.4 Photometric Methodologies

The basic categories of electromagnetic radiation measurement are photometry and radiometry. Photometry is concerned with the measurement of light (luminance and illuminance), and radiometry is concerned with the 'measurement of radiant energy and power' (IESNA Handbook, 2000).

2.4.1 Luminaire Photometrics:

The Illuminating Engineering Society of North America (IESNA) has set standards for far-field photometry protocols used in luminaire characterization. Far field photometrics are used to measure the angular distribution of light, horizontal illuminance, and vertical illuminance in luminaire characterization (Figure 2.10). Visual effect is also included in the characterization. IESNA has also set standards for the electronic transfer of luminaire photometric data. 'LM-63-02, ANSI/IESNA Standard File Format for the Electronic Transfer of Photometric Data and Related Information' (2002) provides a detailed outline for photometric data collection and transfer.

Standardized photometric testing is provided by manufacturers for all luminaires that bear a UL label. The photometric data allows electric lighting designers to accurately predict the interior and exterior performance of architectural lighting.

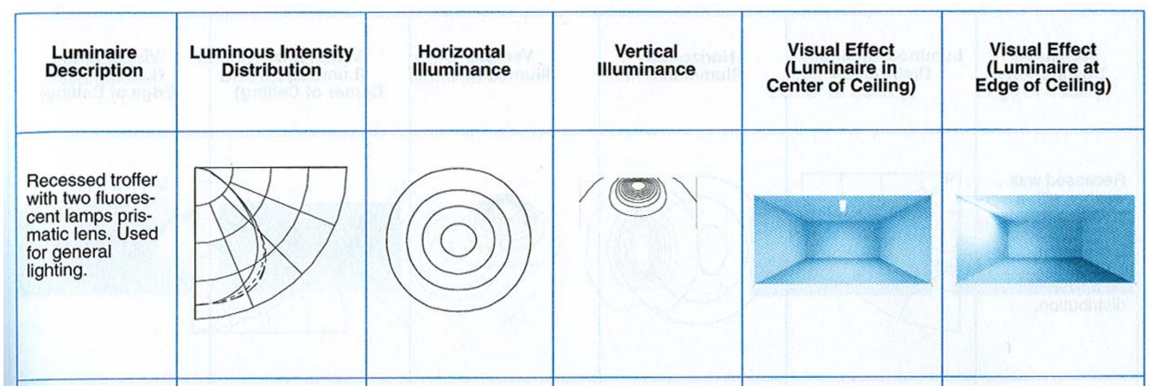

Figure 2.10: Luminaire Performance Chart, (IESNA Handbook, 2000)

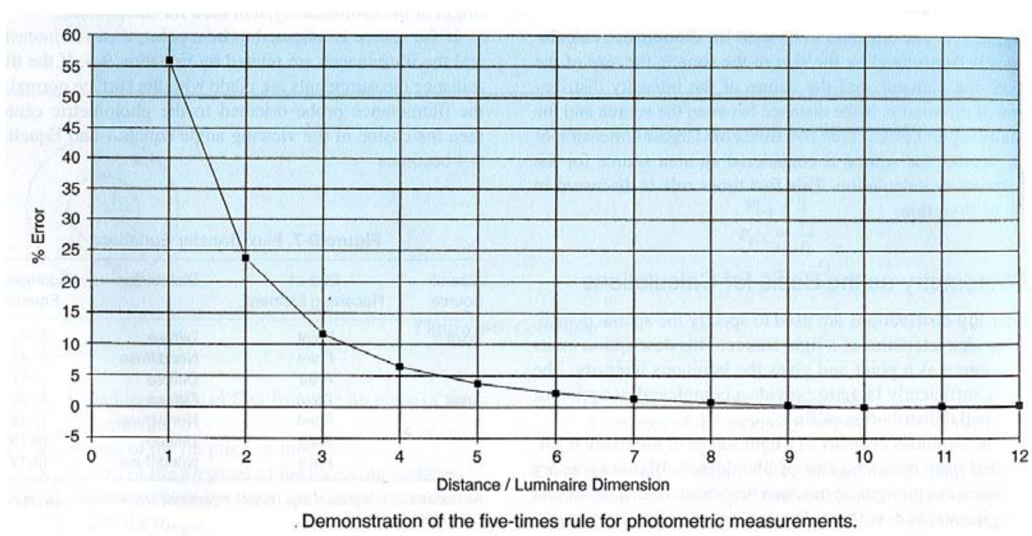

Figure 2.11: Demonstration of the five-times rule for photometric measurement

(IESNA Handbook, 2000)

The essential photometric measurement tool is a goniophotometer, which is used to measure intensity distributions. 'Intensity distributions are used to specify the spatial distribution of a light source. This description treats the source as a point and gives the luminous intensity. The set is sufficiently large to provide a complete description of the spatial distribution of flux' (IESNA Handbook, 2000). A goniophotometer may be constructed in various configurations, provided the photosensor(s) are located at five times the diagonal of the light source away from the center of the source. The five times rule is critical as distance from the source affects accuracy of the measurement (Figure 2.11).

A goniophotometer measures light emitted by the point source in small increments of azimuth and elevation. A goniophotometer may be conceptualized as a spherical array of photosensors at an appropriate distance from a source. The dimensions required to house of a full spherical goniophotometer may be prohibitive. The diameter can be reduced by mirror elements reflecting about the azimuthal and/or elevation axis. The azimuth and elevation angles are defined based upon the specification of the luminaire being tested, and the data being sought, generally 22 ½ degrees of azimuth and 5 degree increments of elevation.

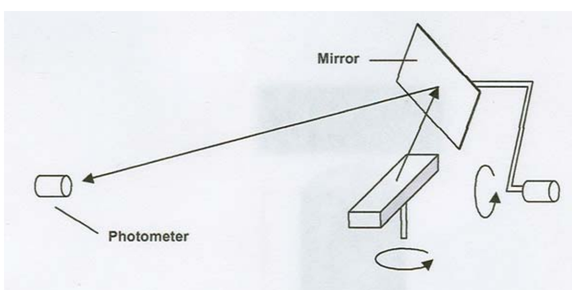

Figure 2.12: Rotating Mirror Goniophotometer Diagram (Ashdown, 2001)

The goniphotometer measures illuminance (lux) which is converted to candela or lumens per steradian (lm/sr). The conversion process from illuminance to candela normalizes the luminous intensity to a solid angle on the measuring sphere. The candela values, which are tied to spatial distribution by azimuth and elevation, can be converted back to illuminance values at different distances from the point source. This conversion allows lighting designers by knowing the distance and angle to a fixture from the surface of interest to use the intensity distribution data for the fixture to determine illuminance in any setting or fixture orientation.

Ian Ashdown has detailed the luminaire photometric process, issues of reliability and accuracy, and in-depth understanding of photometric reports (Ashdown, 2001). Although photometric data records luminaire performance for designers, most photometric data is collected by manufacturers because it is required to obtain a UL label for a product. It is thus part of product implementation, rather than a research process. Ashdown also provides a detailed explanation of the photometric analysis process from a technical perspective.

Ashdown's explores computational techniques to compare two and three-dimensional photometric distributions (Ashdown, 1999). Ashdown observes designers may be more interested in the general shape of a distribution rather than specific values. The value of graphic representation as an interpretive tool is particularly important to this research as it is directed to lighting designers. Ashdown's computer-based analyses illustrate the ever-emerging power of computers to process information, and represent it in graphic ways.

2.4.2 Photometric Testing Laboratory:

I was given a demonstration by Michael Grather of the rotating mirror goniophotometer at Luminaire Testing Laboratory (LTL) in Allentown, PA. (Figure 2.13), which is used for a complete spherical test of angular flux distribution from a luminaire. It is located in a black room, which accounts for the poor quality of the photograph. The wall mounted lights are only on for the photo. The luminaire is suspended at the center of the apparatus and can rotate 360 degrees at 22 ½ degree increments on a vertical axis to generate azimuth positions, see Figure 2.12. The large armature with a mirror (5-6' wide) rotates 360 degrees in ½ degree increments on a horizontal axis to generate elevation positions. Lamps being tested in the demonstration are reflected in the mirror. Light is reflected by the mirror from each tested position to a single photometer located 28' feet away, which is the IESNA prescribed distance for the test in accordance with the '5x rule' (LM-63-02,2002). The maximum fixture size that can be tested with this equipment is 4' x 4', which is limited by the 29 feet distance to the photometer and the five-times rule (4' x 1.414 x 5 = 28.28ft). Movement of the luminaire and armature, and collection and analysis of data is computer controlled. Positional accuracy is validated by laser measuring instruments. The illuminance data collected is translated into candela and recorded in IESNA file format with proprietary software.

Figure 2.13: Goniophotometer, Luminaire Testing Laboratory

2.4.3 Skylight Photometrics:

Applying photometric protocols to daylighting presents several problems because the solar source cannot be calibrated like a lamp and daylight has spatial and temporal variability. The Heschong Mahone Group (http://www.h-m-g.com) has developed a limited number of IES files for 'well-behaved' skylights, which indicates that it is possible.

Heschong Mahone Group (HMG) and their research consultants have designed and constructed the only goniophotometer in this country that uses daylight as a source (Figure 2.14). HMG tested skylight systems; up to 4' x 4' prismatic domes and pyramids with various dimension shafts, all with prismatic diffusers at the bottom. They were 'well-behaved' systems because issues of spatial temporal variability of daylight were minimized by controlling the distribution with the prismatic diffuser. The testing system had integrated software that puts photometric data in the IESNA electronic file format. HMG demonstrated the possibility and usefulness of skylight photometrics, but within parameters that limited the range of information produced. Their goal was to demonstrate immediate application of the IES files in the selection and specification of skylights. To reach the design community, they introduced IESNA data into SkyCalc, a spread sheet program that provides selection of skylight and performance information for simple applications, such as warehouses (http://www.h-m-g.com).

The skylight mirror goniophotometer has been purchased by VELUX roof windows for product testing about 2½ years ago. I visited their testing facility in Greenwood, SC on March 7, 2005. They have been testing light pipes in a very similar format to McHugh and have been able to make several design improvements by comparing light distributions from several products. This research is time consuming and dependent upon the time of year, sky conditions and weather. A VELUX employee indicated in conversation they do not intend to provide IESNA format photometric data to designers. They were contemplating proprietary software, similar to SkyCalc, and intend to provide simplified performance information in their catalogs.

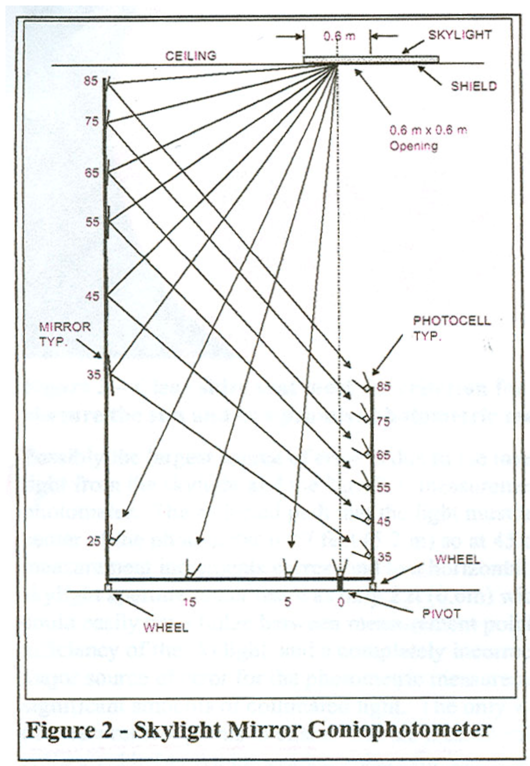

Figure 2.14: Daylighting Goniophotometer (http://www.h-m-g.com)

It is apparent from this section of the literature review, and my observation of luminaire and skylight photometric testing laboratories that the proposed photometric assessment methodology is well-grounded in substantial related research and testing. I have not found any computer simulation analysis of skylight photometrics, which indicates the need to develop an assessment tool in this area.

2.5 Glazing Performance Characterization Methodologies

There is a vast amount of information on glazing science. This section focuses on areas that are particularly relevant to the proposed research.

2.5.1 Standardized Glazing Performance Characterization

Glass is 'the classic selective material, pervious to light but not air or water' (Banham, 1969). Light transmitted through glazing elements, includes visible light and thermal radiation. Glazing can be made selective by the chemical content of the glass and by adding coatings. Glazing components may be composed as systems where the performance characteristics are additive. Standardized performance protocols for glazing have been developed by the National Fenestration Rating Council Incorporated (Figure 2.15). These tests are generally performed in a laboratory where sophisticated equipment and controlled settings are available. The tests are both photometric and radiometric. This research focuses on photometric tests. Glazing performance measures include visible light transmittance/reflectance; total solar energy transmittance/reflectance; U factors; solar heat gain coefficient; and shading coefficient. Visible light transmittance and solar energy transmittance may be measured photometrically; visible light transmittance directly and solar energy transmittance indirectly through absorption.

Glazing elements are generally, but not necessarily, components of daylighting systems. Daylighting apertures, components and systems are similar to stand-alone glazing elements in that they manage the transmission of radiant energy, including visible light and thermal irradiance. They are different because the architectural and/or structural form of the daylighting system, including wall thickness or well dimensions, effects transmission through shading, reflectance and inter-reflectance on opaque rather than translucent surfaces.

Monolithic Glass Performance Data[1, 10]

Product	Nominal Glass Thickness in	Nominal Glass Thickness mm	Visible Light[2] Trans-mittance[3] %	Visible Light[2] Reflect-ance[4] %	Total Solar Energy[2] Trans-mittance[3] %	Total Solar Energy[2] Reflect-ance[4] %	UV[2] Trans-mittance[3] %	U-Value[5] Summer	U-Value[5] Winter	European U-Value (K-Value)[6]	Solar Heat Gain Coeffi-cient[7]	Shading Coeffi-cient[8]
Pilkington Uncoated Float Glass												
Optifloat Clear	3/32	2.5	90	8	86	8	74	1.03	1.12	5.8	0.87	1.01
	1/8	3	90	8	84	8	71	1.03	1.11	5.8	0.86	1.00
	5/32	4	89	8	81	7	67	1.03	1.10	5.8	0.84	0.98
	3/16	5	89	8	80	7	65	1.03	1.10	5.8	0.83	0.97
	1/4	6	88	8	78	7	62	1.03	1.09	5.7	0.82	0.95
	5/16	8	87	8	73	7	57	1.03	1.07	5.6	0.78	0.91
	3/8	10	86	8	70	7	54	1.02	1.06	5.6	0.76	0.88
	1/2	12	84	8	64	6	48	1.01	1.04	5.5	0.72	0.83
	5/8	16	82	8	59	6	44	1.00	1.02	5.4	0.68	0.79
	3/4	19	81	8	55	6	40	0.99	1.00	5.2	0.65	0.75

Figure 2.15: Glazing Performance Data (Pilkington Building Products)

Glazing is tested with the light source normal to the glazing sample. It is understood that transmission and reflectance vary with the angle of the light source. This ‘simplification’ of all the possible source positions reduces the volume of data. The data is, however, compromised because normal incident radiation produces the highest transmission for clear glass and the lowest transmission for reflective.

Thermal transmission characteristics of glazing are normally tested with ‘thermal detectors include(ing) thermopiles, bolometers, and pyroelectric detectors. They produce a voltage proportional to the absorbed radiant power. The absorbing surface of the detector is usually blackened, making it nonselective over a wide range of wavelengths. The signal levels of these detectors are very low, and the detectors are very sensitive to ambient temperature changes. Once used extensively, they are now largely confined to laser light measurements’

(IESNA Handbook, 2000).

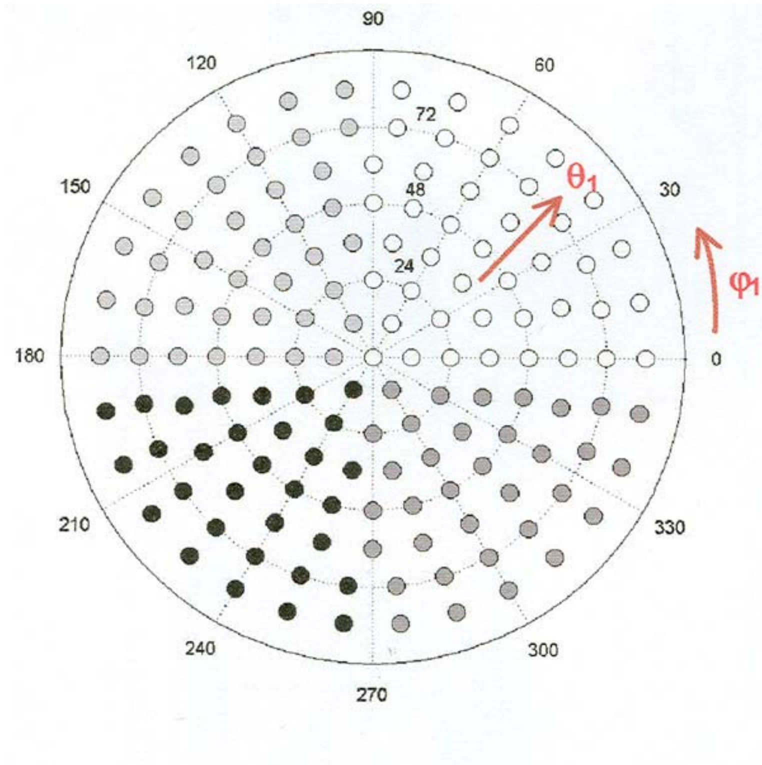

Fig. 32: Light Incidents for Bi-directional Measurements

Figure 2.16: Polar Plan of 145 Sky Points (Aydinli & Kaase,1999)

2.5.2 Bi-directional transmission characterization of materials (near-field photometry)

International Energy Agency (IEA) publication on ‘Measurement of Luminous Characteristics of Daylighting Materials’ (Aydinli & Kaase,1999) reports on glazing material testing with a spiral goniophotometer. 145 sky points were used to define the angles of incidence measured in this experiment (Figures 2.16 & 2.17). There exists general agreement in the daylighting community that 145 points in small circle geometry effectively blanket the sky (Tregenza, et al, 1994). The C.I.E. used these points to produce standard measurements of sky luminance. The lighting source for this research was a parallel beam luminaire. The experimental data was formatted to produce three dimensional graphs of light distribution from various glazing materials (Figure 2.18).

θ_1	φ_1-step	φ_1	**Light incidents must be measured for:**
0°	-	0°	All samples
12°	60°	0°, 60°	All samples
24°	30°	0°, 30°, 60°, 90°	All samples
36°	20°	0°, 20°, 40°, 60°, 80°	All samples
48°	15°	0°, 15°, 30°, 45°, 60°, 75°, 90°	All samples
60°	15°	0°, 15°, 30°, 45°, 60°, 75°, 90°	All samples
72°	12°	0°, 12°, 24°, 36°, 48°, 60°, 72°, 84°	All samples
84°	12°	0°, 12°, 24°, 36°, 48°, 60°, 72°, 84°	All samples
		Additional Measurements if the sample is asymmetric to:	
12°	60°	120°, 180°	φ_1= 90° / 270°
24°	30°	120°, 150°, 180°	φ_1= 90° / 270°
36°	20°	100°, 120°, 140°, 160°, 180°	φ_1= 90° / 270°
48°	15°	105°, 120°, 135°, 150°, 165°, 180°	φ_1= 90° / 270°
60°	15°	105°, 120°, 135°, 150°, 165°, 180°	φ_1= 90° / 270°
72°	12°	96°, 108°, 120°, 132°, 144°, 156°, 168°, 180°	φ_1= 90° / 270°
84°	12°	96°, 108°, 120°, 132°, 144°, 156°, 168°, 180°	φ_1= 90° / 270°
12°	60°	300°	φ_1= 0° / 180°
24°	30°	270°, 300°, 330°	φ_1= 0° / 180°
36°	20°	280°, 300°, 320°, 340°	φ_1= 0° / 180°
48°	15°	270°, 285°, 300°, 315°, 330°, 345°	φ_1= 0° / 180°
60°	15°	270°, 285°, 300°, 315°, 330°, 345°	φ_1= 0° / 180°
72°	12°	276°, 288°, 300°, 312°, 324°, 336°, 348°	φ_1= 0° / 180°
84°	12°	276°, 288°, 300°, 312°, 324°, 336°, 348°	φ_1= 0° / 180°
12°	60°	240°	φ_1= 0° / 180° and φ_1= 90° / 270°
24°	30°	210°, 240°	φ_1= 0° / 180° and φ_1= 90° / 270°
36°	20°	200°, 220°, 240°, 260°,	φ_1= 0° / 180° and φ_1= 90° / 270°
48°	15°	195°, 210°, 225°, 240°, 255°	φ_1= 0° / 180° and φ_1= 90° / 270°
60°	15°	195°, 210°, 225°, 240°, 255°	φ_1= 0° / 180° and φ_1= 90° / 270°
72°	12°	192°, 204°, 216°, 228°, 240°, 252°, 264°	φ_1= 0° / 180° and φ_1= 90° / 270°
84°	12°	192°, 204°, 216°, 228°, 240°, 252°, 264°	φ_1= 0° / 180° and φ_1= 90° / 270°

Figure 2.17: Azimuth and Elevation Angles of 145 Sky Points (Aydinli & Kaase,1999)

Dr. Marilyne Andersen's work is similar to the IEA work described above, but adds correlating results with computer simulations (Andersen, Rubin & Scartezzini, 2003). Dr. Andersen used TracePro software, and the correlation results were very good. Dr. Andersen's process was to digitally simulate the goniophotometer used in the physical experiment. Figures 2.19 and 2.20 diagram the goniophotometer and illustrate the simulated goniophotometer setting respectively. The goniophotometer design used a CCT camera to digitally measure the light projected on a flat surface.

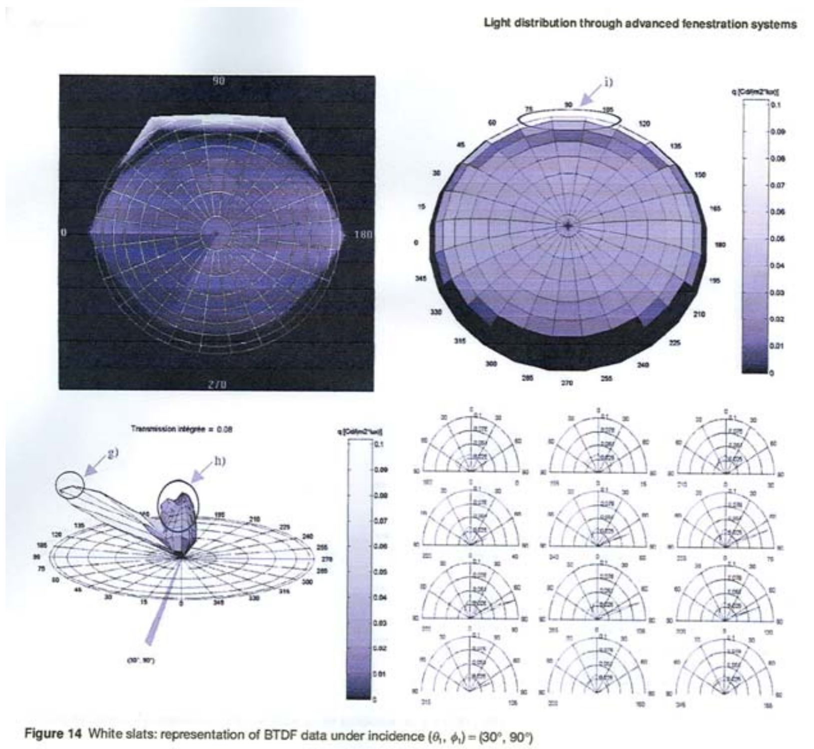

Figure 2.18: Bi-Directional Transmission Diagrams (Aydinli & Kaase,1999)

The shape of the goniophotometer was simulated with photosensors on planar grids. Replicating the luminaire goniophotometer at LTL would require a spherical array of photosensors. Dr. Andersen's other research focuses on side-wall applications using near-field photometry and an electric light source to research bi-directional transmission properties of daylighting materials (Andersen, 2002).

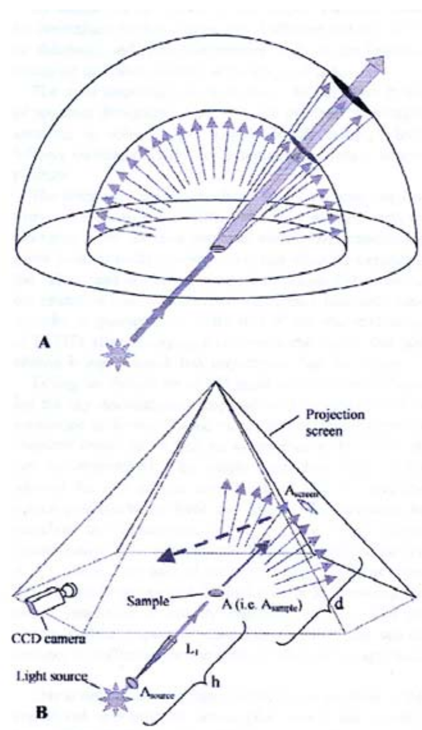

Fig. A.1. Detection of the light transmitted through a sample. (A) Specular component against diffuse transmission. (B) Light transmission and detection with the digital imaging-based photo-goniometer.

Figure 2.19: Spiral Goniophotometer Diagram (Andersen, 2002)

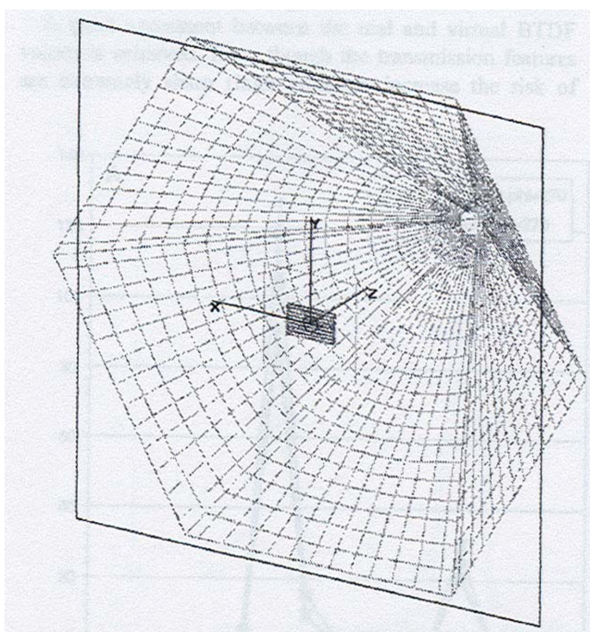

Fig. 5. Simulation model composed of an opaque diaphragm, the considered prismatic panel (sample), a non-interacting incident flux detection surface and six absorbing detection screens split into angular zones of spread $(\Delta\theta_2, \Delta\phi_2)=(5°, 5°)$.

Figure 2.20: Computer Simulation of Goniophotometer (Andersen, 2002)

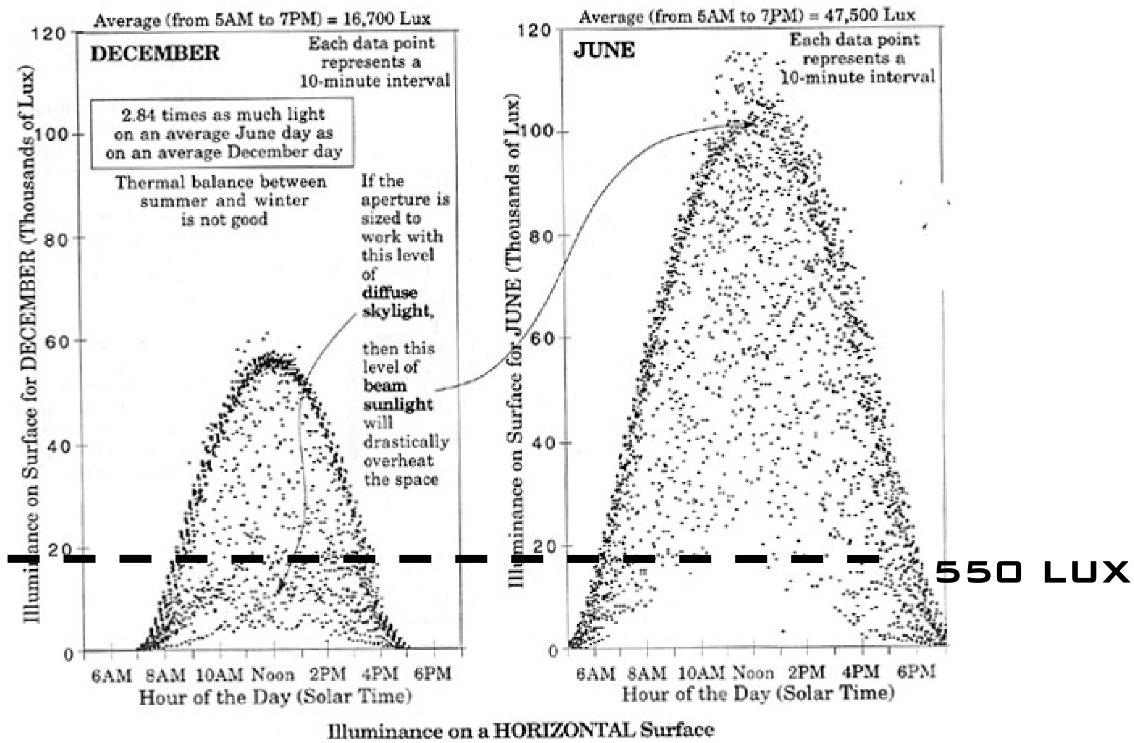

Figure 2.21: Illuminance on a Horizontal Surface

(Place, et al, 1992)

2.6 Toplighting Research

Toplighting research and application developments may be viewed as three inter-related categories. These are increasing the quantity of useful light, improving the distribution of light, and evaluating the energy efficacy of toplighting applications. Toplighting is important, because unshaded roofs are omni-directional receptors of light. This means more light for roof apertures over more of the day than for any other aperture location. Figure 2.21 illustrates rooftop illuminance at ten minute intervals on days in December and June in Raleigh, North Carolina. After 8AM in December and 6AM in June, there is more available illuminance than 550 lux, which is typically recommended in a classroom.

Attempts to increase the quantity of useful light with dynamic systems have generally been related to atria. Atrium light levels fall dramatically below the top few floors. Lam proposed operable mirrors on the Tennessee Valley Authority building to redirect beam sunlight to the floor of the atrium (Lam, 1986). Similar redirecting mirrors were installed on an atrium in an office building at Sozialamt der Bundespost, Germany. This installation which was contemporary with TVA had light shelves to distribute the light on the office floors (Baker, Franchiotti & Steemers, 1993). It is known that Lam worked with scale models to develop his designs, but this researcher unable to find light or thermal data for either of these projects. The Variable-Area, Light-Reflecting Assemblies (VALRA) were designed as a dynamic performance 'lightshelf' to increase light quantity and distribution for lateral openings (Howard, Place, Andersson & Coutier, 1986). Energy analysis was performed using BLAST (Building Loads Analysis and System Thermodynamics) software, and dynamic shading and other aperture enhancements were studied. The research concluded that VALRA could provide 10-15% annual energy savings in cities dispersed across the United States. This is mentioned here, because the research also suggested VALRA could be used for toplighting applications. A conceptually similar dynamic redirecting system for toplighting has been designed and a full scale prototype installation made at the Palm Springs, California City Hall by Lawrence Berkeley Laboratories. Diagrams and pictures are available, but no performance data was found (http://eetd.lbl.gov/). Related studies of light pipes and re-directing systems have been published by Lawrence Berkeley Laboratories (Beltran, et al, 1997 and Lee, et al, 1996).

A series of joint projects between North Carolina State University and Lawrence Berkeley Laboratories researched total energy performance of linear roof apertures (Bauman, et al, 1986), (Place, et al, 1986) (Andersson, Place & Adegran, 1986). The first two studies included experimental design of south facing linear systems. Daylighting performance was tested in models, and energy performance was simulated with BLAST. Daylighting was considered to replace electric lighting when it exceeded 550 lux. The research did not measure the effects of 'over-lighting' or variability of daylighting levels on users. The daylighting system had no load management controls, however, it was observed that load management controls 'would facilitate significant additional reductions in both energy consumption and energy costs' (Place, et al, 1986). The Mount Airy Library Case Study (Andersson, Place & Adegran, 1986) measured building performance and compared it to model and computerized energy performance modeling to speculate on the effects of daylighting enhancements on total energy performance. The study concluded that 'saw-toothed roof constitutes a very effective daylighting system' and 'for static systems: the acceptable configurations of the daylighting apertures (when a daylighting system contributes to reducing heating energy consumption) is south-facing vertical glass with a modest overhang' (Andersson, Place & Adegran, 1986).

An unpublished study by Place (1995) analyzes a large scale louver system installed below a transparent roof. The control focused on single-bounce reflection of unwanted radiation admitted through the transparent roof membrane. Koster (2004) explored a similar concept for lateral opening controls in the form of shaped louver blinds. The principle is that unwanted radiation can be efficiently rejected after passing through the glazing if the glazing is highly transparent and the radiation does not get diffused by the reflecting (redirecting) surface (Figure 2.22). Koester terms this effect 'optical heat control'. Koster's has also studied the effects of control location; exterior, between glazing layers and interior, on daylighting and thermal performance with consistently good results. The use of static control systems for toplighting is recommended, but performance measurements are not included. Since Koster was developing a product and did not provide a detailed description or calculations related to his performance evaluation methodology.

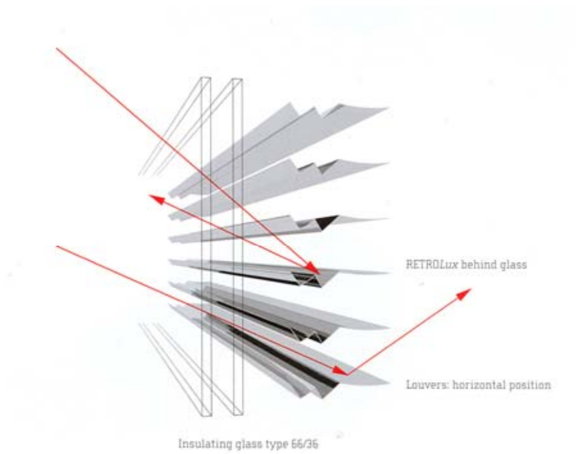

Figure 2.22: Light Reflectances of Retrolux Blinds (Koster, 2004)

Toplighting applications are found in buildings with museums frequently having the most sophisticated systems; however, performance data is not readily available. The University of Michigan made model simulations of the Menil Collection, Houston, which do not appear to be published. A pilot study performed at the museum revealed potential performance concerns, including a system of black-out covers used by the museum because there is no dynamic control and apparent thermal issues with the static control system being located below the glazing. The Getty Museum, California has a dynamic louver control system located outside the glazing. It is designed to select north skylight, and adjusts every thirty minutes to sky conditions. Lawrence Berkeley Laboratories consulted with the architect, Richard Meier. It has been mentioned as a case study by Pacific Gas and Electric, but no performance data has been found (http://eetd.lbl.gov/).

Toplighting research may be seen to have good performance knowledge about static solutions, e.g. Mount Airy Library (Anderson, Place & Adegran, 1986), and little performance knowledge regarding dynamic solutions, e.g. the Getty Museum. No studies referenced considered over-lighting or variability of light levels as critical issues. It was assumed in one case that measured levels averaging six times the IESNA recommended level of 550 lux were acceptable. Issues of glare were acknowledged, but considered to be ameliorated by the high position of the aperture and diffuse distribution.

Regulating the incoming solar volume is essential to providing predictable daylighting levels within buildings. A skylight system manages sunlight through transmittance, orientation, reflectance and distribution, which have been studied by Howard (1986); Beltran (1997) and Lee (1996). Control components manage daylighting through a balance of obstruction and opening. The primary functions of planar control elements are to manage aperture direction or 'sky selectivity' (the part of the sky used for daylighting) and to regulate aperture size.

- <u>Sky selectivity</u> manages the quantity of the solar load by 'focusing' on a sky illuminance level that is consistent with daylighting goals. Sky selectivity is generally used to reduce or obviate the need for aperture size control.
- <u>Aperture size</u> directly manages the luminance admitted.

Secondary characteristics, including shading, reflection, diffraction, diffusion, response time and material performance also affect lighting and thermal performance of planar controls

(Figure 2.23).

Each component in a system effects and is affected by one or more variables. A deeper understanding the cause and effect relationship between one of the components, planar elements, and the related variables, light quantity and quality, and thermal gain/loss is needed. Basic research is lacking for the controls, whereas it's available for other parts of the system, such as, glazing. Systems design is destined, as toplighting design shows, to be trial and error without basic component research. This indicates the need for component assessment tools for daylighting research.

IRRADIANCE TYPE	VISIBLE LIGHT		THERMAL (NON-VISIBLE SPECTRUM)
DAYLIGHTING GOAL	QUANTITY	QUALITY	SEASONAL NEUTRALITY
CONTROL FUNCTION	SIZE	ORIENTATION	GAIN/LOSS FOLLOWS VISIBLE (ADMITTANCE)
OPENING FUNCTION	TRANSMITTANCE	SKY SELECTIVITY	THERMAL GAIN OR LOSS
OBSTRUCTION FUNCTION	REDIRECTION (REFLECTION & SHADING)		ABSORPTION (CONDUCTION, CONVECTION & RE-RADIATION)

Figure 2.23: Performance Chart for Daylighting Control Components

2.7 Daylighting Performance Characterization by Computer Simulation

'Simulation research involves controlled replication of real-world contexts or events for the purpose of studying dynamic interactions within that setting' (Groat & Wang, 2002,). Traditionally, visible light simulation has been done with analog model, full scale being the most accurate (Hu, 2003; Love, 1990; Place, Howard & Howard, 1992). Physical model testing techniques have been evaluated by Littlefair (1992), Navvab (1996) and Spitzglas, Navvab, Kim and Selkowitz (1985). Physical models are effective tools for studying sunlight because the behavior of solar energy scales perfectly and is not changed by the replicated environment of a model.

Analog models are limited in their outputs by placement problems and/or number of photosensors required. In terms of placement, photosensors though small do not scale with the model, which causes problems with narrow and/or angular spaces. Photosensors may be placed in space, but they cast shadows that may interfere with other readings depending on the scale of the test bed. Consequently certain forms of output cannot be obtained through analog models, which may be an underlying reason why daylighting is not evaluated like other building products, i.e. luminaires. Physical model validity can be threatened by imperfect placement of photosensors where slight errors, such as being out of level, can be magnified in outputs (Hayman, 2003).

Computer simulation programs are effective tactical tools to understand solar performance (Hu, 2003). Thermal performance has traditionally been tested with computer simulation (Love, 1990). The particular strength of computer simulations is the consistency of the data sets produced. Their limitation is the accuracy of the mathematical models used to represent real world conditions. 'The computer's ability to substitute a computed simulation for one requiring physical mockups … must be regarded as a potentially foundational shift in simulation research all together' (Groat & Wang, 2002). The specialized programs that are enabling this shift will eventually converge with computer drafting and other forms of representation that have occurred in architectural practice. Several reasons for the increased utilization of computer simulation are as follows:

- High degree of accuracy validated in case studies.
- Economy, speed and flexibility exceed that of physical modeling.
- Programs are available to characterize both visible light and thermal performance of lighting components and systems.
- Specialized programs may be integrated to evaluate whole building performance.
- Computational speed and performance is continually increasing.
- Standardized transfer methods for data produced.

2.7.1 Light Simulation Software

Radiance is a light visualization and measurement tool created by Lawrence Berkeley Laboratories. Radiance is…'a physically-based rendering system tailored to the demands of lighting design and architecture. The (Radiance) simulation uses a light-backwards ray-tracing method with extensions to efficiently solve the rendering equation under most conditions. This includes specular, diffuse and directional-diffuse reflection and transmission in any combination to any level in any environment, including complicated, curved geometries. The simulation blends deterministic and stochastic ray-tracing techniques to achieve the best balance between speed and accuracy in its local and global illumination methods' (Gregory, 1994). Radiance is widely used and validated by research groups around the world for daylighting visualization, analysis and research.

A major disadvantage of tracing the light rays backwards is the results are only valid for one eye point. To visualize from another point of view, the whole calculation has to be performed again. The advantage is that the number of rays that are not relevant is limited and visualizations can be produced with a high quality (Baker, Fanchiotti & Steemers, Eds., 1993).

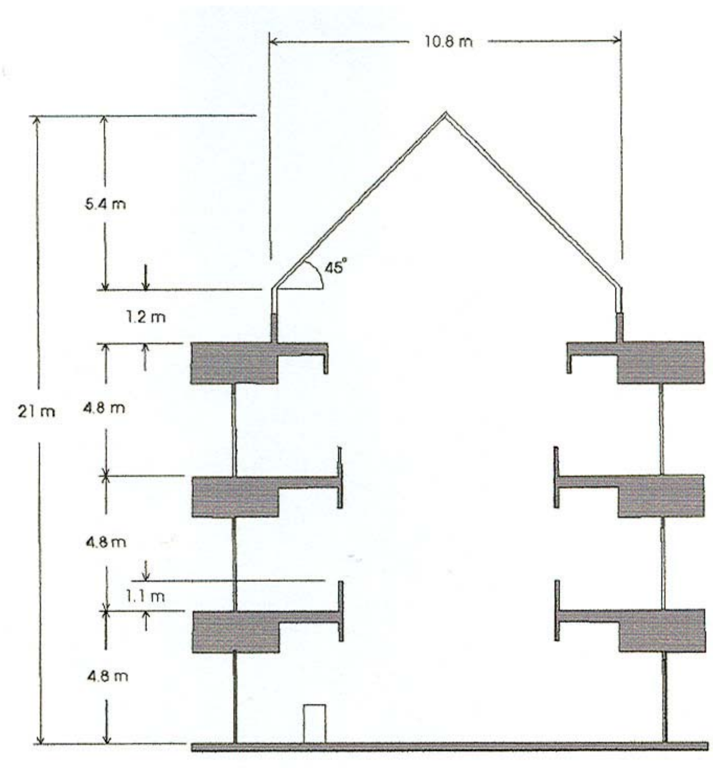

Figure 2.24: Atrium Section (Galasui & Atif, 1998)

'The accuracy of the Superlite and Radiance programs in simulating daylight levels was evaluated based on comparison between the predicted and the on-site measured illuminance' in a real building (Galasui & Atif, 1998). The study was based on a three story atrium space located in Ottawa, Canada (Figure 2.24). The space was complex, including three different types of glazing on the skylight. The study also tested the ability to predict electric lighting savings through daylighting performance. The testing methodology called for photosensors to be located on all floors of the atrium. Simulations and real building tests were made over one week periods around December 21st, March/September 21st and June 21st under different sky conditions. These measurements were used to forecast annual performance.

'The comparison between the measured and the Radiance computed data showed that, for any particular sky condition, the computer model has the potential to accurately model the daylighting performance of a space if relevant input data, such as precise space geometry, construction materials properties and actual sky condition are available' (Galasui & Atif, 1998). Galasui & Atif (1998) found values for 'instantaneous simulated illuminance' of direct sunlight were as much as 100% from measured values. Some variability was attributed to real world issues that couldn't be simulated, such as snow and frost that covered the skylight in winter. However, diffuse daylight was simulated more accurately than direct sunlight with less than 20% instantaneous discrepancy.

2.7.2 Thermal Simulation Software

A survey of digital solar analysis tools, and discussion with Dr. Malkowi at the Building Simulation Group at the University of Pennsylvania revealed several tools that may have applicability to solar thermal research. However, the applicability of many digital tools is limited to a particular design purpose. The spread sheet based programs which use static data to calculate changing configurations are a group that are generally not useful research tools. Computational fluid dynamic (CFD) tools, such as FLOVENT, account very well thermal flows, but do not integrate with typical lighting programs.

ECOTECH has excellent graphic outputs; can interface with Desktop Radiance; and 'over any specified period, can be used to assess the performance of any complex devices. With scripting, even dynamic shading systems can be accurately assessed. Sun path diagrams, shading mask, and solar stress analysis can be carried out for any window or surface in the world. From these diagrams daylight factors, sky factors, vertical sky components (VSC) and partial sky percentages can be instantly derived,' (http://www.squ1.com/site.html). The thermal data may be collected on a visualizing plane. An image from their web site provides a visual example of shading analysis (Figure 2.25).

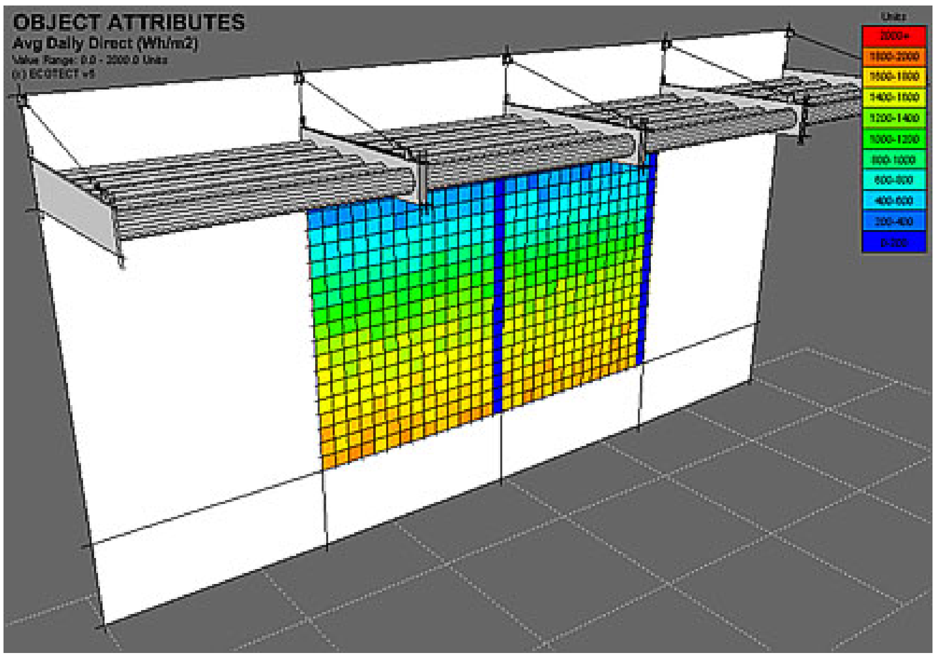

Figure 2.25: Solar Thermal Shading

(http://www.squ1.com/site.html

Limitations may include the simplified calculation method, the interface with Radiance; the programs ability to produce numeric as well as visual information; the need to draw within ECOTECH which prevent files from being easily exported to AutoCad; and validation information has not been found. The strengths of ECOTECH are the ability to evaluate complex forms; quality of graphic outputs including annualized performance representations; and an active development program.

TracePro, which is a forward ray-tracing optical design program, provides radiometric data from the ray-trace analysis. The reflectance and absorption is calculated in watt/meter^2 for each surface in the ray-trace. All ray-trace programs calculate absorption, reflectance and transmission on surfaces in the simulation. Trace-Pro differs from most by keeping track of the energy side of the equation, as well as the light.

2.8 Summary of Literature Review Findings

The literature review has revealed four issues the proposed research will focus on. They are as follows:

- The need for improved daylighting performance characterization methodologies.
- The need for basic research that can be useful to daylighting designers.
- The need for daylighting load management technology.
- The potential for computer simulation as a daylighting research and performance characterization tool.

The scope of these findings suggests the basic approaches in daylighting research need to be re-conceptualized. Daylight performance indicators do not account for significant aspects of visible light and thermal performance, which indicates the need for improved daylighting assessment methodologies. Comprehensive performance characterization protocols exist for luminaires and glazing elements, and they may be adapted for daylighting performance characterization. Photometric assessment may allow daylighting components and systems to be integrated as standard building products rather than specialty products.

In addition, little has been done by daylighting researchers regarding load management control of visible light and thermal characteristics of toplighting systems. Improved load management control techniques are needed to expand the use of daylighting in building. Daylighting load management control will lead to predicted performance which will permit designers to specify daylighting systems on the basis of proven performance, as they currently specify other building products. An increased use of daylighting in buildings will lead to improvements in human health and well-being, and environmental gains related to energy savings.

The literature review also indicates there is little research on the relative performance of daylighting components. Selkowitz (1998) indicated 'the first challenge is to define performance expectations for daylighting.' Application research tends to be setting specific, and cannot be easily applied to other settings. This indicates a need for component rather than system research. Daylight control components are well located for basic research, because of the principle of superimposition: modifications of light and thermal energy by each layer of the systems are cumulative. Thus, if the control component distributes light in a less than useful way, the next component can redirect it just as 'barn doors' or fresnel lens are used to redirect track lights. Thus, components may be successfully configured into systems for various settings.

Existing computer simulation technology is capable of accurate visible light and solar-thermal simulation. Hayman (2003), who discussed the potential for measurement error in attempts at absolute accuracy under variable natural daylight conditions, suggests the validity of accuracy as a measure of internal relativity. Computer simulation provides this type of accuracy. Computer simulation also provides the ability to collect, store and analyze large amounts of data. Current daylighting indicators typically simplify the daylighting problem to take an instantaneous measurement rather than making comprehensive evaluation over time. 'Simplifications', which often go hand in hand with compromising the predictive accuracy of the data, have historically been necessary in daylighting research. A computer based characterization methodology may be performed without limitations to the quantity of data. However, integrated procedures for comprehensive daylighting performance evaluation by computer simulation do not exist.

3.0 CONCEPTUAL FRAMEWORK AND RESEARCH QUESTIONS

3.1 Introduction

Basic research into daylighting characterization tools is needed as evidenced by the literature review. 'These tools would include methods of measurement of properties of phenomena, techniques for selection and allocation of cases, techniques for manipulation and control of variables, and techniques for aggregating and analyzing sets of empirical observations' (Brinberg & McGrath, 1985). The proposed characterization methodology proposes new 'methods of measurement of properties' of daylighting fixtures. This research seeks a balance, whereby daylighting science, analytic process, and available computational tools are brought together to create a simulation-based characterization methodology. Demonstrating the proposed methodology touches upon 'techniques for selection and allocation of cases' where the methodology might be applied, and 'techniques for aggregating and analyzing sets of empirical observations' that might be obtained through the methodology. Architectural daylighting is seen as both a strategy and technique to use a renewable energy source and improve the quality of the environment for human habitation. This research describes a daylighting characterization methodology to enable performance-based daylighting design, demonstrates the methodology with computer simulation, and evaluates the capabilities of the selected software to perform the characterization.

The goals of this research are:

1. To articulate a method of daylighting characterization that builds on existing photometric methodologies and expertise commonplace in the electric lighting design process.
2. To articulate the state of the art in terms of knowledge, techniques and software pertinent to the primary goal.
3. To identify research and development targets in terms of tools, techniques and software that could be pertinent to achieving a working example of the proposed method. Information processing pathways that represent potential working models of the method will be identified.

The critical aspect of these objectives is to find working procedures with the selected software programs to create I.E.S.N.A. standard file format for the electronic transfer of photometric data and related information with minimal post-processing.

3.2 Theoretical Perspective

The characterization methodology section defines photometric simulation protocols to characterize visible and thermal performance of daylighting fixtures. A daylighting fixture is defined to include the boundaries and all the components that exist between the admittance plane and acceptance plane of a daylighting aperture. This conceptualization, unlike a daylighting setting, which includes the daylighted space, permits the characterization data to be 'portable' and applied to daylighting fixtures in any setting. The theoretical basis is that the physical attributes of solar energy exist as electromagnetic radiation and can be quantified by objective measures to characterize aperture performance. Specifically, light is characterized by:

- *Color (Spectral Distribution)*
- *Intensity (Amount of flux per solid angle)*
- *Direction (Propagation in straight lines)* (Kraff)

Intensity and direction are fundamental to daylighting in architecture, and a primary focus of this research. Knowledge of the intensity and direction of light admitted by a daylighting fixture over the course of the day and year permit a daylighting designer to predict daylighting performance in a building. Spectral distribution is not a consideration of this research.

When considering daylighting fixtures for buildings, we must also consider thermal characterization. Thermal characteristics include:

- Transmission: Thermal energy admitted with the daylight as radiant energy gain/loss.
- Absorption: Thermal energy absorbed and, subsequently, convected and thermally

radiated by the daylighting system.

The demonstration section illustrates the assessment methodology by 'establish(ing) a cause-effect relationship' (Groat and Wang, 2002) between a treatment (independent variable) and an outcome (dependent variable) through the evaluation of measured results. The assessment demonstration will be conducted using computer simulations. Observations will be made of four daylighting programs, which will allow comparisons and evaluations of their ability to perform the assessment protocols.

The ontological basis for this work is there is an objective reality that is independent from the researcher. The epistemology is that the researcher can be independent and make observation of cause and effect relationships simulated by the computer software.

3.3 Research Questions

Research questions have been formed to address issues of the new methodology and the demonstration. The questions are as follows:

Characterization Methodology:

What photometric performance evaluation factors are applicable to daylighting apertures and how should they be applied?

Demonstration:

What computational methods exist to implement the proposed photometric characterization *protocols as applied to daylighting?*

What computational methods need to be developed to effectively implement the proposed protocols?

3.4 Conceptual Framework for the Characterization Methodology

'Lighting calculations are performed during the design process to obtain information about lighting system performance. A designer can use the results of calculations to choose between design alternatives or to refine a particular design. Lighting calculations are mathematical models of the complex physical processes that occur within a lighted space. Since these models can never be accurate in every detail, the computations are approximations of real situations' (IESNA Handbook, 2000).

Photometric tests to measure the light characteristics have been developed by the Illuminating Engineer Society of North America (IESNA) for luminaries, and by the National Fenestration Rating Council Incorporated (NFRC) for glazing elements. The proposed characterization methodology adapts these existing protocols to assess daylighting performance. Photometric tests are as follows:

Visible Light (Based of IESNA Luminaire tests):

- Angular flux distribution: Flux in candela per solid angle emitted from the interior of the daylighting aperture.
- Room illuminance: Isocontour distribution of illuminance measured in lux on the

floor and walls of a 20’ x 40’ x10’ tall white room with 85% reflectance from a single daylighting fixture centered in the roof.

- Visual effect: The rendered appearance of a 20’ x 40’ x10’ tall white room with 85% reflectance with a single daylighting fixture centered in the roof.
- Visible light transmittance: Visible light transmittance equals the average illuminance admitted by the daylighting fixture divided by the illuminance arriving at the exterior of the daylighting fixture.

Thermal tests:

- Thermal energy transmittance: Average irradiance admitted by the daylighting fixture measured in W/m^2 divided by irradiance arriving at the exterior of the daylighting fixture measured in W/m^2.

3.5 Conceptual Framework for the Characterization Demonstration

A demonstration of the characterization methodology will be performed with four light simulation programs. Simulations will characterize the performance of a toplighting load management control. ‘Variable daylighting levels is a basic problem that needs to be solved to increase the utilization of daylighting techniques’, (Selkowitz, 1998). The Daylighting Input and Output Diagram illustrates the primary issue of load management control technology (Figure 3.1). The solar resource provides much more light than is required, and it is highly variable, both spatially and temporally. Conversely, the desired interior daylighting levels need spatial and temporal constancy. The control components mediate between the exterior and interior by managing quantity and quality of solar energy admitted. Research

’suggest(s) that properly controlled, movable, external shading (or movable insulation) would facilitate significant additional reductions in both energy consumption and energy costs.’ (Place, 1986). The performance of static and dynamic horizontal planar elements on vertical apertures (windows) has been extensively studied by European researchers (Baker, Fanchiotti & Steemers, Eds, 1993; Koster, 2004). Basic research assessment of planar control elements for roof apertures is not available to architects and engineers. The demonstration will have input from fixed solar positions. The independent variable will be the control and treatment, and the dependent variable will be the photometric measurements for the different tests.

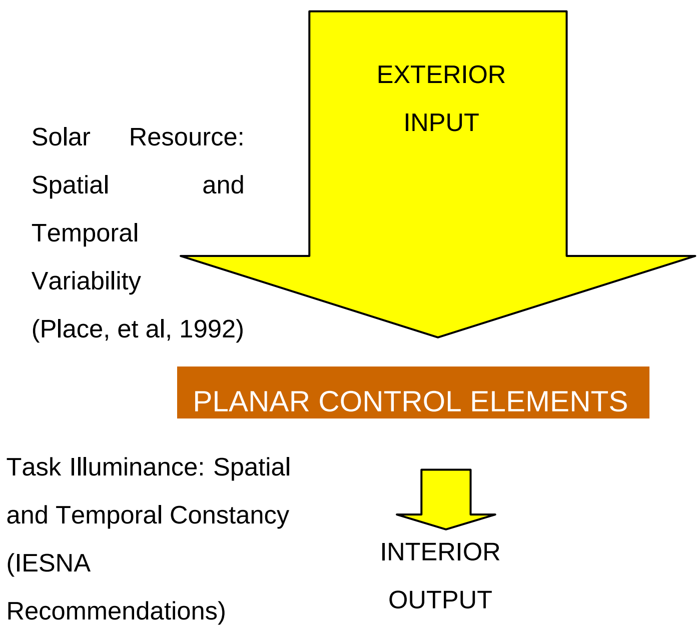

Figure 3.1: Daylighting Input and Output Diagram

Computer simulation is indicated by the complexity of the calculations. ‘The simplest lighting calculation methods can be performed by hand, whereas the more advanced methods can be performed only by using a computer. More advanced models generally provide more accurate information. Accuracy, for the purpose of this discussion, is defined as the degree to which the calculations agree with reality. In actuality, it is very difficult to achieve perfect agreement....' (IESNA Handbook, 2000). A comparison of lighting software capabilities will provide daylighting researchers information to make critical design choices when developing new daylighting software.

3.6 Definitions

Aperture: An opening to admit solar energy defined to be the vertical plane between the planes of solar obstruction created by the physical surround of the opening.

Candela: **cd** the SI unit of luminous intensity, equal to one lumen per steradian (lm/sr). (IESNA Handbook, 2000)

Daylighting fixture: The system of daylighting elements capable of modifying visible light and thermal energy admittance to an architectural space that is contained between the admittance and exit planes of an aperture. The admittance plane is the first plane of modification of light by the daylighting fixture, and the exit plane is where the light is the first plane where the light is no longer modified by the daylighting fixture.

Illuminance: Solar radiation in the visible region of the solar spectrum to which the human eye responds. (http://rredc.nrel.gov/solar/glossary/gloss_a.html)
The luminous flux incident on a surface divided by the area of surface being illuminated, expressed in lumens per square meter (lux) or lumens per square foot (footcandles). (DDN795D Class Notes, 2003).

Integrating Photometer: a photometer that enables geometrically total luminous flux to be determined by a single measurement. The usual type is the Ulbricht sphere with associated photometric equipment for the measuring the indirect illuminance of the inner surface of the sphere. (The measurement device is shielded from the source under measurement.) (IESNA Handbook, 2000)

Integrating Sphere: A hollow sphere coated internally with a white diffusing material and provided with openings for incident beam, specimen and detector used for measuring the diffuse reflectance or transmittance of objects (www.photonics.com).

Irradiance: The rate at which radiant energy arrives at a specific area of surface during a specific time interval. This is known as radiant flux density. A typical unit is W/m^2. (http://rredc.nrel.gov/solar/glossary/gloss_a.html)

Lumen (lm): The SI unit of luminous flux, equal to the luminous flux emitted per unit solid angle by a standard point source having a luminous intensity of 1 candela (www.photonics.com).

Lumen (or flux) method: A lighting design procedure used for predetermining the relation between the number and types of lamps or luminaires, the room characteristics, and the average illuminance on the workplane. It takes into account both direct and reflected flux

Luminance*:* (in a direct and at a point of a real or imaginary surface) the quotient of the luminous flux at an element of the surface surrounding the point, and propagated in directions defined by an elementary cone containing the given direction, by the product of the solid angle of the cone and the surface on the plane perpendicular to the given direction. (IESNA Handbook, 2000)

Luminous flux: Φ radiant flux (radiant power); the time rate of flow of radiant energy, evaluated in terms of a standardized visual response: where

Φ_v = lumens

Φe, λ = watts per nanometer

λ = nanometers

$V(\lambda)$ = the spectral luminous efficiency

K_m = the maximum spectral luminous efficacy in lumens per watt

Unless otherwise indicated, the luminous flux is defined for photopic vision. For scotopic vision, the corresponding spectral luminous efficiency $V(\lambda)$ and the corresponding maximum spectral luminous efficacy K_m are substituted in the above equation. K_m and K'_m are derived from the basic SI definition of luminous intensity and have the values 683 lm/W and 1754 lm/W, respectively. (IESNA Handbook, 2000)

Luminous intensity: $I = d\Phi/d\omega$ (of a point source of light in a given direction) the luminous flux per unit solid angle in the direction in question. Hence, it is the luminous flux on a small surface centered on and normal to that direction divided by the solid angle (in steradians) that the surface subtends at the source. Luminous intensity can be expressed in candelas or in lumens per steradian (lm/sr).

Lux: **lux, lx** the SI unit of illuminance. One lux is one lumen per square meter (lm/m^2). See the Appendix for conversion values.

Luminance: $L = d^2\varphi/(d\omega\ dA \cos\theta)$ (in a direction and at a point of a real or imaginary surface) the quotient of the luminous flux at an element of the surface surrounding the point, and propagated in directions defined by an elementary cone containing the given direction, by the product of the solid angle of the cone and the area of the orthogonal projection of the element of the surface on a plane perpendicular to the given direction. The luminous flux can be leaving, passing through, and/or arriving at the surface. (IESNA Handbook, 2000)

Luminaire (light fixture): A complete lighting unit consisting of a lamp or lamps and ballast(s) (when applicable) together with the parts designed to distribute the light, to position and protect the lamps, and to connect the lamps to the power supply. (IESNA Handbook, 2000)

Normal Incident Radiation: Radiation striking a surface that is facing the sun. Mathematically, the word *normal* is the vector (direction) that is perpendicular to a surface, and the direction of a *normal radiation* source is perpendicular to a radiation source. Global (total) normal solar irradiance is all radiation that strikes a flat surface that faces the sun, while direct normal solar irradiance excludes all radiation that does not come from the direction of the sun in the sky. (http://rredc.nrel.gov/solar/glossary/gloss_a.html)

Steradian, sr *(unit of solid angle):* The solid angle subtended at the center of a sphere by an area on the surface of the sphere equal to the square of the sphere radius**.** (IESNA, Handbook, 2000)

Transmittance: A measure of the ability of an aperture to accept or reject solar energy determined by the percentage of daylight that passes through compared to the radiant energy incident upon the exterior face. *Static transmittance* is when the transmittance characteristic of one or more glazing layers is a constant factor regardless of the level of daylight being received. *Dynamic transmittance* is when the transmittance characteristic of one or more glazing layers and/or control devices can be varied in response to the daylight being received.

Visible Light: Radiant energy that is capable of exciting the retina and producing a visual sensation. A quantity of light is expressed in units of Talbots (Lumen-seconds). (DDN795D Class Notes, 2003)

4.0 DAYLIGHTING PHOTOMETRIC CHARACTERIZATION METHODOLOGY

4.1 Introduction

> *'Progress in a branch of science or engineering is very much dependent on the ability to measure the associated quantities. Lord Kelvin (1824-1907) expressed this most bluntly: When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meager*

> *and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be'.* (IESNA Handbook, 9th edition)

The intention of the methodology is to provide a measured characterization of architectural daylighting performance that will enable and enhance architectural daylighting application development. The proposed daylighting photometric characterization methodology is an outgrowth of the literature review. Daylighting does not have 'a particular procedure or set of procedures' to generate research in a form that would be useful to designers (Love, 1990).

An analogy was drawn between the useful metrics that lighting and glazing manufacturers have been providing to designers for decades, and the information needs of daylighting designers. The proposed daylighting characterization methodology is the outcome of critical research into that analogy. The proposed protocols do not introduce new tests, but focus on established procedures of inquiry, which are modified and appropriately structured to provide a comprehensive characterization of daylight. The characterization is designed to be performed with computer simulation. The intention is to use existing daylighting analysis software for all test procedures. The software selection criteria are described in this section, and an analysis of the programs is provided in the demonstration section.

4.2 Photometric Daylighting Characterization

The standardized characterizations of luminaires and glazing, unlike daylighting indicators, address performance characteristics where the light is produced or modified rather than when it arrives at a task surface. This is a conceptualization that allows performance comparisons between luminaire systems or glazing components independent of location and physical setting. Designers can select luminaires and glazing, based upon these characterizations, which allow performance to be predicted in any location or physical setting. As detailed in the literature review, this cannot happen with the daylighting performance indicators and research methodologies that are currently available.

Daylighting characterization methodologies must respond to spatial and temporal variability of the resource. This requires inputs from numerous solar positions and sky conditions. However, it is not necessary to include all possible tests in a given characterization. For example, luminaire testing protocols do not test all characteristics of visible light. Color spectrum, which is primarily a function of the lamp, is not tested specifically for luminaires. It is also unnecessary to test spectral distribution in the proposed daylighting. In addition, thermal performance is not directly tested in luminaire protocols, whereas, it is important in the characterization of daylighting apertures. Photometric characterization protocols can be designed to produce more relevant daylighting characterization data than is generally available to designers.

Four procedures have been developed to characterize visible light and one procedure will characterize thermal performance. These testing procedures have been selected because they provide a comprehensive evaluation of daylighting aperture performance. Measured performance characteristics include:

- Photometric Measurements (Luminance and Illuminance)

    - Angular Flux Distribution (candela distribution)
    - Illuminance Distribution (lux)
    - Visible Light Transmission (%)
- Visual Representation of Light (Rendering)
- Radiometric Measurement (Thermal Absorption and Transmittance (W/m^2))

The photometric analysis of angular flux distribution is the most important component of the proposed characterizations, because it describes the three-dimensional distribution of luminous intensity from a daylighting fixture. The luminous intensity distribution is derived from illuminance (lux) arriving at photosensors distributed on the surface of a goniophotometer. The illuminance readings are then converted to candela to create a candela distribution. This distribution of luminous intensity is normalized to a unit sphere in terms of flux per solid angle. Luminous intensity is, thus, independent of the setting, and may be converted by designers to illuminance at any distance from an identical light source. The protocol for these tests has been adapted from the IESNA standards for far-field luminaire photometrics, and photometric analysis of toplighting fixture by Heschong Mahone Group as described previously in the literature review. An IESNA electronic format transfer file prepared by Heschong Mahone Group may be found in Appendix Two (Howlett, et al, 2004). The other protocols are based upon IESNA and NFRC standardized measurements and their representation, also as described in the literature review.

4.2.1 Solar Parameters

Characteristics of the solar positions and solar sources to be used in the photometric and thermal tests are as follows:

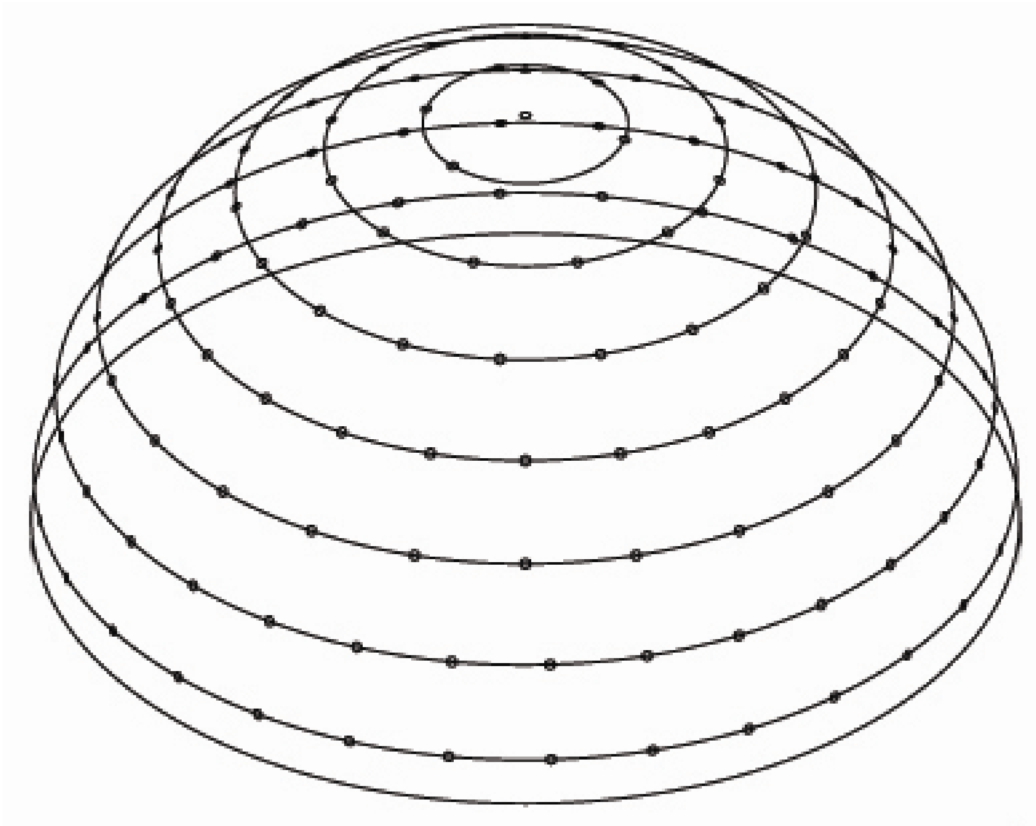

Figure 4.1: Simulated Solar Positions on Sky Dome Diagram

4.2.1.1 Solar Positions

There are 145 solar positions to be tested. They are distributed on a hemispherical sky dome (Figure 4.1). A small-circle geometry pattern has been determined to represent a good distribution of measurement points on the sky dome (Tregenza, et al, 1994). The polar plan pattern of points and the geometric pattern of points on the hemisphere were illustrated respectively in Figures 2.16 and 2.17. The photometric characterization methodolgy requires testing clear sky conditions with the sun in all 145 positions. This geometry has a uniformity of spacing in elevation, and a very high approximation to uniformity in spacing around the small circles. The separation of sampling positions is on the order of, or less than, one hour of solar time, which assures accurate interpolations. It is possible to create small-circle geometries with more sampling positions, but it was determined to be unnecessary given the general reliance in daylighting research on Tregenza's geometry. The correlation of local time and solar time is not required. Time is implicit in solar position and doesn't have to be mathematically determined by location (longitude) (Howlett, et al, 2004).

4.2.1.2 Solar Resource

The C.I.E. (Commission Internationale de l'Eclairage) has developed standard sky models for different sky conditions at different times of day and the year. They are based upon measurements of the entire sky dome done over a period of time (Hayman, 2003). C.I.E. calculations for clear sky may be found in Appendix One. The initial data set should include clear and overcast skies, which represent the widest range of conditions. CIE Standard Overcast Sky is defined to have azimuthally uniform luminance and a steep luminance gradation in elevation, with the zenith being much three times brighter than the horizon (www.AGI32/Help). Clear sky conditions are defined by solar position and the calculated distribution of luminance across the sky dome, see Appendix One for CIE clear and overcast sky calculations. The proposed characterization requires testing clear sky conditions with the sun in all 145 sky dome positions.

4.2.2 Angular distribution or flux per solid angle

4.2.2.1 Setting

The setting is a simulated goniophotometer, which is in the form of a hemisphere with a diameter is no less than five times the diagonal of the aperture being tested (Figure 4.2). Conceptually, the goniophotometer has photometers floating in infinite black space. In those programs where photometers have to be associated with surfaces, the interior surface of the goniophotometer is flat black with 100% absorption. The surface of the hemisphere is divided by 22 ½ degree azimuthal intervals as measured from the designated zero on the symmetry axis of the daylighting fixture. The surface of the hemisphere is divided by elevation positions that begin with zero being down on the major axis of the hemisphere, and proceed; 0^0, 5^0, 15^0, 25^0, 35^0, 45^0, 55^0, 65^0, 75^0, 85^0, 90^0. These azimuth and elevation angles match those used by Heschong Mahone Group (Howlett, et al, 2002), and will augment the database they have begun. Photometers directed toward the center of the hemisphere are located at each intersection. The IESNA file has 176 data points. However, it is one of the idiosyncrasies of the IESNA file format that the 0^0 elevation data point is recorded sixteen times, corresponding to the sixteen azimuthal directions. Therefore, there are 161 independent measurements. The center point of the aperture is at the spherical center of the hemisphere. The great circle of the goniophotometer hemisphere is coplanar with is the aperture plane.

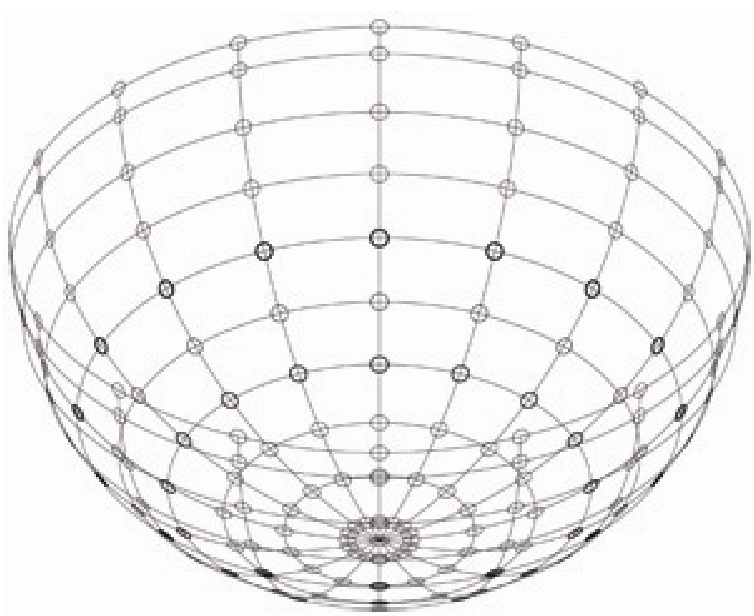

Figure 4.2: Simulated Goniophotometer

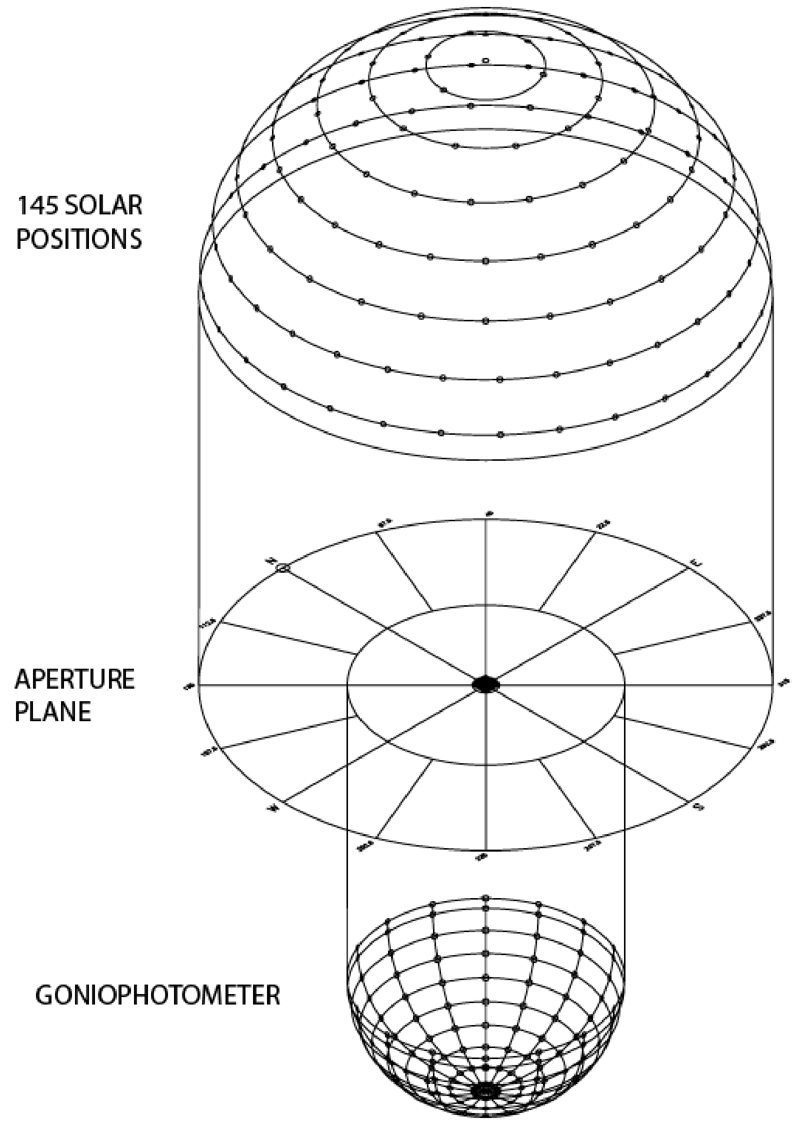

Figure 4.3: Simulated Photometric Testing Assembly

4.2.2.2 Data Collection

The sky positions, a virtual aperture plane and the goniphotometer are brought together as a simulated photometric testing assembly (Figure 4.3). An IESNA file is created for each solar position by measuring the corresponding illuminance (lux) at each photosensor and converting into candela (lm/sr) by the following two step calculation:

Total radiant flux = illuminance (lux) times the area of the measurement sphere.

Candela = total radiant flux divided 4 π stredians

The setting description and candela values for each point are recorded in the IESNA electronic transfer file format. A space delimited EXCEL file may be used to record the dat and produce the electronic .TXT file.

This protocol cannot be used to report beam sunlight. The intensity distribution calculation assumes a luminous point source at the center of the goniophotometer. Reflected and inter-reflected daylight on the diffuse and/or diffusing surface of a daylighting system or component may be considered a luminous or near luminous source at the point it is admitted into the building, i.e. the center of the goniophotometer. If the photosensor(s) see beam sunlight through the daylighting aperture, the candela conversion will be inaccurate, because the luminous source, the sun, is vastly more distant than the radius of the sphere. Thus, apertures that admit beam sunlight cannot be fully evaluated for luminous intensity distribution. They may, however, be evaluated for all positions that do not admit beam sunlight.

4.2.2.3 Angular Flux Data Application

Files in the IESNA format may be imported into various lighting design programs where it can be used to simulate all the effects available through the particular program. These typically include photorealistic renderings, false color rendering and isocontour renderings. The data may be used to produce any numeric report except daylight factor that the software may produce.

4.2.2.4 Angular Flux Data Interpolation

Photometric testing of luminaires is setting neutral, and effectively orientation neutral. Luminaires are tested in the designed installation position, which allows the candela distribution data to be rotated for any installation setting. Similarly, photometric testing of daylighting at the point it is admitted into the space is setting and orientation neutral. In this characterization the candela data is linked to both the orientation of the aperture and the solar positions. Daylighting apertures are receptors of light rather than producers of light, and the shape of the aperture and/or shading devices associated with the daylighting system may function differently depending on the position of the sun. In the case of roof apertures, the intensity distribution and sky positions may be rotated to conform to any azimuthal installation position of the aperture. This is useful, because the solar positions, which are now points corresponding to the rotated intensity plots, may be used to determine intensity distributions for any location or orientation by overlaying a solar path diagram for the location in question (Figure 4.4). Solar paths are know for all location and all times of year. Solar path locations register though the intersecting solar 'positions' with their corresponding intensity distribution.

The steps of this interpolation for roof apertures are as follows:

1. Perform angular flux protocol for all sky dome positions. Each sky dome position has a corresponding IESNA file.
2. Rotate the sky dome positions and the corresponding IESNA files to the azimuthal orientation of the aperture installation.
3. Overlay rotated data set with solar path diagram for the locations in question (Figure 4.5).

4. Select time of day and time of year on the solar path diagram. The corresponding sky dome position is linked to the IESNA luminous intensity distribution for that time of day and year, and orientation and location.

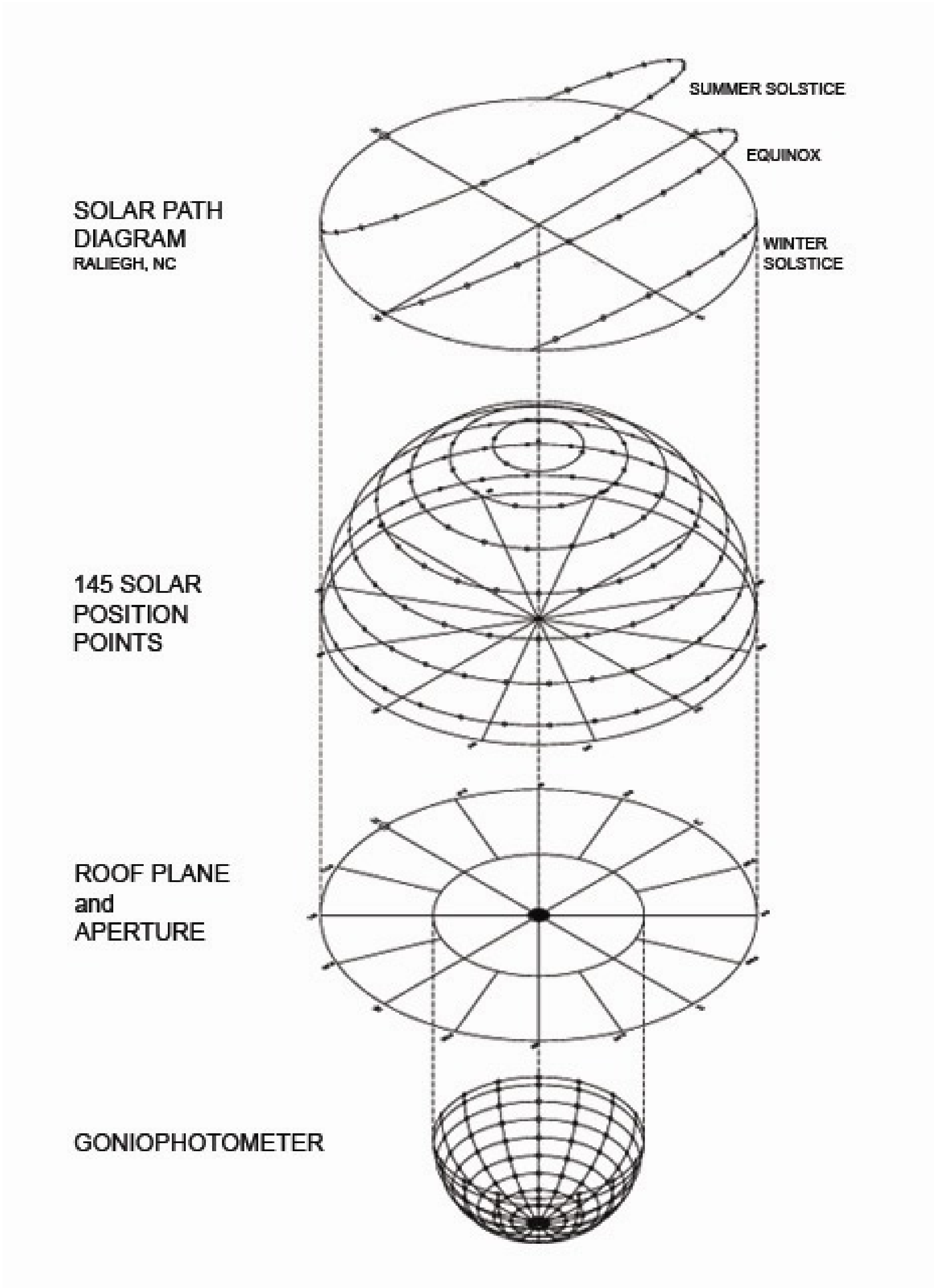

Figure 4.4: Simulated Test Assembly with Solar Path Overlay

When data for a particular orientation has been obtained the illuminance readings for the 4’ x 4’ aperture may be interpolated through the principle of superposition to account for patterns of multiple apertures and/or different aperture configurations.

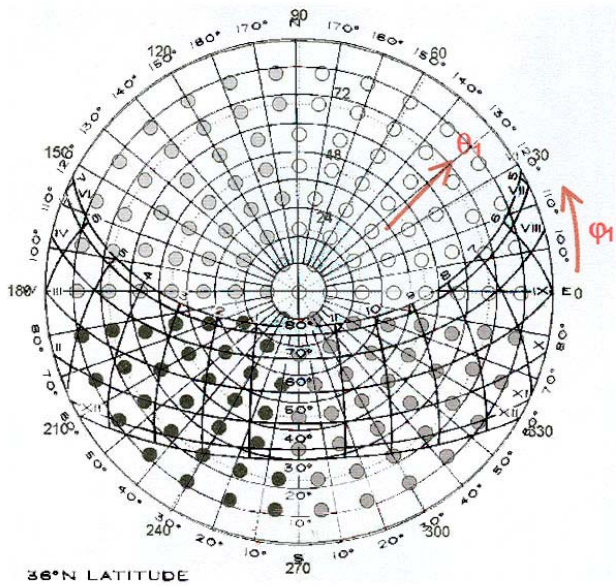

Figure 4.5: Solar position data with solar path overlay.

4.2.3 Illuminance Distribution

The room illuminance test measures illuminance (lux) distributed to all surfaces in a virtual room. Photosensors are located on a 12” x 12” grid, normal (perpendicular) to all surfaces to produce point illuminance readings.

4.2.3.1 Setting

The setting is a room 10’ tall by 20’ wide by 40’ long. The long dimension of the room is located on a north-south axis. The aperture is located in the center of the roof. The surfaces of the room are all 85% reflective. Illuminance distribution includes light reflected within the virtual room. The setting is idealized, not having furniture or other light modifying elements. The floor is also more reflective than a typical room.

4.2.3.2 Illuminance Data Presentation

Illuminance data may be presented as values corresponding to the grid points in a report or in the room. It may also be presented with isocontours, which represent illuminance ranges, in axonometric or perspective from within the room. Figure 4.6 illustrates illuminance isocontours with visual effect.

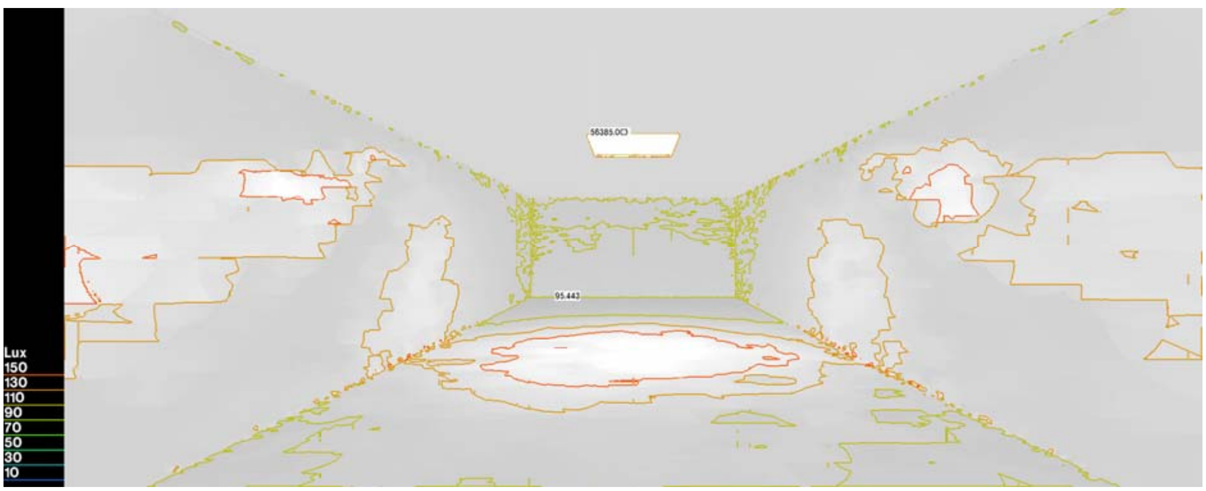

Figure 4.6: Illuminance Isocontours with Visual Effect

Figure 4.7: Visual Effect

4.2.4 Visual Effect:

Visual effect renders the pattern of daylight arriving in the test typical room. The virtual room from the room illuminance test is used for this test (Figure 4.7). Visual effect may also be presented in false color or gray scale. The goal is to provide a hierarchy of information about the data. If the visual effect seems desirable, a daylighting designer might evaluate the associated data. The visual effect may be a representation of the IESNA photometric file or a daylighting simulation.

4.2.5 Visible Light Transmittance

The room described above is the setting for the visible light transmittance calculation. Visible light transmittance is the percentage of visible light passing through the daylighting aperture, component or system. It is the average interior illuminance at the photosensors, divided by the illuminance arriving at the exterior. The exterior sensor is located adjacent to the aperture and normal to the aperture plane. The interior illuminace values are from a 12" x 12" grid located 30 inches above the floor. The sensors are normal to the grid, which represnts a work surface.

4.2.6 Solar Energy Transmittance

Solar energy transmittance is the percentage of total solar irradiance arriving to the interior at the admittance plane of the aperture divided by the total solar irradiance arriving at the acceptance plane of the aperture. The light simulation programs being evaluated for this research are currently unable to make this calculation. It is anticipated that thermal transmission will be extrapolated from solar absorption data provided by TracePro in the demonstration section. Solar transmittance measurements will be taken for all treatments corresponding to all sky dome positions.

4.3 Lighting Simulation Programs

The characterization protocols have been developed to be implemented with computer simulation program. 'The radiative transfer equation can be solved using finite element (radiosity) methods, ray tracing techniques (forward, backward and Monte Carlo), and hybrid approaches. These approaches are collectively referred to as global illumination algorithms by the computer graphics community. Unlike simpler computer graphics techniques, global illumination algorithms are based on physical principles. Because they model the physical behavior of light, they can be used in lighting simulation software programs to create photorealistic architectural renderings and perform sophisticated illumination engineering calculations' (IESNA Handbook, 9th ed.). The intention is to use daylighting simulation programs in all the protocols described above. However, a review of program capabilities revealed that no available program could perform all the requirements of the characterization methodology without modification. It was, therefore, determined to compare program capabilities to implement the characterization methodology. Lighting simulation programs using a variety of ray-trace techniques were selected for the demonstration. They are Desktop Radiance, AGI32, Lumen Designer and TracePro. Further detail on particular programs is provided in the demonstration section.

Thermal characterization is generally not generally available as an output in radiant transfer programs. Photometric evaluation of thermal energy relies on the ability to calculate absorption of solar flux (W/m^2). Ray-tracing lighting simulation programs follow the path of light, and calculate presumably absorption, reflection, and transmission on a point-by-point basis when the light strikes an object. Some light analysis programs, such as TracePro, track absorption computations and provide reports for 'real' and measuring surfaces in the simulation. This computation does not address thermal effects of absorption in terms of convection, conduction, and radiation, however, it provides more information than is generally available to daylighting designers.

Computer simulation was also chosen for the following practical research concerns:

- *Too complex to do by hand:* The knowledge scientific knowledge of light has existed, but the calculations to make an accurate daylighting representation were too complex without computer simulation.
- *To expensive to do with physical models:* To construct the proposed treatments as physical models, which could give accurate results, would be very expensive and time consuming.
- *Computer technology:* Increased speed of desktop computers allow them to run programs with extensive calculations and graphic output..
- *Software developments:* Software is available and constantly improving, making this methodology increasingly viable.

Computer simulation is particularly suited for component performance evaluation for the following reasons:

- Permits abstract setting.
- Allows complex models and material definition.

- Can measure visible light and thermal performance.
- Provides light contours, false color and point measurements.
- Not limited in location and number of points.
- Independent validations have been performed

4.3.1 Software Selection

Computer modeling of visible light performance will be simulated with Radiance, AGI32, Lumen Designer and TracePro. Thermal performance will be simulated with TracePro, as it is the only program selected that outputs absorption calculations. These programs were selected because they presented a range of capabilities to implement the characterization methodology.

The ability to simulate daylighting performance and to report the data in electronic format I.E.S. files were the driving issues. I.E.S. files are a crucial building block and lighting information transfer tool, and a pervasive format required to consider light in many software programs. Creating and exporting I.E.S. files from a daylighting source is the essence of the software problem. Daylighting simulation is based upon C.I.E. computational models, which are the agreed standard for sky characterization. They include the C.I.E. standard clear, intermediate and overcast skies per Technical Report CIE 110-1994, *Spatial Distribution of Daylight-Luminance Distributions of Various Reference Skies* (see Appendix One).

Four programs were selected to implement the characterization methodology. They are Desktop Radiance, AGI32, Lumen Designer, and TracePro. Although all are ray tracing or hybrid programs, the goals and method of calculations differ. The first three have daylighting calculation capabilities based upon the C.I.E. formulae. Radiance is a reverse ray-tracing program, and AGI32 and Lumen Designer are hybrid programs, which means they have backward and forward ray-tracing capabilities. TracePro has Monte Carlo ray-tracing. It is intended for optical designers rather than architects, and does not have a sky calculation. However, it has the ability to represent luminous surfaces. TracePro was selected for the range of outputs not available in traditional daylighting programs. Detailed descriptions of the calculation concepts and methods of these programs is provided in Appendix

They were also selected for economy and availability. Radiance is a free resource on line from Lawrence Berkeley Laboratories . AGI32 provided an educational copy at no cost, and Lumen Designer provided an educational copy at low cost. TracePro provided a research copy of their expert version in support of this research. The first three programs are designed for architects, and, therefore, easily implemented in an office. TracePro is an optical design program, so it incorporates many analytic features that are outside architecture. Specifically it does not include a sky source, however, it is superior to the architectural lighting programs in tracking and reporting capabilities.

4.3.2 General Requirements for Light Simulation Software

This section enumerates requirements perceived to be useful in light simulation software to implement the proposed characterization methodology. The list represents criteria that will used to evaluate each of the selected software.

4.3.2.1 Validation

Validation by comparison of computer simulation of daylight with actual daylight in a physical setting or model is desired. The BRE-IDMP Validation Dataset, which includes 'sky luminance measured at 145 'patches'; direct normal illuminance; internal illuminance measured at six points an office with various glazing systems; vertical N, E, S & W illuminance, temperature, humidity, etc.' is considered the 'gold standard' (www.iesd.dmu.ac.uk/jm/pdfs/BRE-IDMP.pdf). C.I.E also developed a CIE 171-2006 test suite for validation, which is being implemented by a selected software.

4.3.2.2 I.E.S. File Format Inputs

'Photometric files are datasheets containing information on the measured photometric values associated with specific luminaires. Photometric files can be downloaded from most luminaire manufacturer's Internet web sites' (Lumen Designer/Help 2006). The IESNA Standard File Format for the Electronic Transfer of Photometric Data and Related Information', document LM-63_02 defines descriptive, geometric and photometric criteria for electronic files. Virtually all lighting fixtures are tested according to IESNA prescribed tests.

'It is important to realize that without luminaire photometric information, (light simulation programs) cannot perform any electric lighting computations. Therefore, photometric files are essentially the catalyst required to make the software function'! (AGI32/Help 2006).

4.3.2.3 Sky Distribution

The prescribed photometric characterization described in the previous chapter requires the ability to locate the sun by azimuth and elevation at 145 sky points (Tregenza) to create a uniform distribution of solar positions across the sky dome (Figures 2.14 & 2.15).

4.3.2.4 Modeling Optical Elements

Modeling programs define complex forms through surface, geometry, and spatial orientation. A goal of this research is compatibility with AutoCad, an architectural representation program which is considered a 'standard' in the field. The ability to import and manipulate files from AutoCad is seen as a general requirement in software selection.

4.3.2.5 Material Properties

Surface material properties including color, texture, reflectance, and transmission should be available in the program database, and the program should allow new materials with surface properties created by the user. TracePro, which is a selected program, also has the ability to characterize luminous surfaces.

4.3.2.6 Goniophotometer

A simulated Goniophotometer uses photosensors placed in a hemispheric array to measure illuminance. The lighting program must have the capability to locate the sensors on the surface or in space at exact azimuth and elevation in relationship to the aperture, and have the capability to focus them at the center of the aperture.

4.3.2.7 Thermal Energy Characterization

Certain programs have the ability to measure transmitted irradiance (w/m^2) on surfaces that are otherwise invisible in the simulation. These surfaces can be located at the admittance and exit planes of the daylighting aperture to measure irradiance and calculate solar transmittance. A less accurate alternative is to measure irradiance through absorption. Approximately half the thermal energy in daylight is in the visible spectrum. At each bounce of a ray trace a portion of the daylight is absorbed and a portion reflected. A portion will also be transmitted if the material is translucent or transparent. Absorption is part of the ray trace calculation and could provide useful thermal data, however, numeric outputs for absorption are not available in all daylighting software.

4.3.2.8 Numeric Outputs:

The principle issues are the availability of data, range of data, and methods of output. The intention is to have as much of the desired data as possible produced by the software program made available for processing and post-processing by the researcher. Processing is traditional evaluation of data reports from the software in an appropriate format. Post-processing is the ability to covert data, such as a .TXT file, into another useful form, such as import into EXCEL as a space delimited or comma delimited file which may be manipulated by that program.

4.3.2.9 I.E.S. File Format Outputs:

The primary goal of the characterization is to create I.E.S.N.A. standard file format for electronic transfer of photometric data and related information in accordance with LM-63-02. Angular flux files are lacking in daylighting research, and perceived to be a very important daylighting design tool. A further objective is to create these files with little post-processing of data obtained from the selected software programs.

4.3.2.10 Graphic Outputs:

Examples of graphic outputs are illuminance and luminance iso-contours, false color renderings, and (photorealistic) visual effect renderings. Graphic outputs indicate the pattern (quality) and relative value (quantity) of daylight distribution in a virtual setting. They are useful to designers as representations of daylighting performance, and efficient tools to transfer relative information. The intention is to produce those and to explore additional outputs that may be useful to daylighting designers.

4.3.2.11 Simulation Procedure

The simulation procedure for the angular flux characterization will be outlined for each lighting software demonstrated. The basic simulation procedure described in the characterization protocol is as follows:

1. Insert a Treatment in the roof plane aperture. Establish north. If the aperture is directional, the primary opening should face north.
2. Construct Goniophotometer with a radius five times the longest diagonal of the treatment being tested. Locate photosensors at 22.5 degrees of azimuth and at 0^0, 5^0, 15^0, 25^0, 35^0, 45^0, 55^0, 65^0, 75^0, 85^0, 90^0 in elevation.
3. Simulate sky conditions for 145 sun positions on the sky dome.
4. Collect illuminance data and convert to candela, and record in IESNA electronic data files for each sun position.

4.4 Selecting Angular Flux Distribution Files

The following steps permit the angular flux data to be determined for any location, orientation, time of day and time of year:

1. Rotate the simulation goniophotometer and sky dome to the orientation of the roof aperture being studied.
2. Overlay the Solar Path diagram for the location of interest on the simulation assembly.
3. Interpolate data from the nearest sky points for photometric performance at different times of the day and year.

4.4.1 Solar Path

The Solar Path for all locations is mathematically understood for all times of day and times of year in relationship to the latitude and longitude of the given location.

4.4.2 Location Neutral

Uniform distribution (Tregenza, et al,2000). of sun positions across the entire sky domes permits interpolation of data for any location.

4.4.3 Orientation Neutral

Rotate all elements of the assembly, except the Solar Path Diagram, to the orientation of the proposed building. Place the Solar Path Diagram in the north orientation, and the Sky Points intersected by the Solar Path will provide the correct data.

4.4.4 Setting Neutral

The 3-dimensional angular flux distribution of light where it is admitted through the aperture is measured before it arrives on any surfaces in a setting. It is therefore, setting neutral and may be imported to any setting with the same degree of accuracy.

4.5 Characterization Quality Considerations

The validity of this experiment will be planned at each step through the quality measures described below. They include *internal validity*, which is related to the truth value of the experimental results; *external validity*, which is related to generalizability and applicability of the results; *reliability*, which is related to the consistency of the results; and, *objectivity*, which is achieved by the neutrality of the observer (Guba, 1981).

4.5.1 Internal Validity

'Internal validity is logically determinable by demonstrating isomorphism or verisimilitude between the data of the inquiry and the phenomena those data represent' (Guba, 1981). The characterization is designed to measure solar illuminance in a computer simulated setting.

The principle threats to internal validity are the inputs and the computational simulation tools used for this research. The inputs, C.I.E. standard skies, are based on internationally accepted standards, and the software selected have been validated by several independent groups.

The simulated setting and treatments have been designed to measure a single variable, illuminance. Variables inherent in the treatment elements, including position and orientation will remain constant for each test.

4.5.2 External Validity

The external validity is related to the simulated setting and the solar positions tested. The external validity of Radiance has been validated by Atif, Love & Littlefair (1997). Their worked noted the greatest error in direct sunlight measurement. Beam sunlight presents several problems for this method. The primary problem, as with beam sunlight in a real environment, is the contrast may skew interpretation. A secondary issue is the beam might be so small it arrives between the photosensors on the measurement surface. In that case, a potential lighting design problem would not be recognized, however, it would show in the visual effect protocol.

The mathematics of the direct solar illuminance to candela conversion is also problematic due to the distance of the resource and the solid angle. The distance exponentially increases luminous intensity to a point where comparisons with intensities calculated with reflected light from the louver blades as a source are unmeaningful. Whereas, the calculation remains accurate, the most useful aspect of the data is an indication of orientation and/or louver design that produces negative effects.

The external validity of the solar positions tested is based upon the generalizability of the sample. The proposed sampling of distributed solar positions on the sky dome will allow extrapolation of performance data for other locals and times of day and times of year.

Analytical generalization to theory will be based upon the data measured for the performance of the treatments. If it proves that a particular transmission control component achieves superior performance the data may be useful to generalize to theory.

4.5.3 Reliability

'Reliability…is a precondition of validity' (Guba, 1981). Reliability of the computer simulation is based upon internal and external validity testing. Data will be graphed on scale section drawings of the tested space to illustrate the distribution and volume characteristics of the daylighting on the assumed work plane. Consistent output from computer simulation is predicted based upon prior research (Littlefair, 1992 & Hu, 2003). Hayman (2003) has pointed out the value of internal consistency for daylighting research to defend against variability and errors in absolute measurements. In the research, computer simulation provides that consistency and reliability.

4.5.4 Objectivity

The objectivity of this experiment is based upon the investigator being removed from the object of study, which is manifest in the methodology. The conceptual framework and methodology follow research practices described in Groat & Wang (2002), Guba (1981) and Creswell (2002). The use of computer simulation is fundamental to the objectivity. Similar analysis of physical phenomena has proven effective in many types of experimental research projects. In the field of daylighting research, the research methodology includes aspect of and parallels previous research including Beltran,et al, 1994; Howard,1986; Hu, 2003; Lee, et al, 2000; Littlefair,1992; Naavab,1996; Papamichael, et al, 1996; Place, 1986; and, Spitzglas, et al, 1985. The experiment has been designed so the measurements can be replicated by other investigators following the same protocols.

4.6 Conclusion

The proposed methodology represents a substantial increase in scope of data above traditional daylighting indicators and research methodologies. The data is specifically about quantities and qualities of daylight admitted rather than performance of a daylighting system, which makes it useful as a building block to better-performing daylighting systems. The characterization methodology will be performed with state of the art of simulation tools applicable to this methodology. These tests may be further developed if and when the proposed characterization methodology is accepted by daylighting designers, researchers and daylighting fixture manufacturers.

5.0 DEMONSTRATING THE CHARACTERIZATION METHODOLOGY

5.1 Scope of Demonstration

This section seeks to use existing computational tools to implement the proposed characterization methodology on a daylighting fixture. The goal is to make a preliminary evaluation of the capabilities of the lighting programs selected to implement the methodology. Evaluating the overall capabilities of the programs exceeds the scope of this investigation. The three daylighting programs, Desktop Radiance, AGI32 and Lumen Designer, will be evaluated by constructing the simulated testing assembly to generate IESNA photometric files, and by constructing the room for illuminance and visual effect tests. A simple sky will be constructed in the optical program TracePro, which will be used to characterize visible light and thermal transmittance, and to produce IESNA photometric file outputs. The limitation on the depth of the evaluations is offset by the benefit of being able to create a performance matrix comparing their capabilities. It was determined that this was necessary when the software selection process revealed no existing program is able to implement the entire characterization methodology.

Demonstrating a methodology requires a research problem to be addressed. Load management controls for toplighting have been selected. The control of light quality and quantity, which is the goal of solar load management control technology, is an important area for daylighting research and a strategy for saving lighting energy in buildings. 'Variable daylighting level is a basic problem that needs to be solved to increase the utilization of daylighting techniques', (Selkowitz, 1998). Professor Place's research indicates that 'properly controlled, movable, external shading (or movable insulation) would facilitate significant additional reductions in both energy consumption and energy costs.' (Place, 1986). Based upon a literature review, and two unpublished pilot studies, it was determined that daylighting load management controls will make a good test case for the proposed demonstration of the characterization methodology

5.2 Characterization Methodology Demonstration Design

The characterization methodology demonstration, while not rising to the level of experimental research, is organized by the 'defining characteristics of an experimental research design (which) include(s) the following: use of a treatment, or independent variable; the measurement of outcome, or dependent, variables; a clear unit of assignment (to the treatment); the use of a comparison (or control) group; and a focus on causality' (Groat & Wang, 2002). The methodology section defined the variables, simulation settings, and measurement protocols, which are herein adapted, as necessary, to the capabilities of the simulation programs. Each step of the demonstration is described in detail below. The final stage of the demonstration will be to compare the capabilities of each program against the general requirements of the characterization methodology.

This demonstration is limited to a single daylighting fixture for roof apertures. In future research, a similar demonstration may be developed for daylighting fixtures for window apertures. The demonstration is related to the characterization methodology, and is not designed or intended to produce experimental data to be compared and evaluated in a quantitative manner. This section articulates those aspects of the full characterization methodology that are within the capabilities of the software. If the software appears incapable of implementing any aspect of the assessment, a description of the relevant issues will be made.

The demonstration has been designed to implement the characterization methodology, which focuses on causality 'to ascertain and measure the extent to which a treatment causes a clearly measured outcome within a specified research setting' (Groat & Wang, 2002). All characterization methodologies will be implemented in accordance with the protocols. Characterizations and the software used in each are as follows:

- **Angular Flux Distribution** (candela distribution):

  Desktop Radiance, AGI32, Lumen Designer & TracePro
- **Illuminance Distribution** (lux):

  Desktop Radiance, AGI32 & Lumen Designer
- **Visual Effect** (spatial rendering)

Desktop Radiance, AGI32 & Lumen Designer

- **Visible Light Transmission** (%):

  AGI32

- **Radiant Energy Absorption and Transmittance** (W/m^2)

  TracePro

5.2.1 Setting

The simulated setting for each characterization is constructed in accordance with the methodology section. Special considerations related to how the software may or may not be used to construct the setting are described in the Section 5.3, Computer Simulations.

5.2.2 Solar Positions

The selected programs can not locate the solar position, by azimuth and elevation. It was determined to assess each hour of the day from 8AM to 5PM for clear sky and 12PM for cloudy sky on March 21st in Raleigh, NC.

5.2.3 Control and Treatment Design

The simulated roof plane has a 4’-0” x 4’-0” aperture. The roof plane with no treatment in the aperture will serve as the control. The independent variable or treatment used to demonstrate the characterization methodology is a daylighting fixture with planar control elements designed to fit the 4’-0” x 4’-0” aperture. The treatment is comprised of eight ¼” thick aluminum louver elements that are spaced at 6”-O.C. on the horizontal, with the width of the louvers being such that the effective aperture is vertical. In this particular case, aperture is defined as that potion of the opening that has an unobstructed view of the sky.

The louver blades are set at 35º above horizontal, which implies that the width of the louver blades must be 6"/cos35º=7.32" to create the vertical effective aperture. The louvers are coated with white painted that is 85% reflective. They have closed ends and are flush with the bottom of the simulated roof plane (Figure 5.1). This louvered fixture has a 55% aperture ratio; i.e., the area of the effective vertical aperture is 55% of the 48" x 48" horizontal opening. (Area of the effective vertical aperture is 3.3125"ht x 48"w x 8 apertures = 1272in^2 and the area of horizontal aperture is 48" x 48" = 2304 in^2, yielding a ratio of 1272/2304 = 0.55.). The axis of symmetry of the daylighting fixture will be oriented with the louver apertures facing north.

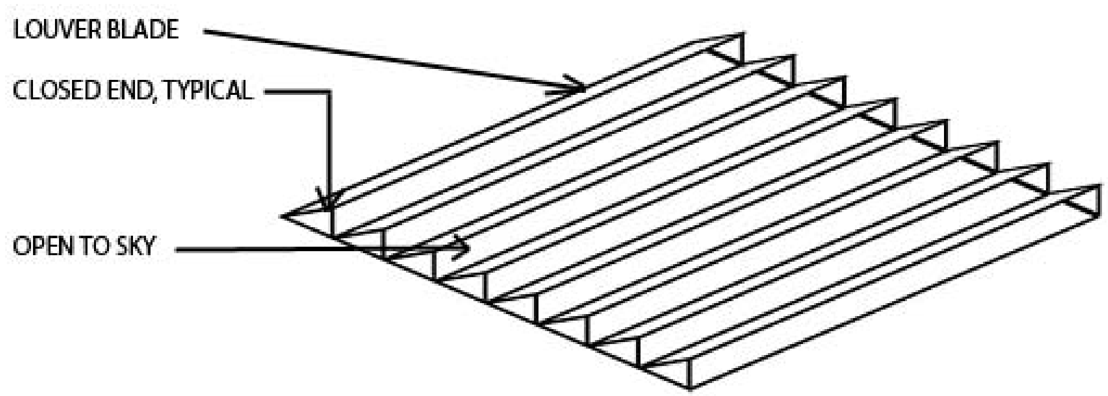

Figure 5.1: Static Louver with 35^0 Angle Blades

The louver surfaces are perfectly diffuse, which means 'the luminous intensity in a given direction is proportional to the cosine of the declination angle from the perpendicular to the surface. The flux reflected from a diffuse surface is not a function of the incident direction or the azimuthal angle. Thus, the reflecting surface exhibits a luminance independent of viewing angle' (IESNA Handbook, 2000). Angular distribution in far-field photometry is based upon measuring a luminous surface, as noted in the literature review and methodology sections.

5.2.4 Data Collection

5.2.4.1 Angular Distribution

Illuminance data measured at the photosensors is converted into candela data in the manner outlined in the next several steps.

I = Illuminance on a photometer on the goniophotometer hemisphere of radius R

LF= Luminous flux on the portion of the hemisphere that is associated with the photometer

= the Illuminance reading on the photometer times the area A of the portion of the hemisphere associated with that photometer

= IA

(For the goniophotometer, the area A associated with a given photometer is the area of the spherical rectangle bounded on two sides by the two parallels halfway between the photometer and the two adjacent photometers on the same meridian and bounded on the other two sides by the two meridians halfway between the photometer and the two adjacent meridians on the same parallel.)

SA = Solid Angle associated with the photometer $= \frac{A}{R^2}$

FD = Flux Density $= \frac{FD}{SA} = \frac{IA}{\left(\frac{A}{R^2}\right)} = IR^2$

The setting description and candela readings are recorded in the IES file format below.

The following IESNA Standard file format description is excerpted from www.AGI32/Help:

The majority of lighting fixture manufacturers are currently employing the IESNA standard recommended file format for luminaire photometry (IES document LM-63-2002).

The ASCII file format is shown below. This is exactly how any IES format file should appear when listed directly from a text editor. The standard for this format is included in the lighting method documentation LM-63 available through IESNA.

IES File Format

Each line marked with an asterisk must begin a new line. Descriptions enclosed by the brackets"<" and ">" refer to the actual data stored on that line. Lines marked with an "at sign" @ appear only if TILT=INCLUDE.

All data is in standard ASCII format.

*IESNA:LM-63-1995

*<keyword [TEST]>

*<keyword [MANUFAC]>

*<keyword 3>

"

*<keyword n>

*TILT=<filespec> or INCLUDE or NONE

@ *<lamp to luminaire geometry>

@ *<# of pairs of angles and multiplying factors>

@ *<angles>

@ *<multiplying factors>

*<# lamps><lumens/lamp><multiplier> <# vertical angles>

<# horizontal angles><photometric type><units type>

<width><length><height>

*<ballast factor><ballast lamp factor><input watts>

*<vertical angles>

*<horizontal angles>

*<candela values for all vertical angles at first horizontal angle>

*<candela values for all vertical angles at second horizontal angle>

* "

* "

<candela values for all vertical angles at last horizontal angle>

***NOTE:** At the time of release of this publication some luminaire manufacturers do not employ the IESNA:LM-63 keyword scheme. Lighting Analysts programs do not require the IESNA:LM-63 keywords, however, the AGI32 Instabase uses keywords if present. Without keywords, all information preceding the TILT= line is read as descriptive information.*

5.2.4.2 Room Illuminance

All illuminance readings included those from beam sunlight will be taken.

Illuminance readings are not sensitive to the distance of the source, and the introduction of beam sunlight may be desirable in certain architectural spaces.

5.2.4.3 Visual Effect

Visual effect renderings will be made directly from the illuminance simulation of the room. The renderings will not be enhanced in any way for the purposes of the demonstration.

5.2.4.4 Visible Light Transmittance

Visible light transmittance measurement will only be performed in TracePro, since that is the only software program that provides this functionality.

5.2.4.5 Thermal Energy Transmittance

Thermal transmittance measurement will only be performed in TracePro, based upon examination the capabilities of the selected software.

5.2.5 Software Evaluation

The goal of the data analysis is to evaluate daylighting performance for load management control components to allow designers to choose daylighting components consistent with project performance requirements. Analysis will include graphic outputs related to annualized performance and the ability of controls to approximate luminaire performance standards per IESNA.

The simulation software will be evaluated in accordance with the software requirements put forth in the Methodology Section. They are the following categories:

- Validation
- IESNA File Format Inputs
- Sky distribution
- Optical elements
- Material Properties
- Goniophotometer
- Illuminance
- Visual Effect

- Visible Light Transmittance
- Thermal Energy Transmittance
- Numeric Outputs
- IESNA File Format Outputs
- Graphic Outputs

5.3 Computer Simulations

5.3.1 Desktop Radiance

Desktop Radiance and Radiance are available free online at http://radsite.lbl.gov/deskrad. This research assesses Desktop Radiance, which is Radiance with a graphic user interface (GUI). Radiance is the UNIX-based software that underlies Desktop Radiance. Radiance was designed as a photorealistic rendering program using reverse ray tracing. The GUI of Desktop Radiance does not access all the capabilities of Radiance, but the computer language of Radiance was deemed to have a learning curve that would restrict interest among architectural firms.

5.3.1.1 Validation

Desktop Radiance has not been validated, but the underlying program, Radiance, has been validated using the dataset (www.iesd.dmu.ac.uk/jm/pdfs/BRE-IDMP.pdf). The validation indicated that 'the accuracy of Radiance predictions was high: 66% of predictions were within +/-10% of the measured values, and 95% were within +/-25%. The accuracy of the Radiance predictions was comparable with the measuring instruments themselves and much higher than that demonstrated for scale models' (Mardaljevic J., 2004). The results reported by Mardaljevic are consistent with case study results obtained by Atif, Love, Littlefair (1997).

5.3.1.2 I.E.S. File Format Inputs:

Lawrence Berkley Laboratories provides a library of luminaire files in IESNA Format for use with Desktop Radiance. These and other IESNA files, such as those provided by luminaire manufacturers can be imported and placed as luminous sources.

5.3.1.3 Sky Distribution

In Desktop Radiance, C.I.E. standard clear or intermediate, and overcast skies are provided based upon C.I.E. equations. Sky turbidity may also be controlled by relative values. The sky argument was provided by Greg Ward (Larsen), co-author of Radiance, during an e-mail exchange is fall 2005 (Appendix 4). The current document, CIE 110-1994, *'Spatial Distribution of Daylight- Luminance Distributions of Various Reference Skies',* has been slightly revised from the one used by Greg Ward Larsen in Radiance (Appendix Three).

In Desktop Radiance, Solar position is set by time of year, time of day and geographic location.. Radiance allows the solar azimuth and elevation to be set with the 'Gensky' command. The purpose is to set 'sky and sun brightness…in terms of either the zenith radiance or the horizontal diffuse irradiance' (Larsen & Shakespeare, 2003).

5.3.1.4 Modeling of Optical Elements

Desktop Radiance opens within AutoCad, which makes all AutoCad commands available for drawing, including import and export of drawing files. Desktop Radiance material attachments and analysis work only with surfaces. .DWG files with primitive solids (objects) may be converted to .3ds files (3D Studio), and re-imported with surface properties before use in Desktop Radiance. Simulations performed on drawing files automatically create .RAD, Desktop Radiance files.

5.3.1.5 Material Properties

Desktop Radiance materials can be attached, detached and viewed in a pull down menu. There is an opaque material library and additional opaque materials may be defined by reflectance and color. There is also a window library available from Lawrence Berkeley Laboratories that can be used to import windows and glazing material with transmission and reflectance corresponding to manufacturer's NFC (National Fenestration Council) test data.

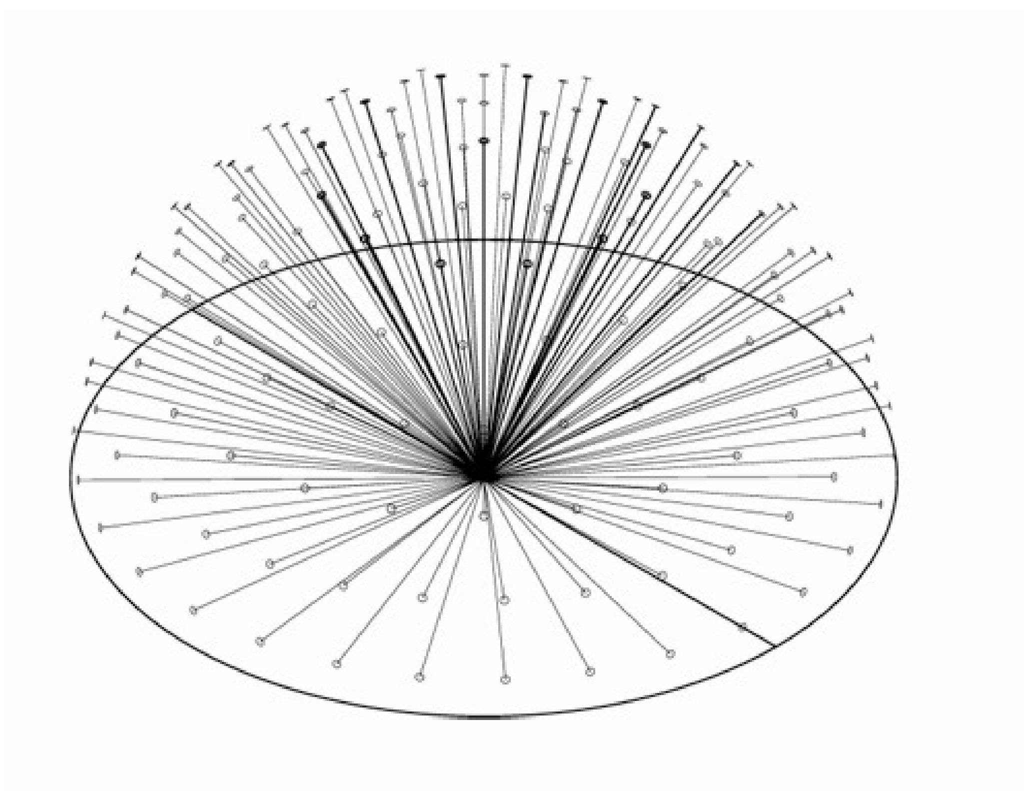

Figure 5.2: Planes for 145 Sky Positions

5.3.1.6 Goniophotometer

In Desktop Radiance, the hemispherical form of a goniophotometer may be created and photometers may be located according to IESNA photometric testing procedures. Desktop Radiance photometers are limited to measuring illuminance perpendicular to a reference plane, which means 145 planes need to be defined as facets on the hemisphere and the photometers must be pointed toward the center of the hemisphere (i.e., toward the center of the daylighting fixture. This may be accomplished by locating circles at the end of a line the length of the goniophotometer radius (29’-0”), and rotating them to the 145 distinct azimuths and elevations (Figure 5.2). Each plane requires a UCS (user coordinate system) with the ‘Z’ axis pointing to the center of the goniophotometer. The photometers inserted at the center of each circle with the corresponding UCS will focus on the center of the goniophotometer. Individual tests for each photometer will produce illuminance data for each point that could be converted to candela data for an IESNA file. This process was determined to be too time-consuming. Therefore, Desktop Radiance data in the form of false color and isocontour images was collected in a hemispherical dish representing a goniophotometer.

5.3.1.7 Room Illuminance

In desktop Radiance, illuminance and luminance values can be simulated for individual photometers and planar grids of photometers. The isocontour display is noteworthy because it displays on all surfaces in the simulation without locating sensors, see figures 5.4 – 5.7.

5.3.1.8 Visual Effect

In Desktop Radiance, visual effect renderings and renderings with illuminance isocontours were simulated in the room setting (Figures 5.6and 5.7 respectively).

5.3.1.9 Visible Light Transmittance

Desktop Radiance was not used to measure visible light transmittance.

5.3.1.10 Thermal Energy Transmittance

Desktop Radiance cannot provide data other than illuminance that is useful for thermal load assessment.

5.3.1.11 Numeric Outputs

For Desktop Radiance, numeric outputs are limited to luminance or illuminance measurements in individual photometer simulations or planar grid reports. Photosensors arrayed on non-planar surfaces, such as the hemispherical surface of a virtual goniophotometer, must have individual simulations to generate illuminance readings.

5.3.1.12 IESNA File Format Output

Desktop Radiance does not provide IESNA File Format outputs. It lacks a method of running a single test and collecting the data from many points on the simulated or virtual surface of the goniophotometer hemisphere. It was determined that the false color and isocontour images simulated in the hemispherical dish could be overlaid with a plan of the desired data points, and the points could be interpolated (Figure 5.3 & 5.4). The illuminance could then be converted to candela and entered into and IESNA electronic file. This is a lengthy and inaccurate process, which was deemed not appropriate to pursue. It was noted in the research that macro commands may be programmed into Radiance to collect data from numerous points.

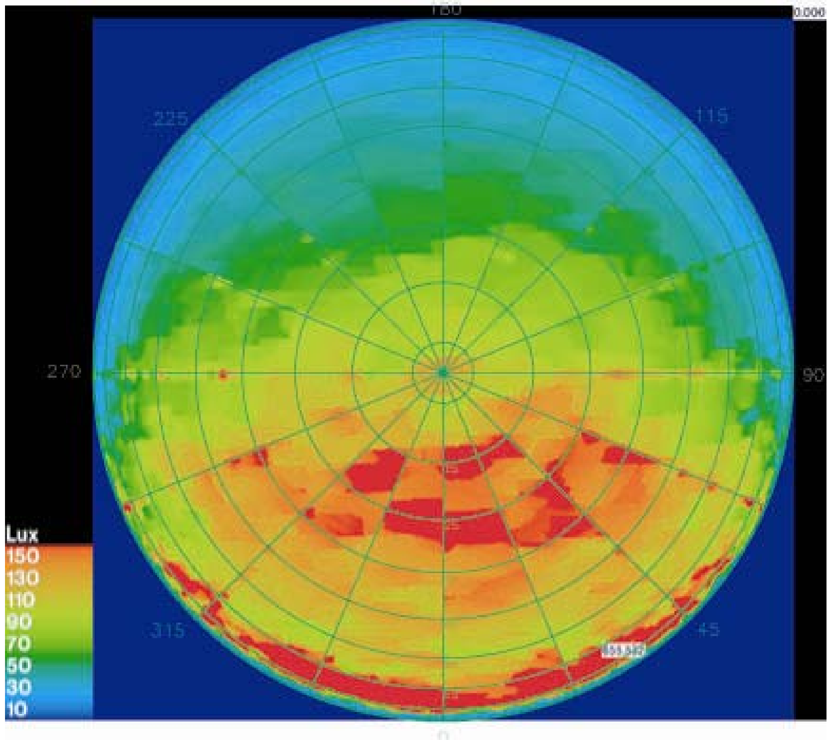

Figure 5.3: False Color View of Illuminance in Hemisphere

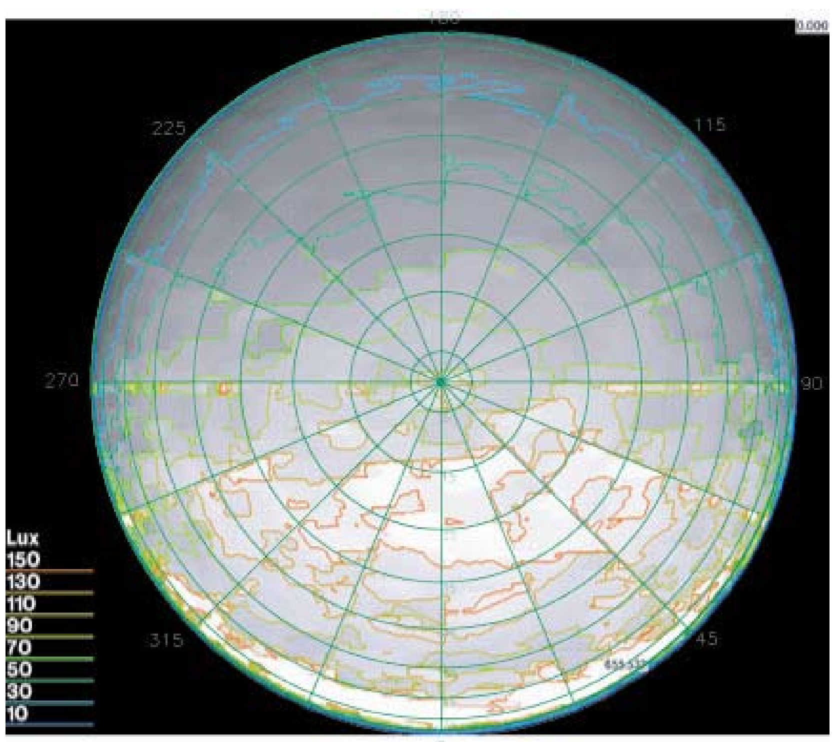

Figure 5.4: Isocontours of Illuminance on Hemisphere

5.3.1.13 Graphic Outputs

For Desktop Radiance, visual outputs include renderings, false color and isocontour plots of illuminance or luminance. A particular strength of Desktop Radiance is that false color and isocontours can be obtained for all surfaces in any view. The false color and isocontour renderings illustrate measured levels of light. The range of each level is called a NIT. The absolute range of the illuminance Nits may be specified, but it is not possible to have a range of interest that doesn't start at zero.

Figure 5.5: Visual Effect of Illuminance

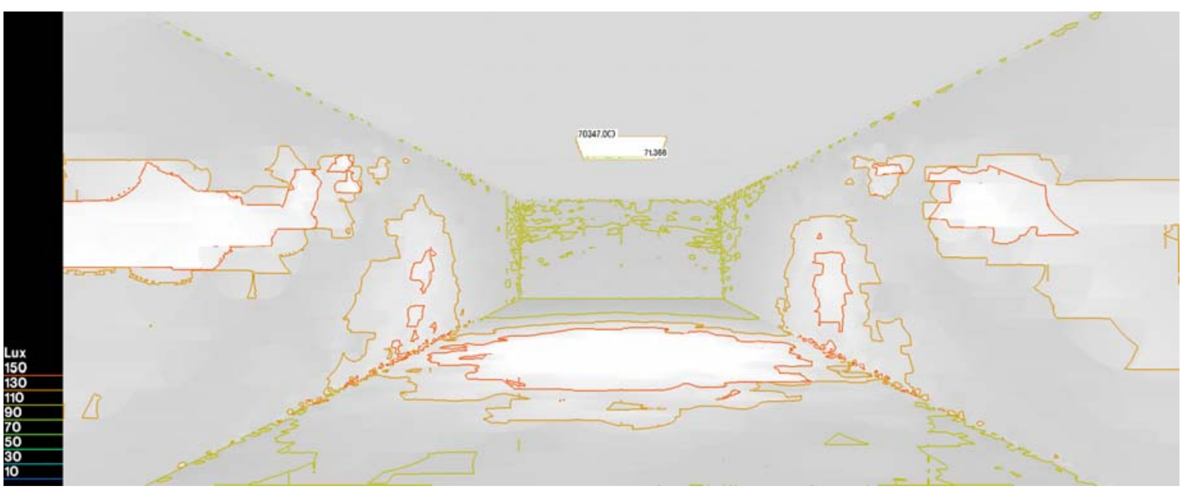

Figure 5.6: Isocontours of Illuminance in Visual Effect Room

Desktop Radiance was also used to produce Visual Effect renderings, which are illustrated in Figures 5.5 & 5.6. Uneven light distribution was noted on all outputs. This could be improved but not removed by adjusting simulation settings, such as light bounces and other commands that increased processing time in the program. Greg Ward (Larson) indicated in a fall-2005, e-mail communication that settings need to be manipulated to provide the best rendering.

5.3.2 **AGI 32** (http://www.lightinganalysts.com/):

'AGI32 is a computational program that performs numerical point-by-point calculations of incident light on any real surface or imaginary plane. Within this scope it is used to predict or quantify the distribution of artificial or natural light in the environment. AGI32 has two calculation modes….the direct calculation mode will consider the shadowing effect of objects in the scene and produce point-by-point illuminance…. (The) full calculation mode will compute the interaction between light and surface using its state-of-the-art Radiosity calculation engine. In this mode all surfaces can be assigned a color and reflectance and accurate luminance levels are computed for all surfaces. Radiosity computations consider all reflective surfaces to be diffuse, allowing the end result to be viewed interactively without re-calculation' (http://www.lightinganalysts.com/). Diffuse surfaces are very common in architecture, but having all diffuse surfaces may limits the accuracy of certain simulations. The demonstration simulations were performed in 'full calculation' mode.

5.3.2.1 Validation

For AGI232, validation studies are currently being 'performed by an independent party in accordance with the new CIE 171-2006 test suite' for Lighting Analysts, per e-mail correspondence with AGI32 support (February, 2006).

5.3.2.2 IES File Format Input

For AGI32, I.E.S. files, such as those provided by luminaire manufacturers can be imported and placed as sources.

'AGI32 requires that a luminaire type be defined before it is located in the project file. The luminaire definition includes photometric information as well as a symbolic representation of the luminaire. Each occurrence of the luminaire will access these parameters in addition to the aiming information specified by the user. AGI32 places no limits on the number of luminaire definitions available in a job file.'

'The first step in defining a luminaire type to be used in AGI32 is the retrieval of the specific luminaire photometric information. Once the photometric file has been opened and a definition created, it is available to that job file until deleted. There is no need to redefine it to use it repeatedly. The defined luminaires represent a catalog of luminaires that can be conveniently located on the drawing by AGI32. It is often convenient to define all of the desired luminaires at the beginning of the project, however, additional luminaire types may be defined at any time.' (AGI32/Help)

5.3.2.3 Sky Distribution

In AGI32, the solar position is 'set by time of year, time of day, and geographic location. Sky turbidity may also be controlled by relative values' (AGI32/Help). Lighting Analysts responded to an e-mail query about specifying solar position, indicating that it was not currently possible, but that they would consider adding that feature in a future release.

'*The sky conditions used in AGI32 are based on accepted IES and CIE equations. C.I.E. standard clear or intermediate, and overcast skies are provided. The CIE recognizes the Kittler (CIE Clear Sky model and the Moon and Spencer (CIE Overcast Sky) model as well as 15 additional Standard General Sky models. The IESNA further recognizes the Pierpoint (Partly Cloudy) model. AGI32 allows you to include a realistic Sky Dome in your daylight enabled renderings. The sky dome changes color slightly depending on the sky model selected and includes a small sun image'* (AGI32/Help).

5.3.2.4 Modeling of Optical Elements

'AGI32 has a drawing systems and tool based upon planes. One does not draw a line, but a surface. AutoCad DXF and DWG files may be imported, but primitive solids are not recognized. DWG files with primitive solids must be exported to 3D Studio, which converts them to surfaces, and imported as a new DWG, which can then be imported to AGI32. AGI32 will import 3D entities composed of the following entity types: 3DFaces, 3DSolids, 3DMesh, Regions, and Bodies. If no 3D entities are found in the file, AGI32 will import it all as line data. Once the surface orientation is verified, the surfaces are loaded into the 3D Entity import dialog. The 3D Entity dialog contains a summary of 3D entities contained in the CAD file and an OpenGL graphic view of the imported information' (AGI 32/Help).

5.3.2.5 Material Properties

In AGI32, the principle material properties are color, texture, reflectance and mesh. Reflectance is defined by color hue, saturation, and luminance. *'The Surface Edit command* *allows you to modify surface attributes for any selection of Rooms and Objects. Users may quickly select individual surfaces or multiple surfaces collectively, for which they wish to change material properties such as color, texture, meshing, etc. When a texture is added to the Textures database, its average reflectance and color is calculated. This value is stored along with the texture in the database. You may search the database by average reflectance ranges if desired. This ability allows you to quickly find all textures within the same reflectance range - like light colored surfaces (i.e., for ceilings or walls). The HSL (color selection) method matches human perception of color by first prompting for a color (hue), then a shade of that hue (Saturation and Luminance)*.' (AGI32/Help).

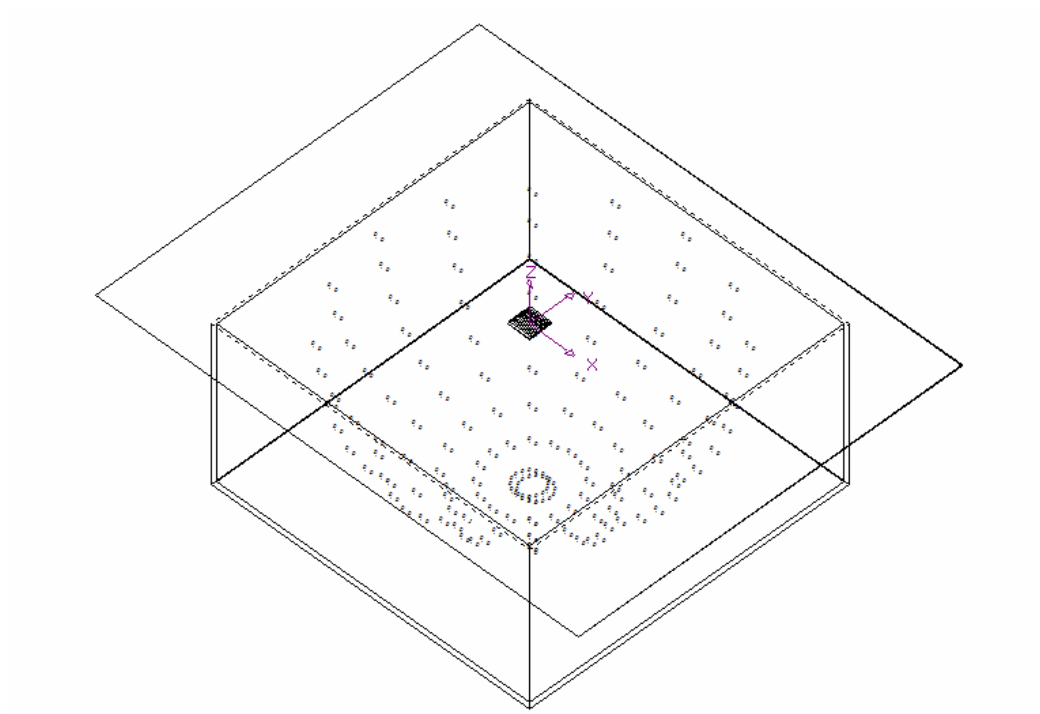

Figure 5.7: AGI32 Simulated Goniophotometer

5.3.2.6 Goniophotometer

In AGI32, photosensors can be located at intersections in virtual space and pointed toward the source of luminance at the center of the daylighting fixture in the center of the roof. The virtual goniophotometer is enclosed with a blackbody (100% absorptive) box, which is capped by the roof plane for the simulations (Figure 5.7).

5.3.2.7 Room Illuminance

In AGI32, room illuminance studies were produced with grids of photosensors on the walls and floor. The illuminance measurements may be indicated numerically at the sensor location, and/or with isocontours (Figure 5.8).

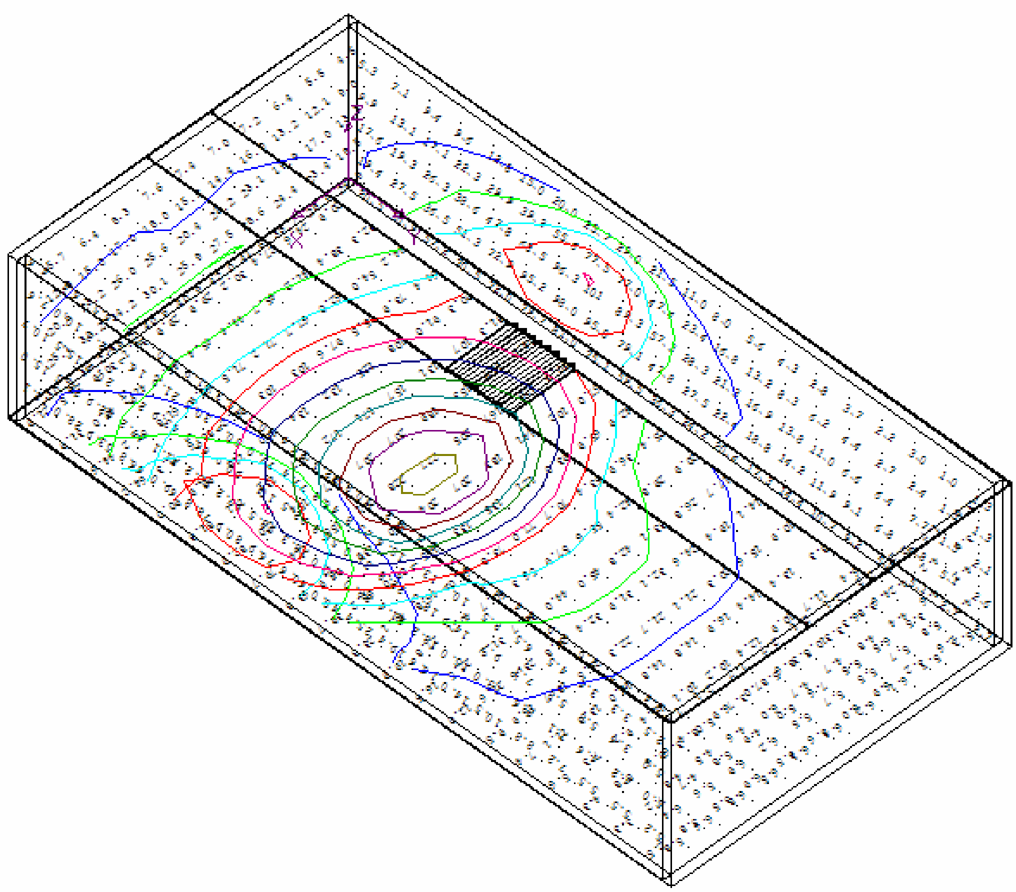

Figure 5.8 AGI32 Simulated Test Room

5.3.2.8 Visual Effect

In AGI32. visual effect renderings including false color and gray scale, were simulated in the room setting (Figures 5.9 and 5.10 respectively).

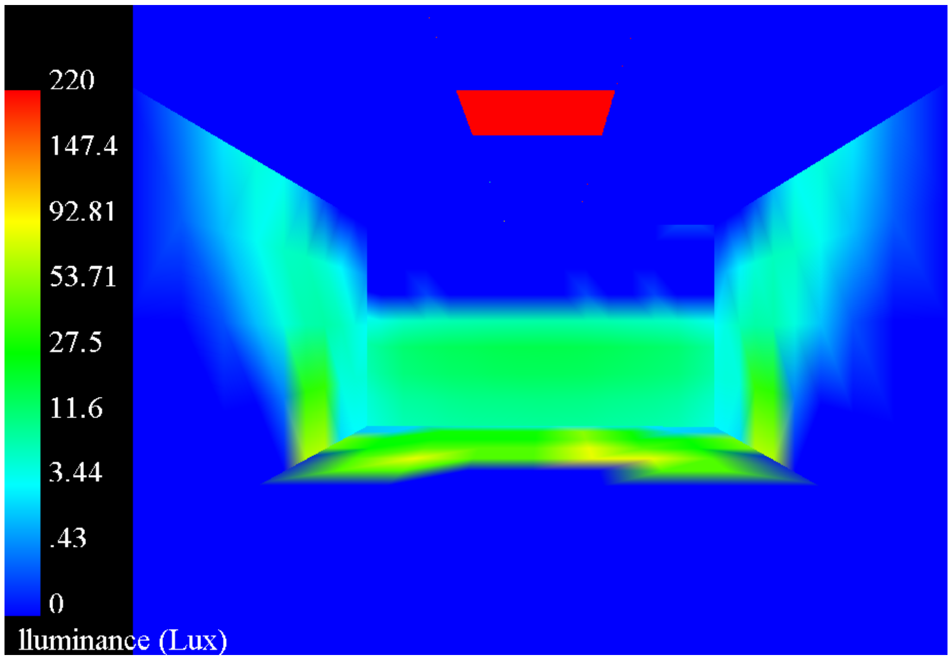

Figure 5.9: AGI32 False Color Room Illuminance

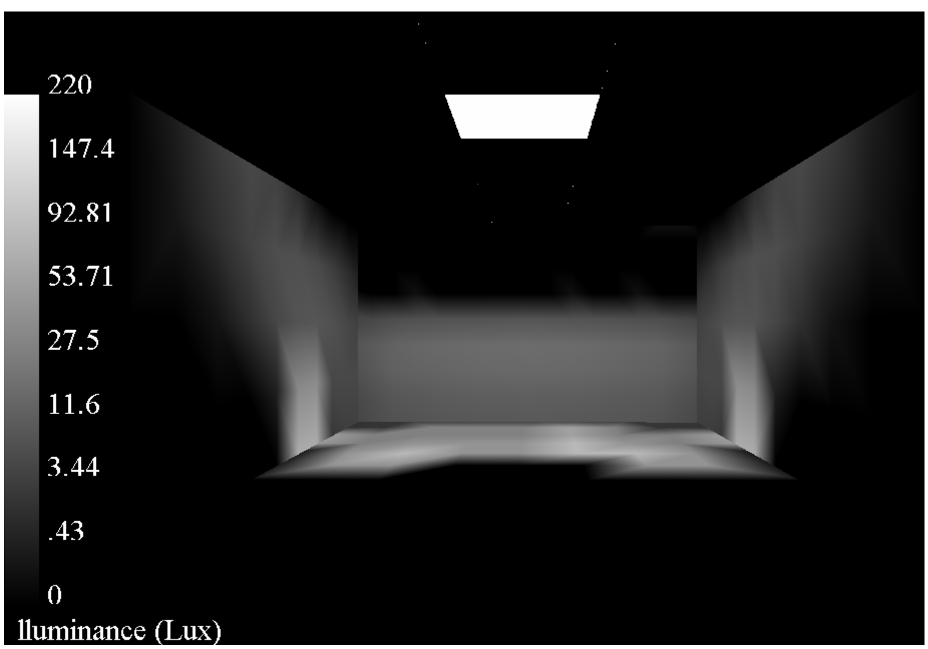

Figure 5.10: AGI32 Gray Gcale Rendering of Room Illuminance

5.3.2.9 Visible Light Transmittance

AGI32 does not provide a direct means to determine the overall transmittance of the daylighting device. However, the total luminous flux incident on the daylighting fixture can be obtained by multiplying the area of the daylighting fixture times the reading on a photometer placed just above the daylighting fixture, with the photometer pointed toward the zenith. The total luminous flux admitted by the daylighting fixture can be calculated by integrating over all the solid angles associated with the half of space below the admitting roof plane. The transmittance can be calculated by dividing the luminous flux admitted by the daylighting fixture by the incident luminous flux.

5.3.2.10 Thermal Energy Transmittance

The program has no thermal characterization capabilities, per se. However, once the goniophotometer has been set up and computational mechanism have been established to determine the total amount of admitted luminous flux (by integrating the luminous flux distribution over all the solid angles below the roof plane), the total admitted radiant flux can be calculated by dividing the total amount of admitted luminous flux by the luminous efficacy of the admitted light.

5.3.2.11 Numeric Outputs

AGI32 can produce reports of all sensor readings, regardless of whether the photometers are located on real of 'imaginary' surface, and whether or not those surfaces are flat or shaped. Data is reported from all sensors for each simulation in a .TXT file. The scope of data reported is an important advantage of this program over the other lighting simulation programs evaluated.

5.3.2.12 I.E.S. File Format Output

The illuminance reports produced by AGI32 list the data in the order in which the sensors were put into the model, which means that editing of the illuminance file is required to make it conform with IESNA azimuth and elevation format. The modified illuminance .TXT file can then be converted into candela values. These values can then be formatted in an I.E.S.N.A. electronic file format in EXCEL. As part of the demonstration, illuminance reports from the goniophotometer were converted into candela and processed into an IESNA Photometric File Format. The file was then imported into a lighting simulation in AGI32 as a daylighting fixture. This produced significant inconsistencies between the daylighting simulation illuminance values in a room and the illuminance values produced with the IESNA electronic file. These inconsistencies have not been explained, see Appendix F. These inconsistencies are significant enough that they need to be resolved before the software can be applied in the methodology proposed in this dissertation. It is not within the scope of this dissertation to resolve these inconsistencies. They are part of a larger validation of the software, particularly, as it applies to the proposed methodology. Additional I.E.S. outputs, such as polar candela plots may also be produced by processing the illuminance data in EXCEL.

5.3.2.13 Graphic Outputs

In AGI32, the goniophotometer was simulated as a black box with the louvered daylighting fixture, with photometers located on a virtual hemisphere and pointed toward the center of the aperture. (See Figure 5.8).

5.3.3 Lumen Designer

5.3.3.1 Validation

A validation of Lumen Micro, which is an earlier version of Lumen Designer, comparing 'predicted light levels versus measured light levels' was performed at the University of Colorado Illumination Laboratory. Electric light prediction was tested in a simple room with no opening. The average difference between measured and predicted illuminance levels was 6%. Daylighting performance was not validated. ('Comparison: Lumen Micro and Measured Results, July 9, 1991, Lumen Designer/Help)

5.3.3.2 IES File Format Input

The following 'photometric file types that Lumen Designer can import' was excerpted from Lumen Designer/Help:

- IESNA LM-63-02
- IESNA LM-63-95
- IESNA LM-63-1991
- IESNA LM-63-1986
- EULUMDAT
- CIBSE-TM14
- LTLI

Importable file types:

- IESNA (*.IES)- North American standard
- EULUMDAT (*.LDT. *.ELX, *. EUL) - European standard
- CIBSE (*.TM4, *.CIB)

- CIE (*.CIE)
- LTL (*.LTL)

5.3.3.3 Sky Distribution

For Lumen Designer, sky luminance distribution information references, such as CIE standard skies, were not available. Solar position is determined by time of day, time of year and geographic location. It is not possible to locate the solar source directly by azimuth and elevation.

5.3.3.4 Modeling of Optical Elements

Lumen Designer has CAD drawing tools to create complex forms, and can import .DXF/.DWG files from other platforms. Models are constructed with surfaces, as in the other lighting simulation programs.

5.3.3.5 Material Properties

*Material Type Properties in Lumen Designer:

Color - *used to define the color of a surface at any point in space. It may be as simple as a plain color which specifies all parts of the surface to have a uniform color, or it may define complex surface patterns, such as marble or wood. Every surface must have a color source associated with it, and for a given surface its color source will only be called for those pixels (if any) at which the surface is known to be visible.*

Reflectance - *the behavior of a surface in the presence of light is represented by a reflectance model which defines how much light is reflected by the surface towards the* *viewer. Thus, the result is dependent upon both the material properties of the surface and the lighting environment that illuminates the surface. Unlike the color sources which specify the pure color of a surface and are therefore independent of any light sources, reflectance models must account for each light source in calculating their results. Reflectance types may be thought of as defining a surface's 'finish', and are used to model reflectance properties such as matte, metal and plastic.*

Transparency - *used to define how transparent or opaque a surface is, and thus how much light is able to pass through it. It is important to realize that the Material Manager supports two subtly different conceptions of 'transparency'. The first related to the concept of coverage—for example, it is possible to see 'through' a sieve, or a fine wire mesh. This fine wire mesh may be thought of as being '50% transparent', in the sense that half the light hitting it travels through and half is reflected. It is important to realize, however, that, if the mesh were made of bright green wires, the mesh would be visibly green, but any light passing through the mesh would be simply occluded by the wires, and not tinted green in any way. On the other hand, the second way of thinking of 'transparency' could perhaps more properly be referred to as 'translucency'. For example, a colored piece of glass could reflect half of the light incident on it, and let half through—but the light transmitted through the glass would also be colored by the glass. A red piece of glass would not only appear red, but light passing through it would be tinted red. In this case, the 'transparent' object is acting as a filter. Since the rendering engine is capable of accounting for both of these effects, it is important to understand which effect a given transparency type is modeling. This should be clear from the parameter names provided by the types—rather than specify a simple 'transparency' (or alpha value as it is sometimes known in other renderers), you are asked to supply either an R,G,B (Red,Green,Blue) color value. Transparency types range from a* *simple, plain, uniform transparency to more complex, regular or irregular, eroded patterns that would be difficult to represent using modelling techniques.*

Displacement **-** *small surface perturbations can be supported by means of displacements. Typically, displacements will give an otherwise smooth surface an irregular or indented appearance by modifying the surface normal vector which is used in subsequent shading calculations. Displacements are used to represent features that would be difficult, impossible, or inefficient if conventional modeling techniques were used. For example, rough, metal castings and the regular indentations produced by pressed sheet metal can be simulated.*

Texture **-** *different from other material types in that the contribution that they make to the final intensity of pixels is less obvious. Their effect upon perceived pixel intensities is indirect rather than direct, since they serve to modify the environment within which color source, reflectance model, transparency source, and displacements operate. The latter four texture types may opt to perform their calculations based upon a two-dimensional coordinate system known as texture space. It is this coordinate system which is defined by a texture space. Textures are used to ''wrap' the effects of texture types around surfaces in predefined ways. Planar, cylindrical and spherical mappings are all supported.*

*Excerpted from Lumen Designer/Help 2006)

5.3.3.6 Goniophotometer

In Lumen Designer, a 'black box' goniophotometer with photosensors located on a hemispherical virtual grid in space was created in a manner similar to what was done in AGI32 (Figure 5.11). The photometers can be located in a polar array, but their orientation will be vertical. They can not be focused in a polar array, which means it is necessary to focus each photometer individually with tilt and orientation commands. This is easier than directing photometers in Desktop Radiance, but not a easy as locating them in AGI32.

5.3.3.7 Room Illuminance

In Lumen Designer, room illuminance studies were produced with grids of photosensors on the walls and floor. The illuminance measurements were indicated numerically at the individual sensor location (Figure 5.12).

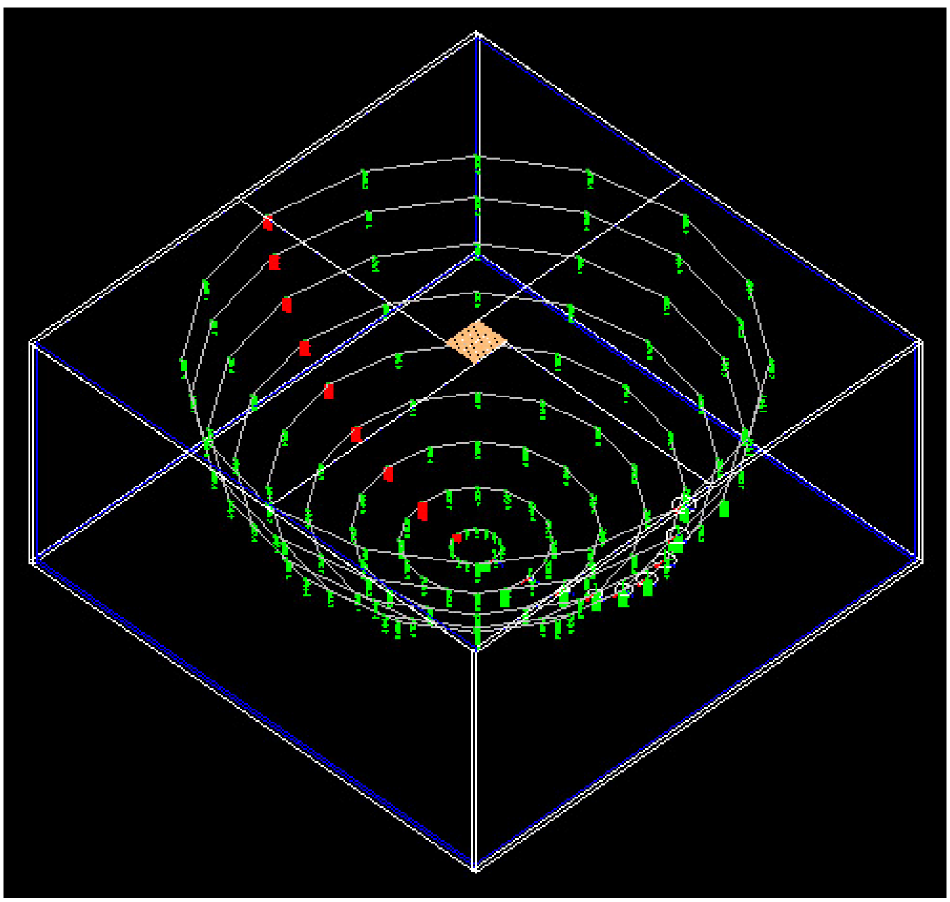

Figure 5.11: Lumen Designer Goniophotometer

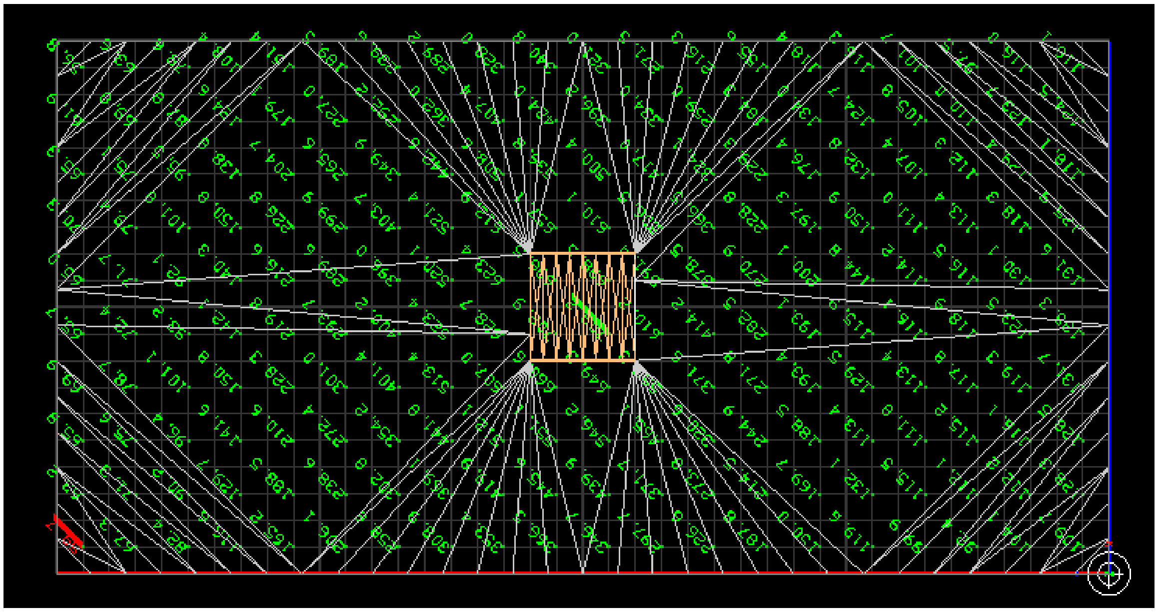

Figure 5.12 Lumen Designer Plan of Room Illuminance Grid

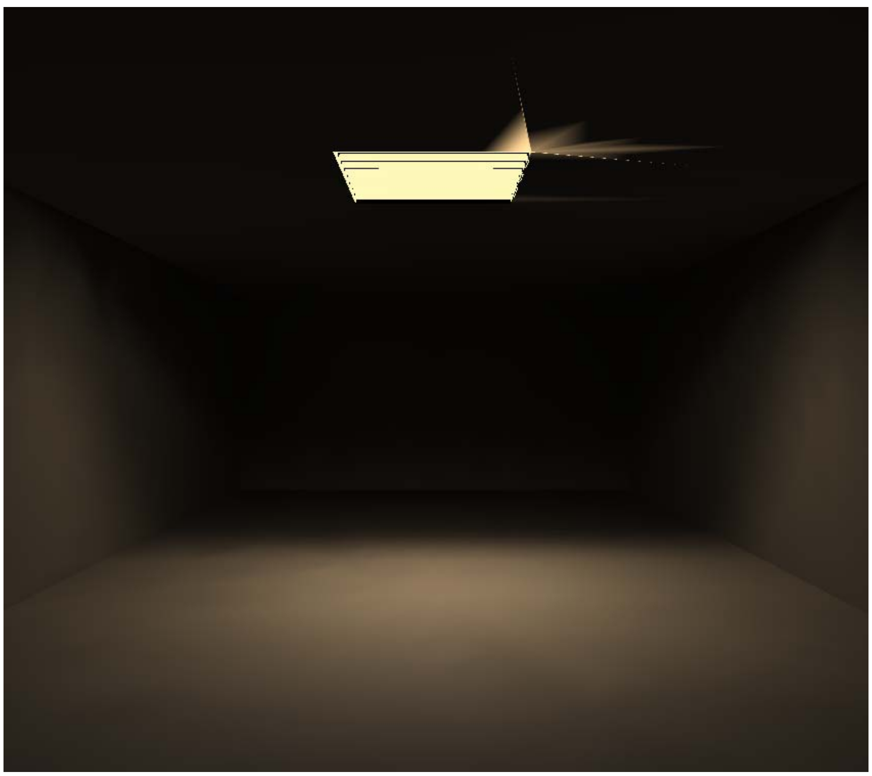

Figure 5.13: Lumen Designer Gray Scale Visual Effect

5.3.3.8 Visual Effect

In Lighting Designer, gray-scale visual effect renderings were simulated in the room setting

(Figures 5.13).

5.3.3.9 Visible Light Transmittance

It was determined not to conduct visible light transmittance tests, because Lumen Designer did not appear to have the most useful tools. It lacks the ability to measure illuminance on an 'imaginary' grid.

5.3.3.10 Thermal Energy Transmittance

Lumen Designer has no thermal assessment capabilities.

5.3.3.11 Numeric Outputs

Lumen Designer has statistical summary reports of individual photometers and grids using internal calculation metrics. Files may be exported to tab delimited .TXT files for post-processing in EXCEL.

**Calculation metrics are settings for the meters that receive light and calculate numerical values at each grid point.*

Types of Metrics:

Horizontal Illuminance *- the density of the luminous flux incident on a horizontally oriented meter.*

Vertical Illuminance *- the density of the luminous flux incident on a meter oriented vertically in the north, south, east or west direction.*

Perpendicular Illuminance *- the density of luminous flux normal to the plane of the analysis grid, at each point on the grid.*

Arbitrary *- the density of the luminous flux incident on a meter with a user-defined orientation.*

Statistical summary components:

Name *- Identifies the grid by the name you specified in the Grid Editor.*

Grid Description *- Displays the additional location or function information you provided.*

Statistical Area *- Identifies the statistical area by the name you entered when it was defined.*

Metric *- Shows the orientation and tilt angles of the preset or user-defined metric.*

Average *- Displays the average value calculated for the grid/stat area.*

Max *- Displays the highest single point value calculated for the grid/stat area.*

Min *- Displays the lowest single point value calculated for the grid/stat area.*

Avg/Max *- Shows the ratio of the average value to the highest value.*

Avg/Min *- Shows the ratio of the average value to the lowest value.*

Max/Min *- Shows the ratio of the highest value to the lowest value.*

CV *(Coefficient of Variation) - The weighted average of all values, which is calculated as the ratio of standard deviation of all values to the mean.*

*Excerpted from Lumen Designer/Help 2006)

Lumen Designer has a structured report format that is excellent for individual photometers, but limits individual sensor data in multi-sensor reports.

5.3.3.12 I.E.S. File Format Output

Similar to AGI32, illuminance reports produced required editing to conform with IESNA azimuth and elevation format. The modified illuminance .TXT file can then be exported to EXCEL and converted into candela values. These values can then be formatted in an I.E.S. electronic file format in EXCEL. Additional I.E.S. outputs, such as polar candela plots may also be produced by processing the illuminance data in EXCEL. Given the effort required in placing the photosensors and creating multi-sensor reports, it was determined to simulate all the illuminance measurements on a single line of azimuth.

5.3.3.13 Graphic Outputs

For Lumen Designer, drawing images may be exported as .DXF/.DWG files or Windows Bitmap Image Format, .BMP. Renderings, false color renderings, and line drawings of the simulation settings can be produced, as illustrated above.

5.3.4 TracePro (Expert Version):

'TracePro is a state-of-the-art ray-tracing program for optical analysis. You can use it to predict stray light in optical systems, to predict the performance of light pipes and illumination systems, luminaires, projection systems-almost anywhere light is used. TracePro is a non-sequential ray-trace program that accounts for absorption, specular

reflection and refraction, ad scattering of light as it propagates through a solid model' (TracePro, Release 3.3, Technical Sheets). The demonstration of TracePro is limited to the conceptual application of potential methodological tools, because it has no daylighting function.

5.3.4.1 Validation

Dr. Marilyne Andersen, et al made a comparison of TracePro predictions with physical goniophotometer testing of bidirectional transmission of glazing materials, as indicated in the literature review. She simulated a goniophotometer in TracePro and found a high degree of correlation between the simulation results and measurements obtained in a physical goniophotometer (Andersen, et al, 2003). This constitutes a substantial validation of the luminous and optical computation. TracePro does not have a sky distribution computation and, therefore, it cannot be validated in a manner appropriate to the purposes of this characterization methodology.

5.3.4.2 IES File Format Input

IESNA files can not be imported into TracePro.

5.3.4.3 Sky Distribution

TracePro is not a daylighting simulation program, and does not have a simulated sky distribution. A simple sky model was created for the purpose of the simulations. The sky was configured as a hemispherical dome at five times the radius of the goniophotometer (5 x 29'radius = 145'radius). The aperture is at the origin of the UCS in Figure 5.14. The entire surface of the sky dome was given a uniform flux of 50,000 lumens on a diffuse white surface.

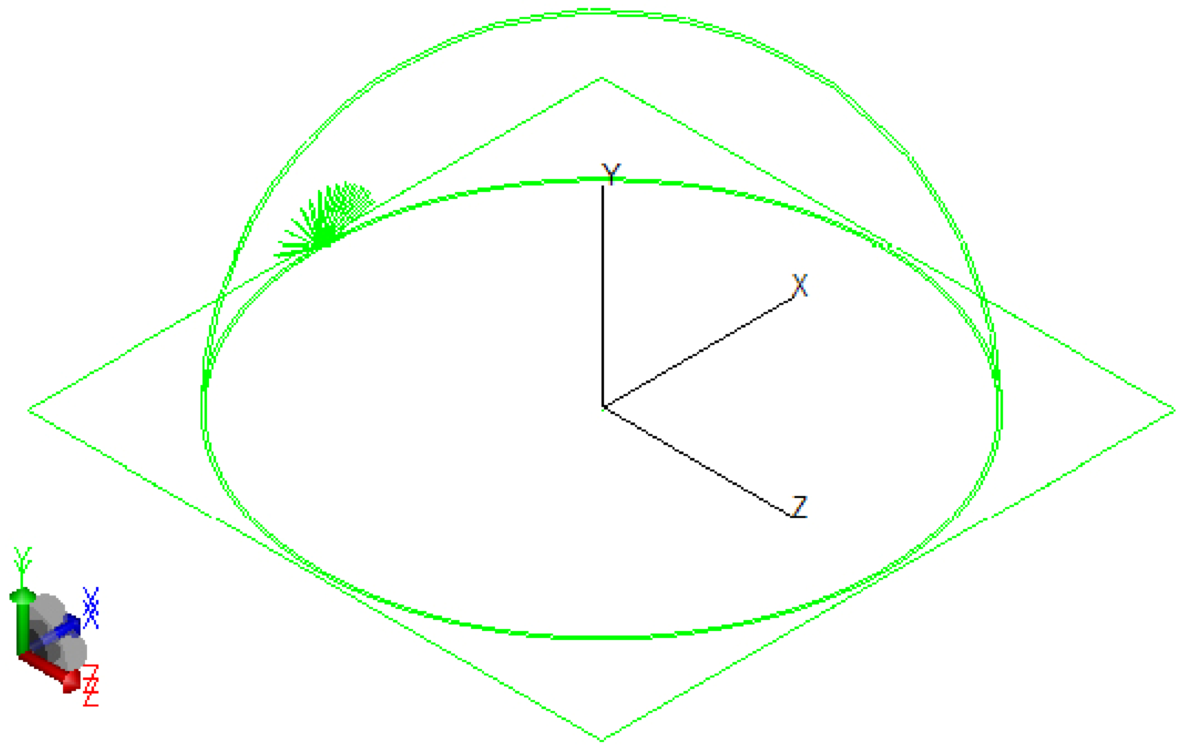

Figure 5.14: Sky Dome and Roof Plane for TracePro

5.3.4.4 Modeling of Optical Elements

'TracePro is based upon the industry standard solid modeling kernel, ACIS, made by Spatial Corporation. TracePro can share solid modeling data with other software based on ACIS, and exchange data with most other CAD programs and analysis programs via IGES and STEP files. It can also import data from popular lens design programs (OSLO, ACCOS V, Code V, Sigma, and ZEMAX). TracePro runs under Windows based PCs' (TracePro, Release 3.3, Technical Sheets).

5.3.4.5 Material Properties

The ability to create and manipulate materials and surface properties is much more extensive in TracePro than other software reviewed in this research. TracePro is designed to understand the physics of light, rather than the visualization of light, which is the design goal of the light simulation programs.

'In TracePro, material properties are identified by name and stored in a database. The Material Properties editor allows you to create and edit material properties for use in your models. Surface properties refer to absorptance, BRDF, BTDF, specular reflectance and transmittance. In TracePro, surface properties are identified by name and stored in a database. For instance, the TracePro database includes the characteristics of "flat white paint." The Surface Property editor allows you to edit surface properties that exist in the surface property database or create new surface properties' (TracePro/Help).

5.3.4.6 Goniophotometer

In TracePro, IESNA photometric file format outputs can be created from an exit surface of interest. It is, therefore, not necessary to construct a goniophotometer. The goniophotometer calculation is done automatically within the software.

5.3.4.7 Room Illuminance

TracePro was not used for a room illuminance study, because of sky and rendering limitations.

5.3.4.8 Visual Effect

TracePro was not used to create visual effect, because of sky and rendering limitations.

5.3.4.9 Visible Light Transmittance

An exit surface was created at the (bottom) plane of the daylighting fixture.

5.3.4.10 Thermal Energy Transmittance

**The Flux report provides a raytrace summary of the most recent raytrace information. This is also available from saved ray data. The data may also be saved to a tabbed delimited text file for viewing and post-processing via the Save As menu.*

Data columns include Surface Area, Number of Incident rays, Incident and Absorbed flux, and the Lost flux. Lost flux data is broken into various categories to identify which mechanism caused the ray to be added to the lost flux data. Data is displayed for bulk absorption and incident flux for each object. The incident flux is the sum of the flux entering the object so that the ray data is not doubly counted. For polychromatic raytraces, either wavelength or waveband data sets may be selected, as well as individual wavelengths.

The data is displayed for each object (data is red) and for the object's surfaces (data is blue), (TracePro/Help 2006).

5.3.4.11 Numeric Outputs

TracePro outputs include the following data and reports:

Model Data

- *TracePro (OML)*
- *ACIS (SAT)*
- *IGES (IGS)*
- *STEP (STP)*
- *Bitmap (BMP)*
- *Metafile (WMF)*
- *Hoops Stream File (HSF)*
- *VDA-FS (VDA)*
- *Catia V4 (MODEL)*
- *Catia V5 (CATPART)*

***Note**: IGES, STEP, VDA-FS, Catia V4/V5 translators require optional licenses* (TracePro/Help).

Irradiance Maps

- *Tab delimited ASCII text*
- *Bitmap*
- *Binary Data*
- *AutoCAD DXF (for contours)*

Reports and Ray Histories

- *Tab delimited ASCII text*

Incident Ray Tables (Flux Reports)

- *Tab delimited ASCII text*

- *Comma delimited (CSV)*

Binary source file (SRC)

*Excerpted from TracePro/Help

5.4.3.12 IESNA File Outputs

In TracePro, an IESNA file was generated by designating an exit surface on the admittance side of the daylighting fixture in the demonstration.

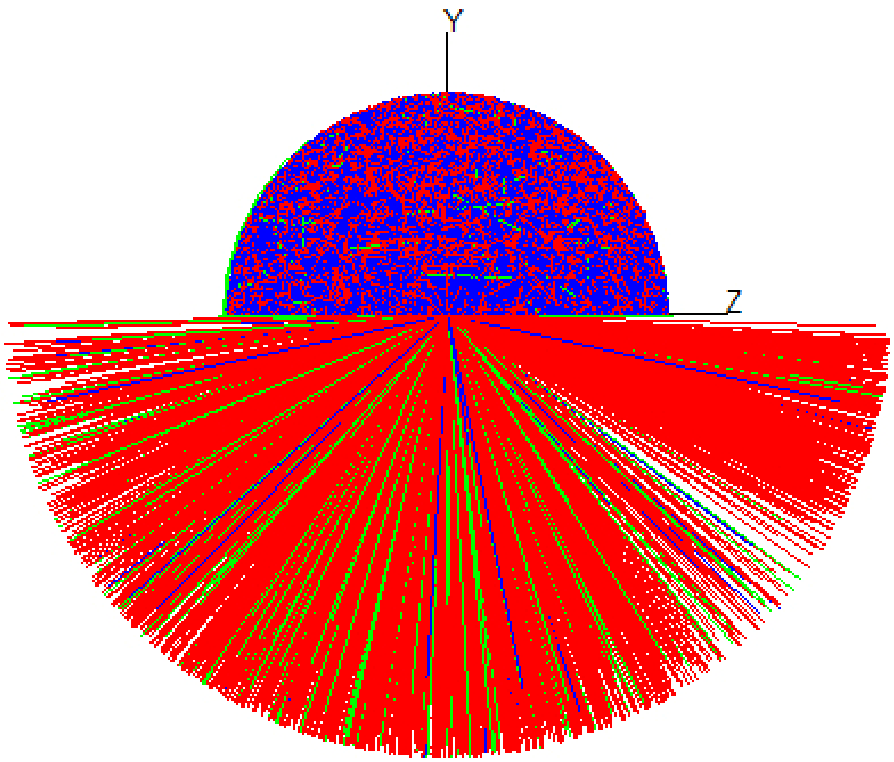

Figure 5.15: TracePro Ray-Trace Simulation

5.3.4.13 Graphic Outputs

TracePro is the only program used in the demonstration that produced illustrations of the individual ray-trace (Figure 5.15). TracePro also has several irradiance and candela reports, as noted above, that are not found in the daylighting programs. They are perceived to be useful tools for daylighting characterization, because they graphically display photometric and radiometric information of incident rays upon real or 'imagined' surfaces. A polar isocandela plot of missed rays and a polar candela distribution are illustrated below (Figures 5.16 & 5.17 respectively). The graphic outputs fully are supported by numeric reports, which is not the general case with the other programs evaluated.

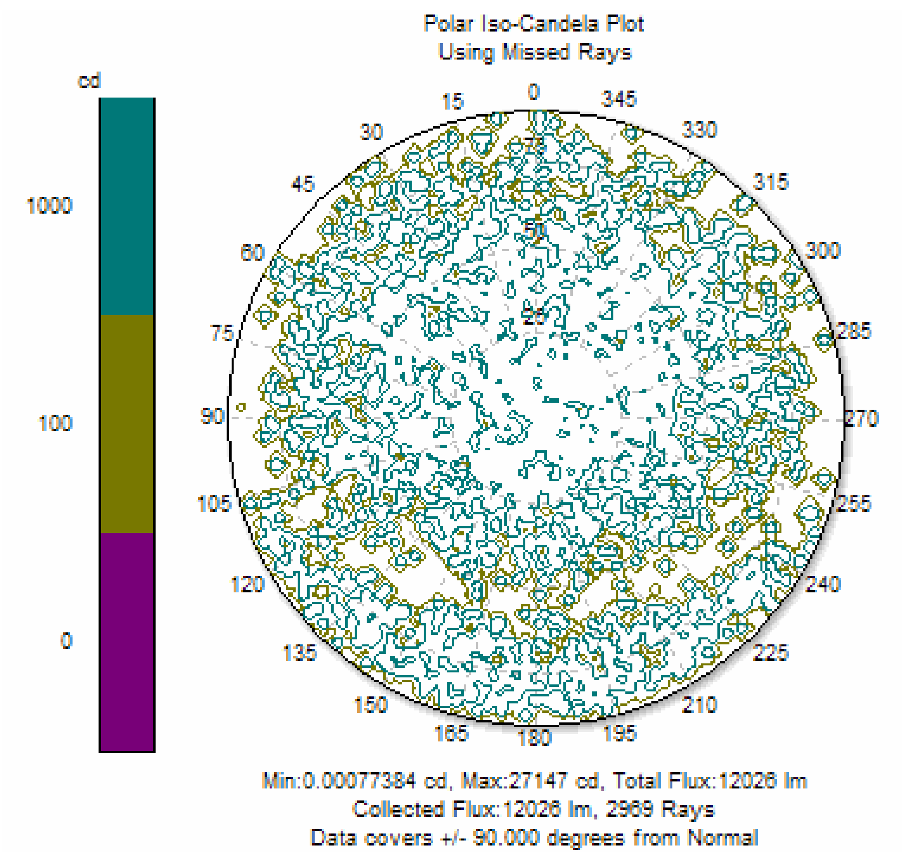

Figure 5.16: TracePro Iso-Candela Plot of Missed Rays

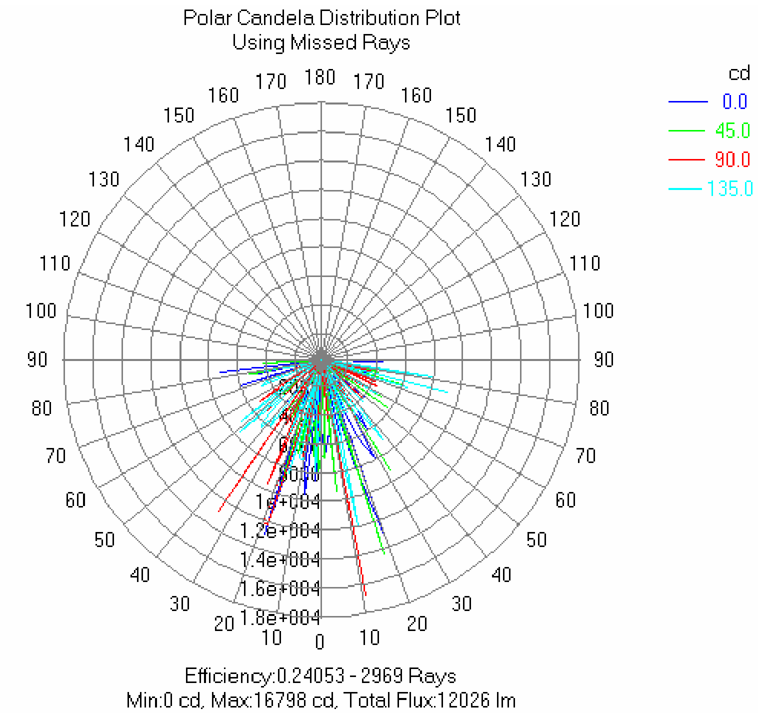

Figure 5.17: TracePro Candela Distribution Plot

5.4 Software Comparison

The demonstration process produced preliminary indications of the performance capabilities of four lighting programs. This section compares the capabilities of each program to implement the protocols of the characterization methodology. The capabilities examined include requirements, protocols, and goals of the characterization methodology. Characterization requirements include validation, IESNA file input, sky distribution and material properties. Validation is required to confirm the computational accuracy of the program. The ability to simulate sky conditions and material properties are integral to the validation. The characterization methodology sky distribution also requires the program to be able to locate the solar position by azimuth and elevation. The IESNA file is not an essential requirement, but allows completion of the loop by accepting an angular distribution file created by the characterization methodology. Characterization protocols include the five tests described in the methodology section; goniophotometer, room illuminance, visual effect, visible light transmittance, and thermal energy transmittance. The demonstration section above described how each program performed the protocols.

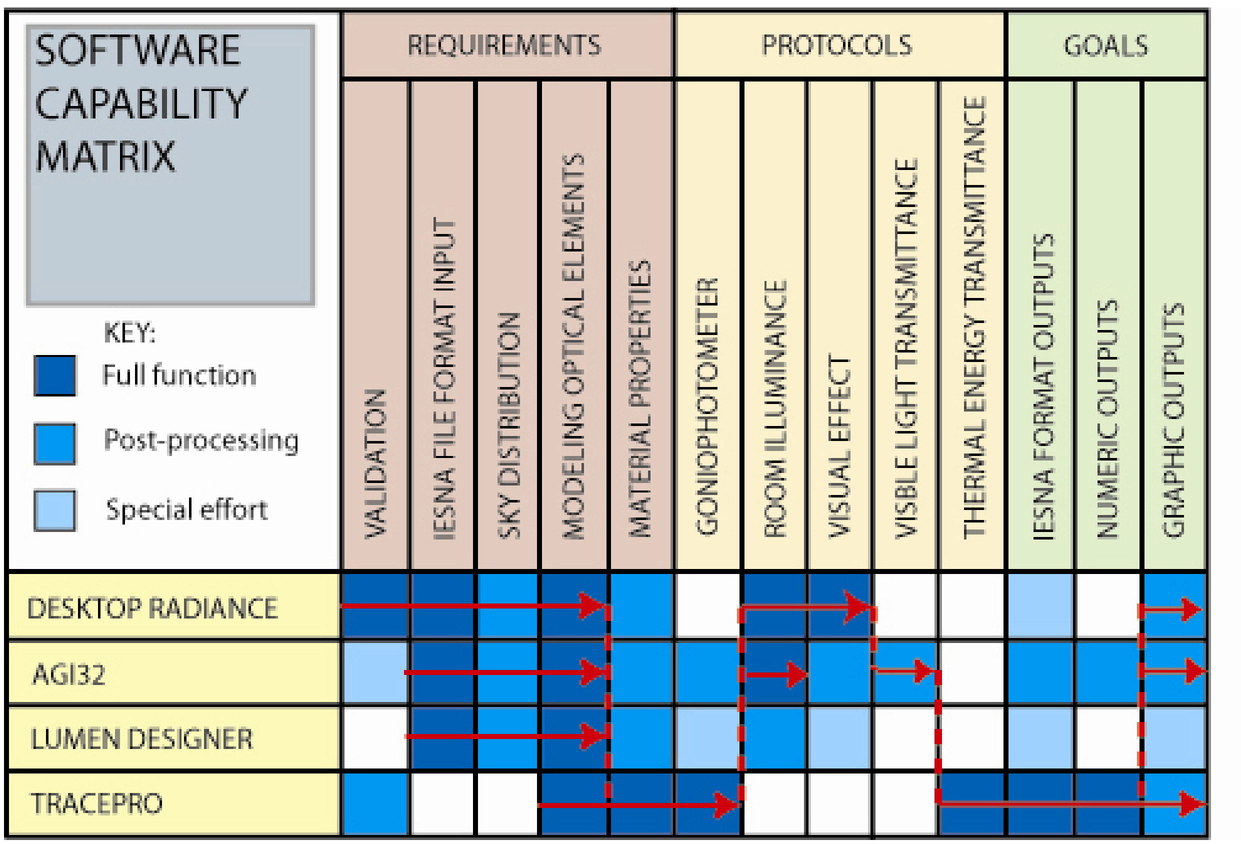

Figure 5.18: Software Capability Matrix

To evaluate the programs, a matrix has been developed rating the capabilities on a color-coded scale with values for (1) 'possible' with special effort; (2) provides useful information which requires 'post-processing', and (3) 'fully functioning' characterization methodology tool (Figure 5.18). Blanks in the matrix indicate the software can not implement the characterization protocol. The matrix values are qualitative, based upon the research experience, rather than quantitative. The values are relative in each column, although the criteria from one column to the next may be slightly different, in accordance with particularities of the capability being evaluated. The arrows on the matrix indicate the path of best capability at each stage.

Two things are clear; no one program can implement the entire characterization, and, more positively, all the capabilities exist at some level in at least one of the programs. Desktop Radiance is perceived to have a 'full function' validation, because the core program Radiance has been validated. TracePro was substantially validated by Dr. Andersen (Andersen, et al, 2003), and AGI32 is currently being validated in accordance with CIE standards. The daylighting simulation programs perform equally well on the requirements of IESNA file imports, sky distribution, and modeling of optical properties. TracePro also has 'full function' modeling of optical properties. TracePro has superior material properties. Although the full capabilities of TracePro are not necessary for architects, some of the features in TracePro might be beneficially added to architectural daylighting software. TracePro also has a 'full function' goniophotometer, because the computation is within the program. It remains a concern that the goniophotometer is not described by an image or a report of physical parameters. AGI32 has the modeling and photometer placement capability to construct a goniophotometer. However, the illuminance data requires post-processing to be converted to candela and recorded in IESNA file format. Desktop Radiance and AGI32 have 'full function' in the room illuminance protocol. Desktop Radiance has 'full function' visual effect based upon the ability to simulate luminance and illuminance isocontours on all surfaces of the simulation model. Whereas, this capability is not essential, it is superior. AGI32 and Lumen Designer are able to perform the visible light transmittance protocol by virtue of being able to locate photosensors on an 'imaginary' plane in the simulation. TracePro was able to simulate the thermal energy transmittance data, because it has radiometer measuring capability. TracePro is able to produce IESNA photometric file format outputs automatically, and has generally more comprehensive numeric reports. Graphic outputs were somewhat difficult to quantify, because Desktop Radiance, AGI32, and TracePro each had desirable but different capabilities.

5.5 Software Development Issues

The characterization methodology demonstration indicates that existing daylighting programs will either have to be modified, or new daylighting programs developed to fully implement the methodology. This section discusses a number of capabilities, both available and missing, that were revealed in the demonstration, and would be useful components in software to implement the methodology. Critical capabilities include the following:

Validation: validation by either the BRE-IDMP validation methodology, or the CIE 171-2006 test suite, which is critical to reliability of findings.

Solar Position: the ability to locate the sun and compute sky conditions based upon solar azimuth and elevation, which is critical to defining the solar resource at 145 positions on the sky dome.

'Imaginary' Measurement Planes: the ability to place individual and/or arrays of sensors spatially in the simulation to provide measurements without obstructing the performance of the simulation. These may be used to define the plane of admittance to the daylighting fixture, and plane of exit from the daylighting fixture, which are critical to visible light and thermal transmittance calculations.

Radiometric Measurement: the ability to measure radiant flux (W/m^2) with the same capability the daylighting programs have with luminance and illuminance, which is critical to the thermal performance evaluation of the daylighting fixture.

Numeric Reports: critical reports include the ability to define the simulation setting with material properties and surface areas and properties; absorption reports by surface; and, reports for individual sensors in any spatial array. It has been noted that this data is computed in the daylight simulations, but generally not available in the form of outputs.

Graphic Outputs: a combination of graphic outputs from the programs would provide the critical capability. The graphic components include photorealistic rendering; illuminance, luminance radiometric measurement, isocontours, and false color renderings on all surfaces of three-dimensional models; ray-trace visualization; and graphics with numeric readings at sensor locations.

5.6 Demonstration Conclusions

The demonstration has clearly indicated the software components exist to fully implement the proposed characterization methodology. They simply do not exist in a single program, which makes it impossible to properly implement the proposed daylighting fixture characterization methodology using currently available software. Software developments are based upon the developer's goals. Desktop Radiance focused on the graphic user interface, which emphasizes the visualization tools of Radiance. The tools exist in Radiance for a programmer to perform more of the proposed protocols, but that effort was not within the purview of this research. The goals of AGI32 and Lumen Designer, when compared to Desktop Radiance, were improved graphic user interfaces and numeric reports. AGI32 seems to have more focus on research grade daylighting accuracy than Lumen Design, as indicated by their different approaches to validation, and functional and report limitations in Lumen Designer. TracePro was designed as a tool for the physical analysis of optical design. The physical measurement goals appear to account for many program components that are useful to the proposed characterization methodology.

5.7 Quality Concerns

It is difficult to have a detailed discussion of quality concerns, because the data produced with the software programs was not experimental in nature. Predicting internal validity would require either a clear performance benchmark for validation or a comparison of computational approaches. Other levels of validity and generalizability are not discussed, because they build upon internal validity and the experimental design.

It was observed that certain anticipated correlations of data between the programs were not found. This may be because daylighting simulation is not a mature field with fully resolved computational methodologies, as Love suggested in his comparison of daylighting research to structural engineering. And, these are very complex programs with a large number of variables, which may not have been fully accounted for in the demonstration.

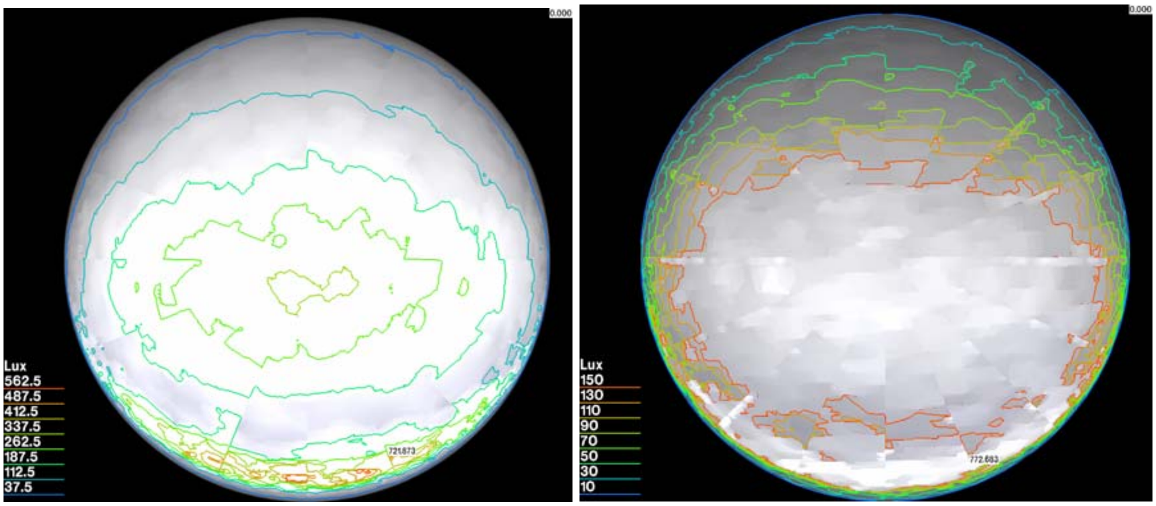

Figure 5.19: Isocontour Comparison: High quality on left and average quality on right.

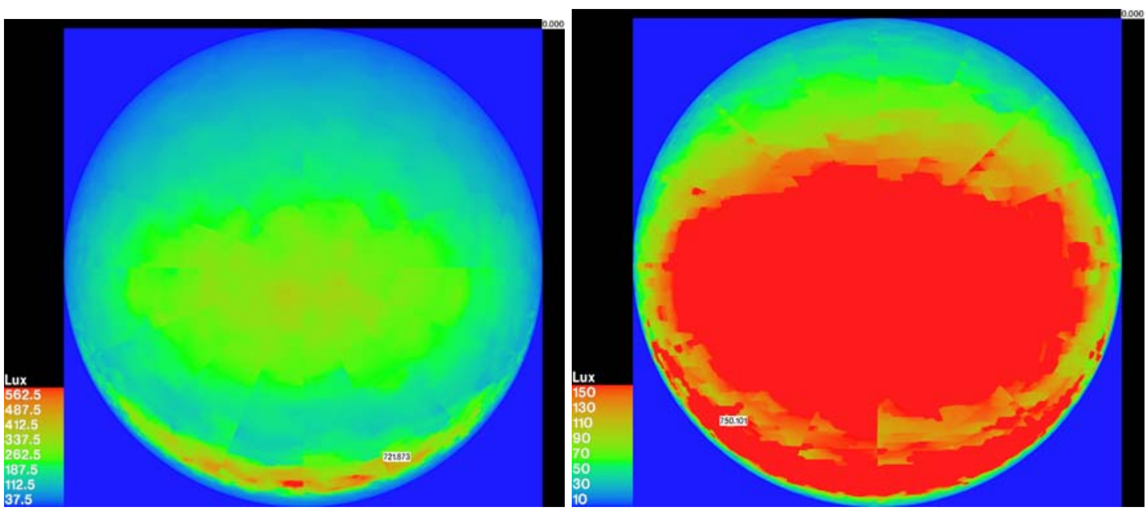

Figure 5.20: False Color Comparison: High quality on left and average quality on right.

There were two quality issues that deserve mention. All the visualization and contour plots produced exhibited blotchiness and/or jagged lines, where smooth distribution and gradations of light were expected. It has been suggested aberrations may be inherent in the way surface mesh geometry intersects in simulation programs (Ashdown, 1999). The hemisphere being tested was constructed in Desktop Radiance as surfaces in the form of faceted ball. The intersections of the facet surfaces occur on different angles and dimensions. Overlaps that occur at a ray-trace point may affect the ray tracing results. Conversations with Greg Ward revealed that higher quality simulations could ameliorate this concern. The basic Desktop Radiance simulation took approximately twenty minutes of computer time. A new simulation that took approximately one hour and twenty minutes was performed for several louvers. Figures 5.19 and 5.20 are examples of isocontour and false color images from these simulations. The longer-duration simulation is on the left and the basic simulation is on the

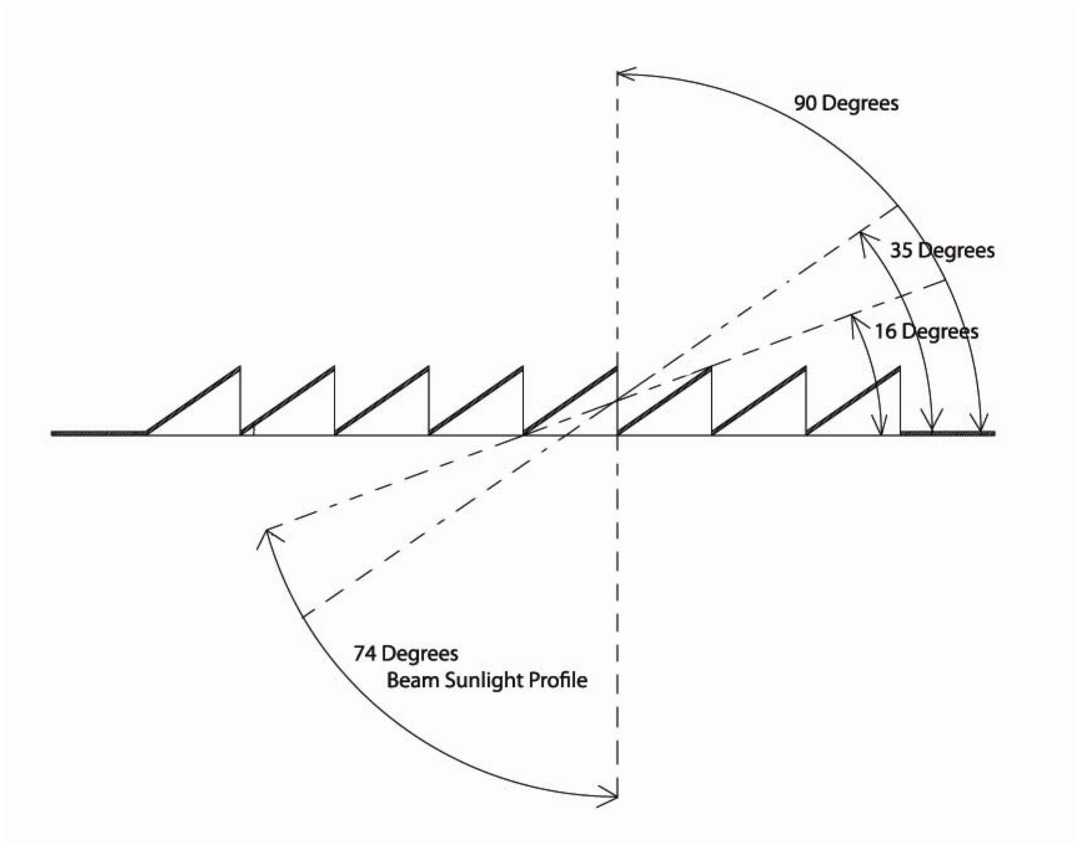

Figure 5.21: Acceptance Angles for Direct Beam Sunlight

right. The scale of the illuminance nits was varied in an attempt to focus more specifically on the light levels, which means the colors can not be compared. These images may be compared for reduced blotchiness and increased smoothness in the contour lines. There is some increase in the smoothness of the contour lines, and a marked improvement in the false color image.

The second quality concern is a need to predict which goniophotometer measurement points will be effected by beam sunlight penetrating directly through the daylighting fixture. When the sun is in certain parts of the sky, the daylighting fixture tested admits beam sunlight into the goniophotometer, which means the center of the aperture would no longer be a luminous source, as required for photometric measurements. The angles of beam sunlight admittance can be geometrically defined, (Figure 5.21). Tests with the sun in that geometric area of the sky, would need to be performed and closely examined to determine the impact on the characterization.

6.0 CONCLUSION

6.1 Benefits of the methodological tool

The proposed daylighting fixture characterization methodology represents a fundamental shift in the availability of daylighting performance data to daylighting designers. The shift is based upon defining and characterizing a daylighting fixture. This conceptualization permits the data created to be carried efficiently and effectively from one application setting to another. It is expected the use of far-field photometry with testing protocols that are already familiar to lighting designers will lead to acceptance of the proposed characterization methodology. Implementation of the characterization methodology will provide comprehensive and accessible data to enable architects, lighting designers and daylighting fixture developers to improve the quality of architectural daylighting performance. Several important advantages of the proposed characterization methodology to daylighting designers include:

- Standardized performance data allowing comparison of daylighting fixtures.
- Three-dimensional analysis of visible light distribution.
- Thermal transmittance data.
- Data may be integrated with electric lighting data in existing design software.

Virtually all buildings admit daylight for human occupants, yet only a small percentage of them have performance-based daylighting design. And, as noted in the introduction, some of those may have performance issues. The proposed methodology will be enabling for designers as a performance specification tool and a development tool. A designer will be able to select daylighting fixtures from a database that meet the needs of particular applications. The choice in *selection* maintains the role of the designer. The principle of super-positioning allows simple daylighting fixtures, such as the louver demonstrated above, to be located in patterns and/or re-sized in linear or other configurations. The characterization methodology will cause the design process for architectural daylighting specification to be compatible with electric lighting design. It is also envisioned that the comprehensive nature of this methodology will contribute to the evolutionary development and functional optimization of daylighting fixtures.

6.2 Research Audience

The proposed characterization methodology will be inextricably linked to and substantiated by predicted outcomes. If the data obtained has no usefulness, then the methodology has no usefulness. This view is colored by my experience as a practitioner, where practical information and problem-solving concepts were highly valued. The evaluation methodology is intended to provide a consistent framework responding to the analysis of both methodological shortcomings and shortcomings in the usefulness of data available from much daylighting research.

There is a gap between research and practice, where researched applications tend not to become building applications, except when the researcher has provided a design consulting service for a specific project. This was alluded to by Selkowitz when he discussed the lack of well daylighted buildings constructed over the last 25 years (Selkowitz, 1998). The scope of daylighting research needs to be reconsidered, and this dissertation proposes a research methodology that might provide the illusive 'useful information' at the appropriate level to be more readily incorporated in diverse daylighting applications. A conceptually based approach relating research to a typological design process was recommended by the European Concerted Action Programme on Daylighting (Baker, Franchiotti & Steemers, eds., 1993). This research into the basic performance of daylighting components fits their suggested model.

Thus, this research is not directed to a single user group, but toward those interested in critical questioning of pre-existing notions and the new information that results.

Consequently, it is directed to several audiences, each relating to different aspects of the research on a level that is appropriate and useful to them. These groups are:

- **Architects and engineers** who will benefit directly in practice.
- **Researchers** who will advance daylighting design knowledge based upon a critical evaluation supporting or refuting my research.
- **Product manufacturers** who will utilize the evaluation methodology if it becomes accepted.

6.2.1 Architects and Engineers

Architects and engineers will benefit directly from the proposed research in the sense that new information focused on their needs will be readily accessible. The outcomes primarily, rather than the evaluation methodology, are directed toward them. The proposed research will provide useful data at the conceptual stages to help designers, particularly architects, select daylighting control components that meet project performance requirements. Graphic performance depictions will provide designers with a strong and substantiated conceptualization of component performance for visible light and thermal gain. This is information that architects currently do not have, and it is qualitatively different than research that addresses particular applications. Architects may avoid application research because of apparent physical constraints, i.e., their building must look like the experimental setting to perform like the experiment, whereas, conceptual information anticipates being modified to meet the programmatic requirements of particular projects. Extensive and detailed data regarding outcomes will be useful to expert consultants, including engineers and lighting designers, who will be assisting in developing the architect's conceptual design. I do not foresee professionals adopting the evaluation methodology, because it only focuses on illuminance and irradiance for one component of a building. There are other tools, such as whole building simulation software that will allow them to evaluate building systems in relationship to each other, and to assess overall building performance.

6.2.2 Researchers

The second user group, those who will increase daylighting design knowledge based upon a critical evaluation of my research, is comprised of other researchers. They are the most critical user group, because they are positioned to either further develop or refute the research and its application. My research methodology builds on existing knowledge while questioning pre-conceived notions to produce new outcomes that result. The methodological approach positions this research well for other researchers to engage at many levels.

Researchers will critically evaluate the proposed methodology as part of a developmental trend toward more comprehensive performance data. The Daylight Factor method, which only dealt with diffuse skylight, evolved into the Lumen Method for Toplighting recommended by IESNA (IES Lighting Handbook, 2000). Other research develops a vertical and horizontal illuminance methodology (Love, 1990). The vertical and horizontal illuminance method, although focusing on side lighting, is conceptually lacking only the angular distribution of the characterization methodology I propose. The thermal characterization may be more creative, because daylighting researchers are still finding their way with thermal issues. The logical step to characterize thermal performance of the treatments analogously to glazing thermal performance is not a dramatic move. The unanswered question is whether or not researchers will perceive the data produced as helpful to bridge the gap between research and practice. One aspect of research is to create questions for the research community. Is this the best performance characterization methodology? Is there a conceptualization that more fully integrates all the lighting sources in a building? How much of a problem is thermal load in well daylighted buildings? What are the best toplighting systems for particular problems of illuminance and irradiance control? Can human factors be related to daylighting performance?

6.2.3 Product Manufacturers

In the long range the evaluation methodology is directed toward product manufacturers. Skylights are generally characterized as ‘specialty products’. The proposed methodology is designed to characterize them conventionally in the sense that the proposed characterization allows comparison and possibly interchangeability with other lighting products. If the proposed evaluation methodology is adopted as a guide for performance characterization of skylights, manufacturers will implement the testing on all their products. Manufacturers may also use the methodology in their ongoing efforts to develop new products. Thus, architects, product manufacturers and researchers will all engage with the research, each at the appropriate level. The challenge is to reach all these groups effectively.

6.3 Data Analysis

The usefulness of a methodology is based upon the data produced and how it may be applied. This section discusses how the data analysis may inform daylighting fixture application and design. The two essential differences between a daylighting fixture and an electric fixture are that daylighting performance varies over the course of the day, and daylighting is a renewable energy source. Thus, analysis of data performance over time and analysis of the efficacy of the daylighting fixture as an energy source are important concerns.

6.3.1 Transmittance Classification

Daylighting fixture performance over time may be understood in general by variability in visible light and thermal energy transmittance, and, more specifically, by variability of candela values.

Visible light transmittance performance varies within five basic ranges, which are as follows:

- The daylighting fixture produces a constant transmittance percentage, regardless of the solar position in the sky dome.
- The daylighting fixture admits a greater percentage of visible light when the sun is at a higher elevation.
- The daylighting fixture admits a lesser percentage of visible light when the sun is at a higher elevation.
- The daylighting device has a selective performance range where an element such as a shading device produces a significant step in transmittance at a given solar position.
- The daylighting fixture has dynamic control characteristics that vary transmittance.

A similar analysis can be performed for thermal energy transmittance. Together, these analyses will be good indicators of the energy performance efficacy of the daylighting fixtures. Graphing transmittance characteristics overtime produces different shapes. Figure 6.1 illustrates plots of four types of transmittance performance on the available illuminance for a June day. The selective performance type is not plotted.

Similar graphs may be produced for thermal energy transmittance. Each graph illustrates information that is not currently available to daylighting designers, and is capable of informing daylighting fixture design and specification decisions.

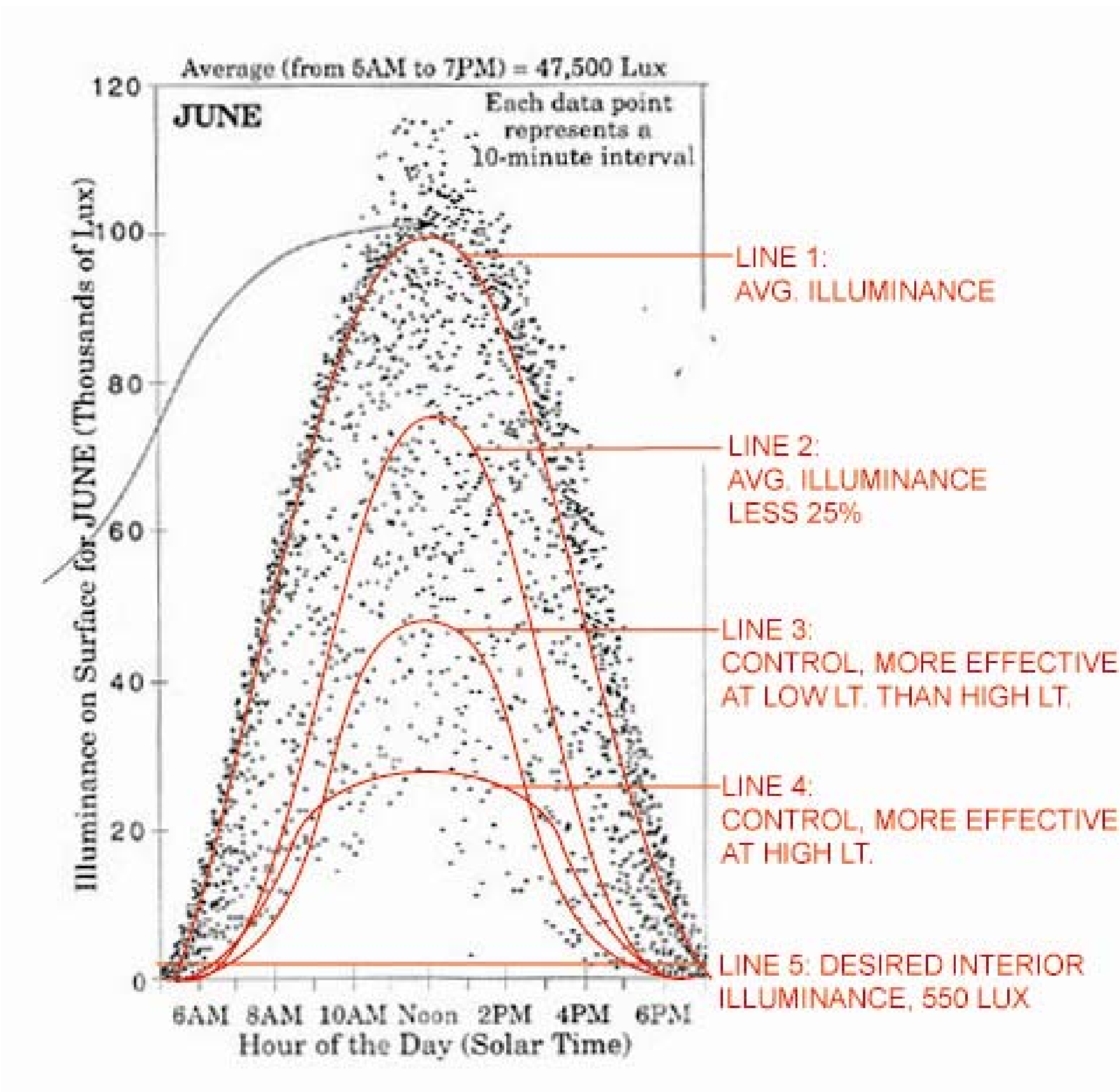

Figure 6.1: Visible Light Transmittance Over Time

(Graphed over illuminance data by Place)

The relationship between visible light transmittance and thermal energy transmittance indicates the energy performance efficacy of a daylighting fixture. The energy performance efficacy ratio may also be plotted over time. Since 50% of thermal energy is contained in the visible spectrum, the highest ratio would be 2:1. The energy performance efficacy ratio of daylighting fixtures is not currently available to daylighting designers and specifiers.

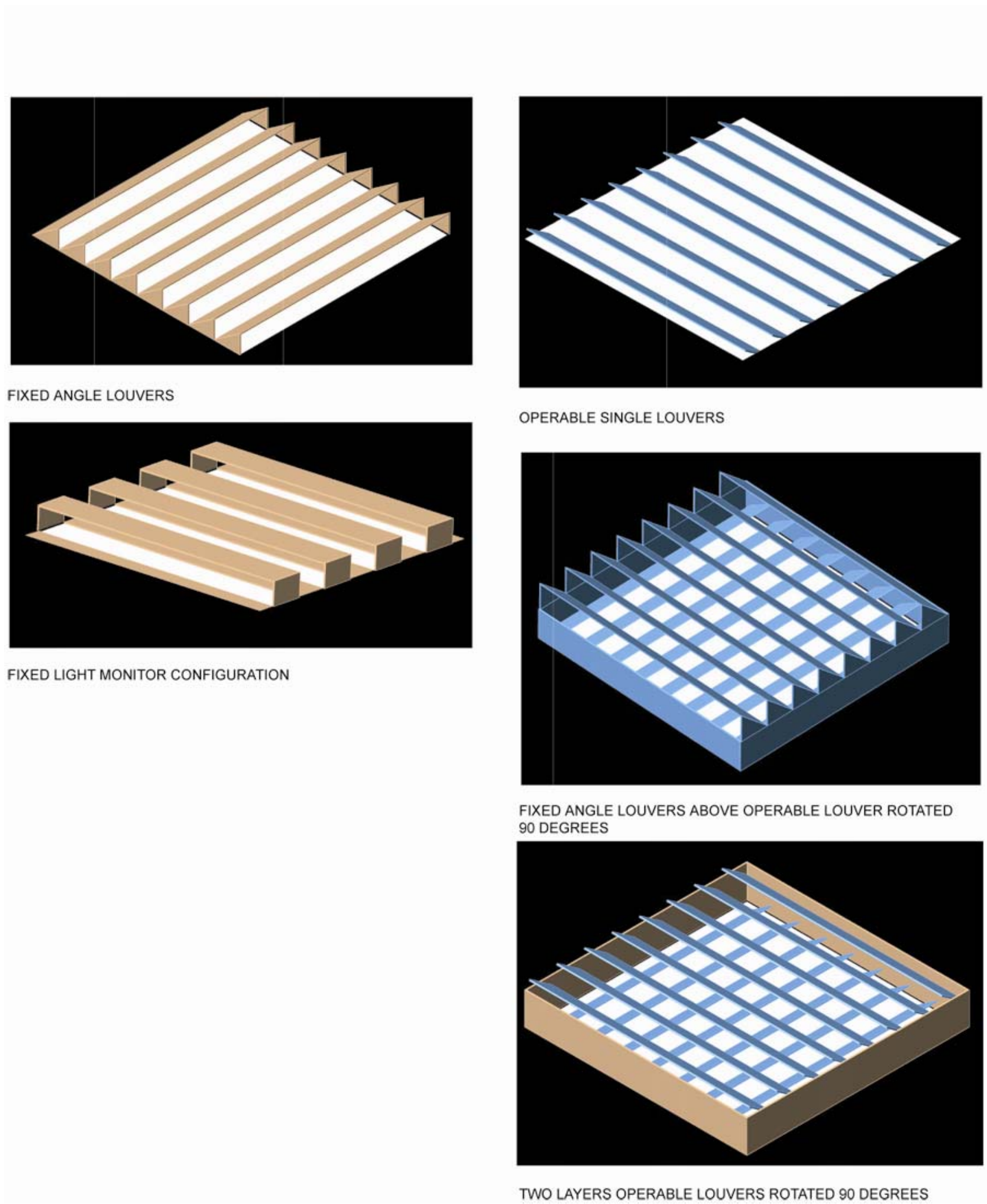

Figure 6.2: Louver Load Management Control Typology

6.2.2 Typological Classification of Data

Professionals require knowledge about daylighting components and systems that 'can be classified with respect to luminous behavior' (Baker, Fanchiotti & Steemers, Eds., 1993). Louvers, as mentioned in the demonstration section, are common daylighting load management devices that may be typologically classified, see Appendix G for description (Figure 6.2). Upon developing candela distributions for various types of daylighting fixtures, the data for each classification may be analyzed by statistical methods to determine variability of luminous intensity over the course of a day, allowing the designer to select occupancy/time sensitive performance. Variability can be interpreted in terms of quantity and quality of daylight. Greater luminous intensity indicates higher quantity, while less variability indicates higher quality. Undesirable conditions such as contrast and over-lighting can be determined from the analysis.

6.4 Future research

This research generates several clear paths for future research for researchers, daylighting designers and daylighting fixture manufacturers. Researchers are necessary to develop the characterization methodology and producing a simulation program to implement the methodology. Research needs to be done to vet the methodology for clarity, simplicity and validity. Can the characterization methodology be simplified to fewer tests that will produce the similarly usable data? Is all the data as useful as perceived by this researcher? Are different forms of data necessary to integrate daylighting design with electric lighting design?

Producing or developing a daylighting simulation program to implement the characterization methodology will be a major undertaking. Further questions need to be answered about the characterization methodology during that process. Is it possible to reduce the number of settings? No one has explored the capabilities of goniophotometers to perform tests other than angular flux distribution. Can the goniophotometer configuration be used to measure visible light and/or thermal energy transmittance in a new simulation program?

Designers and manufacturers will have to embrace the concept of a daylighting fixture to advance this research. The concept exists for a electric lighting fixture, and all the tools and techniques used for electric lighting design will become available to daylighting designers if this methodology is accepted. The obvious benefit is that daylighting and electric lighting will be designed together, which is a significant opportunity for improved energy performance in buildings. Standardized testing of daylighting fixtures to producing a consistent product data base available to daylighting designers is, therefore, an important area of future research.

Ultimately, it is necessary to complete the development of the new characterization methodology and allow its usefulness to be determined in practice.

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APPENDICES

APPENDIX A:

CIE Clear and Overcast References Skies, CIE 110 -1994, 'Spatial Distribution of Daylight – luminance Distributions of Various Reference Skies".

3. CLEAR SKY AND OVERCAST SKY AS REFERENCE SKIES

3.1 Clear sky

3.1.1 Relative luminance distribution

Expression of the CIE standard clear sky [1.1-4, 1.1-6] is one of the reference skies.

For practical purposes the sky luminance L_{cl} (γ_s, γ, ζ) at an arbitrary position P of the sky shown with γ, ζ, α and α_s in Fig.3.1 depends on the solar altitude γ_s and is expressed as a relative value. (Symbols are listed in 6.4 of Chapter 6.)

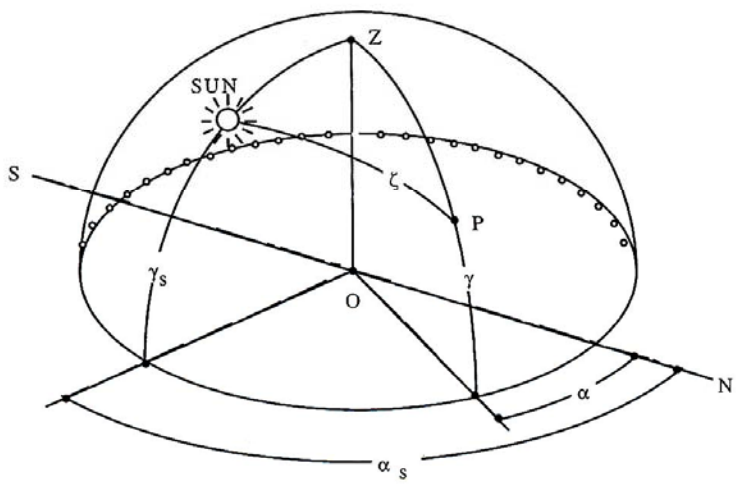


Fig.3.1. Angle signification for the positions of the sun and a sky element P

$$\frac{L_{cl}(\gamma_s,\gamma,\zeta)}{L_{zcl}(\gamma_s)} = \frac{\phi(\gamma)\cdot f(\zeta)}{\phi\left(\frac{\pi}{2}\right)\cdot f\left(\frac{\pi}{2}-\gamma_s\right)} \qquad (3.1)$$

where, $L_{zcl}(\gamma_s)$: clear sky luminance of the zenith

$\phi(\gamma) = 1 - \exp(-0{,}32/\sin\gamma)$, $\phi(\pi/2) = 0{,}27385$

$f(\zeta) = 0{,}91 + 10\exp(-3\zeta) + 0{,}45\cos^2\zeta$

$f(\pi/2 - \gamma_s) = 0{,}91 + 10\exp\{-3(\pi/2 - \gamma_s)\} + 0{,}45\cos^2(\pi/2 - \gamma_s)$

$\zeta = \arccos(\sin\gamma_s \sin\gamma + \cos\gamma_s \cos\gamma \cos|\alpha_s - \alpha|)$

For polluted atmosphere, $f'(\zeta)$ and $f'(\pi/2 - \gamma_s)$ are used for $f(\zeta)$ and $f(\pi/2 - \gamma_s)$ respectively.

$f'(\zeta) = 0{,}856 + 16\exp(-3\zeta) + 0{,}3\cos^2\zeta$

$f'(\pi/2 - \gamma_s) = 0{,}856 + 16\exp\{-3(\pi/2 - \gamma_s)\} + 0{,}3\cos^2(\pi/2 - \gamma_s)$

γ_s, γ, ζ, α and α_s : units [rad]

Recently Kittler [1.2-13] has pointed out that the CIE standard indicatrices $f(\zeta)$ (by Kittler) and $f(\zeta)$ (by Gusev) correspond to T_{vL} = 2,45 and 5,5 respectively, where T_{vL} is illuminance turbidity factor (see 6.1, equation (6.1)).

3.1.2 Zenith luminance

According to the climate condition in a given geographical location an appropriate equation can be adopted from the equations shown in 6.1.2.1. Turbidity factor (T_L) or illuminance turbidity factor(T_{vL}) can be used as climate index of clear sky in the location. (It is desirable to know the relationship between the horizontal illuminance from unobstructed clear sky and the zenith luminance of the same sky with distribution expressed by eq.(3.1). Krochmann and Aydinli [5.1-1] proposed a method of obtaining such a relationship. (See 6.1.2.1.) To know this relation is also desirable for the overcast or intermediate sky, and this is described in the following sections 3.2 and 4)

3.2 Overcast sky

3.2.1 Relative luminance distribution

Expression of the CIE standard overcast sky [1.4-1, 1.1-6] is one of the reference skies. It is given by

$$\frac{L_{oc}(\gamma)}{L_{zoc}(\gamma_s)} = \frac{1+2\sin\gamma}{3} \qquad (3.2)$$

3.2.2 Zenith luminance

Several equations shown in 6.1.2.3 have been proposed. According to purposes of calculation an appropriate equation can be adopted from these equations.

The horizontal illuminance from the unobstructed overcast sky is $E_{voc}(\gamma_s) = (7/9)\,\pi \cdot L_{zoc}(\gamma_s)$, where $L_{zoc}(\gamma_s)$ is the zenith luminance.

APPENDIX B:

SkyCalc Photometric File, Howlett, O., Jon McHugh, Lisa Heschong, 'Skylight Design: Photometric Characteristics', 2004 IESNA Annual Conference Proceedings, IESNA, New York

IESNA:LM-63-1995

[TEST] LSI T15773-40A; NBI PIER TEST NO.6

[LUMINAIRE] Dome skylight; single glazed; white acrylic glazing

[OTHER] 3 ft deep white light well

[_SKYLIGHT] yes

[_NOTE] Header angles are in degrees counterclockwise looking down;

[_MORE] 0 = North for major axis and 0 = South for solar azimuth

[_MAJOR_AXIS] 0

[_GLAZING_VT] 0.626

[_GLAZING_HAZE] 1.000

[_GLAZING_CLARITY] 0.187

[_UNITS_TYPE] Feet

[_GLAZING_AREA] 16

[_INCLUDE_FILE] None

[_WELL] yes

[_WELL_HEIGHT] 3

[_WELL_WIDTH] 4

[_WELL_LENGTH] 4

[_WELL_REFL] 0.82

[_REFL_TYPE] Diffuse

[_BOTTOM_DIFFUSER] No

[_DIFFUSER_VT]

[_DIFFUSER_HAZE]

[_DIFFUSER_CLARITY]

[_SOLAR_ELEVATION] 40

[_SOLAR_AZIMUTH] -69

[_SKY_RATIO] 0.08

[_SKY_CONDITION] clear
[_TEST_LONG] 111.91
[_TEST_LAT] 33.62
[_TEST_ELEV] 1500
[_TEST_DATE] 09/03/2001
[_TEST_TIME] 09:23
[_TEST_TZ] MST=7
TILT=NONE
1 1000 0.823 11 17 1 1 4 4 0
1 1 0
0 5 15 25 35 45 55 65 75 85 90
0 22.5 45 67.5 90 112.5 135 157.5 180 202.5 225 247.5 270 292.5 315 337.5 360
182.63 179.22 185.81 165.93 119.38 75.67 38.66 29.81 12.23 2.65 0.
182.63 184.18 196.86 190.13 141.76 83.87 37.71 28.19 11.57 2.62 0.
182.63 191.14 213.91 212.05 177.94 92.19 44.19 26.72 11.23 2.58 0.
182.63 193.93 225.26 232.7 188.97 113.59 35.47 26.24 10.99 2.29 0.
182.63 191.72 223.89 230.99 174.06 103.79 35.92 26.52 11.06 2.17 0.
182.63 189.73 207.65 198.96 148.27 86.12 36.21 27.19 11.3 2.11 0.
182.63 183.61 183.35 168.34 129.2 71.26 41.18 28.84 11.76 2.68 0.
182.63 186.8 175.48 141.76 104.17 68.08 41.05 32.03 12.74 3.01 0.
182.63 180.06 167.98 130.81 94.29 64.1 43.77 35.15 13.76 3.31 0.
182.63 177.76 155.12 115.23 83.48 60.54 44.09 37.61 14.36 3.44 0.
182.63 174.35 143.82 107.86 77.63 59.98 46.09 40.4 15.36 3.8 0.
182.63 171.87 141.71 103.71 75.18 59.77 48.34 43.37 16.12 3.34 0.
182.63 170.87 138.84 108.62 80.64 61.22 50.36 43.72 16.25 4.11 0.
182.63 174.59 142.52 111.77 80.28 59.76 47.48 40.55 15.16 3.24 0.
182.63 180.42 153.6 120.13 88.2 63.81 44.11 35.86 14.05 3.62 0.
182.63 176.25 171.5 141.34 101.94 67.72 41. 32.16 13.04 2.91 0.
182.63 179.22 185.81 165.93 119.38 75.67 38.66 29.81 12.23 2.65 0.

APPENDIX C:

Ray-tracing calculation concepts and techniques:

AGI32:

The following is excerpted from AGI32/Help:

Ray Tracing - Concepts

Ray tracing is a rendering technique that creates realistic images by simulating the method that light wave rays travel. In AGI32, backwards ray tracing is applied, which means that the rays are traced from the observer position backwards into the scene. For every pixel in the generated Ray Trace image, four pixels (or more, depending on the anti-aliasing level) are traced to the corner of each pixel to check for interactions with the objects in each scene. Every time an object is encountered, the color of the surface at that pixel is calculated. If the surface is specular or transmissive, additional secondary rays are traced to determine the contribution of reflected and refracted light and shadows to the final surface color.

In the real world, rays begin at the light sources and are recursively traced from surface to surface, illuminating all the objects in their path. The light reflects and refracts through transparent surfaces over and over again. Only a partial amount enters our eyes or a camera lens. The vast majority of rays never encounter the observer directly, at least in the initial few bounces. Following the rays through this forward ray tracing technique, past the first few bounces, is impractical because it would take an unreasonable amount of time to render the scene and trace the majority of rays back to the observer.

AGI32 allows you to consider both forward ray tracing and backwards ray tracing at the same time by selecting the Ray Trace Direct Illumination option in the Ray Tracing Parameters dialog. When this option is chosen, the Number of Bounces selected determines how many recursive (or repeating) rays are traced both forwards and backwards from each object intersection. Be aware, each light source (both the Sun in daylighting and Electric sources) will require a complete set of ray traces through each pixel, so your processing time may increase dramatically. The calculation time is proportional to the number of sources in each environment, regardless of whether they are directly visible in the current scene.

The Ray Trace images AGI32 generates are based on the Radiosity calculations AGI32 has previously performed. The Radiosity calculations provide the Interreflected flux transfer distribution to the final images. When Ray Tracing is applied to the specified Viewpoint, the

Direct component previously calculated in the Radiosity process is removed, and added again through Ray Tracing back to the environment.

Lumen Designer:

The following is excerpted from Lumen Designer/Help:

About Calculations

Radiosity calculation provides the ability to simulate the way in which real world scenes are lit not only by direct light, but also by diffuse light which bounces off directly lit surfaces onto other areas of the scene which are not directly lit. Lumen Designer offers a radiosity calculation, followed by a hybrid rendering. This combined solution uses the radiosity calculations as its starting point. From a specified perspective, it then removes and recalculates the direct light, accounting for specularity. Whereas radiosity does not consider specularity of surfaces, the hybrid solution uses raytracing to model individual rays of light from a perspective and does consider specularity.

Features of radiosity calculations:

- *Generating an image of a radiosity solution is a two phase process. In the first phase a radiosity solution is computed; in the second phase, an image of the solution is generated from a specific view point.*
- *Since the solution generated is independent of view, the scene can be rendered from different viewpoints without needing to run the radiosity simulation more than once.*
- *Progressive radiosity does not produce a single answer; the longer it runs the more accurate the result.*
- *Progressive simulation, allowing a balance to be made between speed and accuracy based on the user's requirements.*
- *Adaptive triangulation algorithm, providing high quality solution meshes without over-meshing.*
- *Visibility for indirect illumination is performed efficiently by the raytracer module, minimizing solution times and memory requirements.*
- *Support for both view-independent and view-dependent meshing, with the latter delivering reduced solution times or increased accuracy.*

Radiosity Concepts:

The radiosity method is used to evaluate the distribution of all the light energy in an environment; by applying the conservation of energy at every surface. This is in contrast to other rendering techniques, where only the light entering the camera is modelled. The solution generated encapsulates the light distribution throughout the scene, accounting for all diffuse interreflections, and is independent of any particular viewpoint. It should be understood that the radiosity algorithm solves the lighting problem, not the visibility *problem. Once the solution has been generated, images can be rendered using standard visibility and shading algorithms.*

Advantages of radiosity techniques:

- *The method accurately models environments where matte surfaces diffusely reflect light in all directions, including towards other matte surfaces; the inside of a building is a common example of such an environment. It should be noted that many surfaces in such an interior are not lit by any direct illumination at all, and are lit only because light reaches them having bounced off other surfaces in the environment. In fact, such illumination may be intentional, on the part of the architect, or lighting designer.*
- *Note that a surface illuminated indirectly may appear to be a different color than it would appear if lit directly, since color from one surface can 'spill' or 'bleed' onto another, particularly if bright colors are placed next to more subdued hues.*

Radiosity is therefore an important technique for architects, builders and lighting engineers, as well as for more general computer graphics users, who are simply interested in creating realistic images.

Disadvantages of radiosity techniques:

- *It is costly in terms of computer time and memory. It is hard to give definite rules, but a fully converged radiosity solution would typically be markedly more costly to evaluate than a single ray traced image. When only partially-converged solutions are required, or when multiple images of the same scene are required, then the pendulum swings back in favor of the radiosity method.*

The method remains an efficient technique for the reproduction of physically accurate lighting conditions in a large class of common scenes.

Three stages of a radiosity solution:

1. *A mesh of patches is produced on all of the active geometry in your model.*
2. *The radiosity value for each patch is computed.*
3. *The solution is displayed on each calculation grid point, as well as in the rendered view*

APPENDIX D:

C.I.E. sky arguments used in Radiance, from Greg Ward via e-mail, fall 2005.

3. CLEAR SKY AND OVERCAST SKY AS REFERENCE SKIES

3.1 Clear sky

3.1.1 Relative luminance distribution

Expression of the CIE standard clear sky [1.1-4, 1.1-6] is one of the reference skies.

For practical purposes the sky luminance $L_{cl}(\gamma_s, \gamma, \zeta)$ at an arbitrary position P of the sky shown with γ, ζ, α and α_s in Fig.3.1 depends on the solar altitude γ_s and is expressed as a relative value. (Symbols are listed in 6.4 of Chapter 6.)

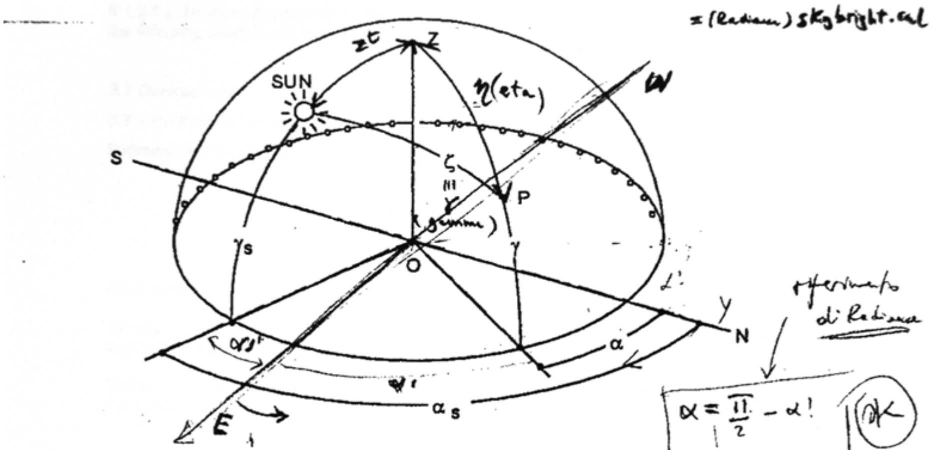


Fig.3.1. Angle signification for the positions of the sun and a sky element P

$$\frac{L_{cl}(\gamma_s,\gamma,\zeta)}{L_{zcl}(\gamma_s)} = \frac{\phi(\gamma)\cdot f(\zeta)}{\phi\left(\frac{\pi}{2}\right)\cdot f\left(\frac{\pi}{2}-\gamma_s\right)} \qquad (3.1)$$

where, $L_{zcl}(\gamma_s)$: clear sky luminance of the zenith

- $\phi(\gamma) = 1 - \exp(-0{,}32/\sin\gamma)$, $\phi(\pi/2) = 0{,}27385$
- $f(\zeta) = 0{,}91 + 10\exp(-3\zeta) + 0{,}45\cos^2\zeta$
- $f(\pi/2 - \gamma_s) = 0{,}91 + 10\exp\{-3(\pi/2 - \gamma_s)\} + 0{,}45\cos^2(\pi/2 - \gamma_s)$

$\zeta = \arccos(\sin\gamma_s \sin\gamma + \cos\gamma_s \cos\gamma \cos|\alpha_s - \alpha|)$

For polluted atmosphere, $f'(\zeta)$ and $f'(\pi/2 - \gamma_s)$ are used for $f(\zeta)$ and $f(\pi/2 - \gamma_s)$ respectively.

$f'(\zeta) = 0{,}856 + 16\exp(-3\zeta) + 0{,}3\cos^2\zeta$

$f'(\pi/2 - \gamma_s) = 0{,}856 + 16\exp\{-3(\pi/2 - \gamma_s)\} + 0{,}3\cos^2(\pi/2 - \gamma_s)$

γ_s, γ, ζ, α and α_s : units [rad]

5

Recently Kittler [1.2-13] has pointed out that the CIE standard indicatrices f (ζ) (by Kittler) and f (ζ) (by Gusev) correspond to T_{vL} = 2,45 and 5,5 respectively, where T_{vL} is illuminance turbidity factor (see 6.1 equation (6.1)).

3.1.2 Zenith luminance

According to the climate condition in a given geographical location an appropriate equation can be adopted from the equations shown in 6.1.2.1. Turbidity factor (T_L) or illuminance turbidity factor(T_{vL}) can be used as climate index of clear sky in the location. (It is desirable to know the relationship between the horizontal illuminance from unobstructed clear sky and the zenith luminance of the same sky with distribution expressed by eq.(3.1). Krochmann and Aydinli [5.1-1] proposed a method of obtaining such a relationship. (See 6.1.2.1.) To know this relation is also desirable for the overcast or intermediate sky, and this is described in the following sections 3.2 and 4)

3.2 Overcast sky

3.2.1 Relative luminance distribution

Expression of the CIE standard overcast sky [1.4-1, 1.1-6] is one of the reference skies. It is given by

$$\frac{L_{oc}(\gamma)}{L_{zoc}(\gamma_s)} = \frac{1+2\sin\gamma}{3} \qquad (3.2)$$

3.2.2 Zenith luminance

Several equations shown in 6.1.2.3 have been proposed. According to purposes of calculation an appropriate equation can be adopted from these equations.

The horizontal illuminance from the unobstructed overcast sky is $E_{voc}(\gamma_s) = (7/9)\,\pi \cdot L_{zoc}(\gamma_s)$, where $L_{zoc}(\gamma_s)$ is the zenith luminance.

APPENDIX E:

Simulation procedures

DESKTOP RADIANCE SIMULATION PROCEDURE:

The Goniophotometer is simulated as follows:

Setting: A hemisphere with a 58 feet diameter is created in AutoCad. The intersections of the facets of the sphere are coordinated with the photosensor locations, i.e. at 5^0 of elevation and 22.5^0 of azimuth. A simulated roof plane .25" thick with a 4' by 4' aperture at the center is place of the hemisphere. The daylighting louver to be assessed is placed in this aperture.

Photosensor Location:

Photosensors in Desktop Radiance must be placed on a plane. This would require 188 reference planes be inserted in the model. It was determined to evaluate illuminance on the hemisphere without photosensors.

Material Properties: Using the Material Editor, the surface of the hemisphere and both sides of the roof plane were defined as black with zero reflectance. All surfaces of the louver were defined as diffuse white with.85% reflectance.

Simulation Settings: The "Simulation" command is used to create the daylighting settings for the scene. Sky conditions and location were chosen, and camera position and number of bounces were set.

Running Simulation:. The "simulate" command is used and the calculations are run.

Graphic Outputs: The .RAD files created of the simulations could be saved as .TIFF to print or export..

Numeric Outputs: Illuminance reports were available for flat grids, but photosensors on different planes had to have separate simulations. Since better simulations of the goniphotometer took approximately an hour, it was determined not to seek that information.

Simulation Procedure – Room

Setting: A test room was constructed in AutoCAD 2000 file. The room is 40 feet long, 20 feet wide, and 10 feet high. Centered on the room's ceiling is a 4' by 4' aperture. A daylighting louver has been placed in this aperture.

Photosensor Location: The strength of this program in support of the assessment is the illuminance isocontour display. The isocontours are illustrated on all surfaces of the model. It was determined not to proceed with photosensor grids.

Material Properties: Using the Material Editor, the interior surfaces of the room and the louver were defined as diffuse white with.85% reflectance. The exterior of the room was defined as flat black with 100% absorption.

Simulation Settings: Same as above.

Running Simulation: Same as above.

Graphic Outputs: The rendered visual effect and the illuminance isocontours were produced.

Numeric Outputs: As notes above, it was determined not to produce grid data.

AGI32 SIMULATION PROCEDURE:

AGI32 – Simulation Procedure – Goniophotometer

Setting: A box with a series of 16-sided polygons imported from an AutoCAD 2000 file. The box is 60 feet long, 60 feet wide, and 30 feet deep. Centered on the box's "ceiling" is a 4' by 4' aperture. A daylighting louver has been placed in this aperture.

Photosensor Location:

1.) The "CalcPts – Scattered" command is used to set a control calculation point outside of the box.

2.) The points of each polygon represent the photosensor locations of a goniophotometer. The "CalcPts – Scattered" command is used to place photosensors on these points. In order to get the desired numeric output, the locations for the photosensors must be chosen in a specific order.

3.) The largest polygon is at 5 degrees latitude. Make the first series of photosensors along the points of this polygon. Check with the model in AutoCAD to determine the depth, or Z-coordinate, of the polygon. Place the first photosensor at "North," then place the rest at the polygon's points in a clockwise rotation.

4.) Repeat step 3 for the polygons at 15, 25, 35, 45, 55, 65, 75, and 85 degrees latitude. Finally, place a final photosensor at the pole of the goniophotometer, 28 feet deep.

Material Properties: Using the Surface Editor, the surfaced defining the interior of the box were set to Surface Type "Daylight Exterior Single Sided" with a Reflectance of .01. Also using the Surface Editor, the Louver was set to Surface Type "Daylight Exterior Double Sided" with a Reflectance of .8.

Simulation Settings: The "Daylighting Parameters" command is used to create the daylighting settings for the scene. Check the "Enable Daylighting" command, and use the Sky Condition "Overcast." The coordinates for the location, as well as the date and time, are filled in.

Running Simulation: No calculation settings are changed. The "Calculate Now" command is used and the calculations are run.

Graphic Outputs: Outputs can be exported by using the "Copy" command in the Edit menu to copy the viewport as a picture file.

AGI32 – Simulation Procedure – Room

Setting: A test room imported from an AutoCAD 2000 file. The room is 40 feet long, 20 feet wide, and 10 feet high. Centered on the room's ceiling is a 4' by 4' aperture. A daylighting louver has been placed in this aperture.

Photosensor Location: The "CalcPts – Automatic Placement" command is used to create a grid of photosensors on the floor and three walls of the test room. The Calculation Type was set to "Illuminance," and the photosensors were located 2 feet apart.

Material Properties: AGI32 was used to set the surface properties for this room. Using the Surface Editor, the surfaces defining the room were set to Surface Type "Daylight Exterior Single Sided" with a Reflectance of .8. Also using the surface editor, the louver was set to Surface Type "Daylight Exterior Double Sided" with a Reflectance of .8.

Simulation Settings: The "Daylighting Parameters" command is used to create the daylighting settings for the scene. Check the "Enable Daylighting" command, and use the Sky Condition "Overcast." The coordinates for the location, as well as the date and time, are filled in.

Running Simulation: No calculation settings are changed. The "Calculate Now" command is used and the calculations are run.

Graphic Outputs: The grids of photosensors will show the results of the calculations. The "CalcPts Status Manager" command is used to toggle the grids off and on from visibility. Additionally, Isolines can be visualized in the CalcPts Status Manager. The "CalcPts – Isoline Values" command is used to set the values at which the lines will run.
These outputs can be exported by using the "Copy" command in the Edit Menu to copy the viewport as a picture file.

Numeric Outputs: The "Print Text" command in the File Menu is used to export the calculation points as a text file. Choose to save the text file, then in the "Contents Box," check the "Numeric Summary" box, and the Detailed summary type. Save the file, and open it to view the output.

LUMEN DESIGNER SIMULATION PROCEDURE:

Lumen Designer – Simulation Procedure – Room

Setting: A test room imported from an AutoCAD 2000 file. The room is 40 feet long, 20 feet wide, and 10 feet high. Centered on the room's ceiling is a 4' by 4' aperture. A daylighting louver has been placed in this aperture.

Photosensor Location: The "Add Calculation Grid" command in the Designer Shortcut menu is used to locate photosensors. Choose to make a rectangular grid, and drag a rectangle from one corner of the floor plane to the opposite corner. Double-check using a 3-D view to make sure the photosensors are level with the floor plane. Lumen Designer does not seem to draw calculation grids vertically; if this proves to be the case than photosensors cannot be placed along walls.

Material Properties: The "Material Manager" command in the View menu is used to change material properties and create new materials. It seems faster to select the object, and change its material to the desired material using the Properties window.

Simulation Settings: The "Calculation Manager" command in the Calculate menu is used to change simulation settings. Switch to the Daylighting Settings submenu to enable daylighting, and to change the daylighting settings.

Running Simulation: In the Calculation Manager, or in the Designer Shortcut menu, select "Run Calculations" to have the simulation processed.

Graphic Outputs: The grids of photosensors will show the results of the calculations. To edit the graphic output, select the photosensor grid, and press "Edit" in the Designer Shortcut menu. The values and isolines of the grid can be toggled in the Display Settings submenu. The "Grid Results Viewer" command in the Output menu is used to export the drawing.

Numeric Outputs: The "Grid Results Viewer" command in the Output menu is used to view and export the grid results.

TRACEPRO SIMULATION PROCEDURE:

The Goniophotometer is simulated as follows:

Setting: The setting did not require the hemisphere array of photosensors, because PracePro provides the required file. It did however require inputing a sky. A hemispherical dome was created with a luminous surface to represent an overcast sky.

Photosensor Location:

See above.

Material Properties: Required settings were defined in the material editor. An exit surface for the analysis was also established where the light exited the louver.

Simulation Settings: light wave length and luminous intensity of the emitting surface were established.

Running Simulation: Source ray-trace was implemented.

Graphic Outputs: Outputs can be saved as bitmaps and other file types by using the 'save as' command by right clicking on the image to be saved.

Numeric Outputs: Reports can be produced under the analysis menu, and saved in .TXT format.

APPENDIX F:

Creating and Importing an IESNA File in AGI32

File 'r-s1.35_3.21.12pm-cloudy' (see Numeric Summary of Daylighted Goniophotometer below) represents an illuminance data set produced in AGI32 with a 35 degree angles louver for Raleigh, NC on March 21st at noon with cloudy sky conditions. This file was converted into candela and recorded as an IESNA electronic format photometric file (see below). The file was then imported into the typical room to record illuminance values and visual effect. The illuminance distribution was seen to be approximately the same as the daylighted simulation directly beneath the aperture, but much higher (approximately triple) at the perimeter of the room (see False Color Illuminance of IESNA File Input below). A simulation using the same photometric file was then performed in the goniophotometer, where the illuminance levels from the IESNA file averaged approximately one-third of the daylighting simulation illuminance values they were calculated from (see Goniophotometer Illuminance with IESNA File Source below). As noted in the dissertation, these inconsistencies have not been accounted for in the demonstration. Potential sources of error include the construction of the daylighting models, the implementation of the protocols, settings of the program by the operator, and computational issues within the software.

Numeric Summary of Daylighted Goniophotometer (AGI32)

RALEIGH: R-S1.35.12PM-CLOUDY

Control

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Horizontal

Illuminance Values (Lux)

Average = 17823

Maximum = 17823

Minimum = 17823

Avg/Min = 1.00

Max/Min = 1.00

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point			Meter			
No.	X-Coord	Y-Coord	Z-Coord	Orient	Tilt	Value
1	-4.679	1.233	1	0	0	17823

05

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average = 3.28

Maximum = 4.9

Minimum = 2.0

Avg/Min = 1.64

Max/Min = 2.45

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point No.	X-Coord	Y-Coord	Z-Coord	Meter Orient	Tilt	Value
1	0	27.911	-2.443	90	84.998	2.6
2	10.681	25.786	-2.443	67.5	84.998	2
3	19.736	19.736	-2.443	45	84.998	2.5
4	25.786	10.681	-2.443	22.5	84.998	2.3
5	27.911	0	-2.443	0	84.998	3.2
6	25.786	-10.681	-2.443	337.5	84.998	4.2
7	19.736	-19.736	-2.443	315	84.998	4.2
8	10.681	-25.786	-2.443	292.5	84.998	3.5
9	0	-27.911	-2.443	270	84.998	4.7
10	-10.681	-25.786	-2.443	247.5	84.998	3.2
11	-19.736	-19.736	-2.443	225	84.998	4
12	-25.786	-10.681	-2.443	202.5	84.998	4.9
13	-27.911	0	-2.443	180	84.998	2.9
14	-25.786	10.681	-2.443	157.5	84.998	2.5
15	-19.736	19.736	-2.443	135	84.998	3
16	-10.681	25.786	-2.443	112.5	84.998	2.7

15

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average = 8.71

Maximum = 16.6

Minimum = 4.1

Avg/Min = 2.12

Max/Min = 4.05

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point				Meter		
No.	X-Coord	Y-Coord	Z-Coord	Orient	Tilt	Value
1	0	27.046	-7.25	90	74.994	4.1
2	10.35	24.987	-7.25	67.5	74.994	4.4
3	19.124	19.124	-7.25	45	74.994	5.4
4	24.987	10.35	-7.25	22.5	74.994	4.5
5	27.046	0	-7.25	0	74.994	5.1
6	24.987	-10.35	-7.25	337.5	74.994	15.8
7	19.124	-19.124	-7.25	315	74.994	12.8
8	10.35	-24.987	-7.25	292.5	74.994	11.3
9	0	-27.046	-7.25	270	74.994	14.2
10	-10.35	-24.987	-7.25	247.5	74.994	11.9
11	-19.124	-19.124	-7.25	225	74.994	14.2
12	-24.987	-10.35	-7.25	202.5	74.994	16.6
13	-27.046	0	-7.25	180	74.994	4.8
14	-24.987	10.35	-7.25	157.5	74.994	4.8
15	-19.124	19.124	-7.25	135	74.994	5.1
16	-10.35	24.987	-7.25	112.5	74.994	4.4

25

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average = 17.29

Maximum = 34.3

Minimum = 6.3

Avg/Min = 2.74

Max/Min = 5.44

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point				Meter		
No.	X-Coord	Y-Coord	Z-Coord	Orient	Tilt	Value
1	0	25.377	-11.833	90	65.001	6.9
2	9.711	23.445	-11.833	67.5	65.001	7.6
3	17.944	17.944	-11.833	45	65.001	6.3
4	23.445	9.711	-11.833	22.5	65.001	7.3
5	25.377	0	-11.833	0	65.001	7.6
6	23.445	-9.711	-11.833	337.5	65.001	24.6
7	17.944	-17.944	-11.833	315	65.001	34.3

8	9.711	-23.445	-11.833	292.5	65.001	32
9	0	-25.377	-11.833	270	65.001	30.6
10	-9.711	-23.445	-11.833	247.5	65.001	32.3
11	-17.944	-17.944	-11.833	225	65.001	34.2
12	-23.445	-9.711	-11.833	202.5	65.001	24.3
13	-25.377	0	-11.833	180	65.001	8.1
14	-23.445	9.711	-11.833	157.5	65.001	6.8
15	-17.944	17.944	-11.833	135	65.001	7
16	-9.711	23.445	-11.833	112.5	65.001	6.7

35

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average = 25.14

Maximum = 58.5

Minimum = 8.8

Avg/Min = 2.86

Max/Min = 6.65

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point			Meter			
No.	X-Coord	Y-Coord	Z-Coord	Orient	Tilt	Value
1	0	22.936	-16.063	90	54.995	9.1
2	8.777	21.19	-16.063	67.5	54.995	9.9
3	16.218	16.218	-16.063	45	54.995	9.4
4	21.19	8.777	-16.063	22.5	54.995	9.9
5	22.936	0	-16.063	0	54.995	11.2
6	21.19	-8.777	-16.063	337.5	54.995	27.6
7	16.218	-16.218	-16.063	315	54.995	43.6
8	8.777	-21.19	-16.063	292.5	54.995	54
9	0	-22.936	-16.063	270	54.995	58.5
10	-8.777	-21.19	-16.063	247.5	54.995	53.6
11	-16.218	-16.218	-16.063	225	54.995	45.1
12	-21.19	-8.777	-16.063	202.5	54.995	28.8
13	-22.936	0	-16.063	180	54.995	12.7
14	-21.19	8.777	-16.063	157.5	54.995	8.8
15	-16.218	16.218	-16.063	135	54.995	10.2
16	-8.777	21.19	-16.063	112.5	54.995	9.9

45

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average = 27.12

Maximum = 60.5

Minimum = 10.1

Avg/Min = 2.69

Max/Min = 5.99

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point No.	X-Coord	Y-Coord	Z-Coord	Meter Orient	Meter Tilt	Value
1	0	19.799	-19.797	90	45.003	11.1
2	7.577	18.292	-19.797	67.5	45.003	10.9
3	14	14	-19.797	45	45.003	12
4	18.292	7.577	-19.797	22.5	45.003	10.1
5	19.799	0	-19.797	0	45.003	13.1
6	18.292	-7.577	-19.797	337.5	45.003	29.7
7	14	-14	-19.797	315	45.003	46
8	7.577	-18.292	-19.797	292.5	45.003	55.2
9	0	-19.799	-19.797	270	45.003	60.5
10	-7.577	-18.292	-19.797	247.5	45.003	56.5
11	-14	-14	-19.797	225	45.003	48.2
12	-18.292	-7.577	-19.797	202.5	45.003	31.7
13	-19.799	0	-19.797	180	45.003	14.9
14	-18.292	7.577	-19.797	157.5	45.003	12.6
15	-14	14	-19.797	135	45.003	11.3
16	-7.577	18.292	-19.797	112.5	45.003	10.1

55

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average = 27.90

Maximum = 57.9

Minimum = 11.9

Avg/Min = 2.34

Max/Min = 4.87

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point				Meter		
No.	X-Coord	Y-Coord	Z-Coord	Orient	Tilt	Value
1	0	16.06	-22.937	90	34.999	11.9
2	6.146	14.838	-22.937	67.5	34.999	14.6
3	11.356	11.356	-22.937	45	34.999	16.4
4	14.838	6.146	-22.937	22.5	34.999	13.9
5	16.06	0	-22.937	0	34.999	12.7
6	14.838	-6.146	-22.937	337.5	34.999	30.5
7	11.356	-11.356	-22.937	315	34.999	43.3
8	6.146	-14.838	-22.937	292.5	34.999	53.9
9	0	-16.06	-22.937	270	34.999	57.9
10	-6.146	-14.838	-22.937	247.5	34.999	53.1
11	-11.356	-11.356	-22.937	225	34.999	44.4
12	-14.838	-6.146	-22.937	202.5	34.999	32.1

13	-16.06	0	-22.937	180	34.999	19.2
14	-14.838	6.146	-22.937	157.5	34.999	14
15	-11.356	11.356	-22.937	135	34.999	15.4
16	-6.146	14.838	-22.937	112.5	34.999	13.1

65

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average = 27.45

Maximum = 50.1

Minimum = 15.0

Avg/Min = 1.83

Max/Min = 3.34

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point			Meter			
No.	X-Coord	Y-Coord	Z-Coord	Orient	Tilt	Value
1	0	11.833	-25.375	90	25.001	17.3
2	4.528	10.933	-25.375	67.5	25.001	15
3	8.367	8.367	-25.375	45	25.001	16.2

4	10.933	4.528	-25.375	22.5	25.001	15.7
5	11.833	0	-25.375	0	25.001	19
6	10.933	-4.528	-25.375	337.5	25.001	28
7	8.367	-8.367	-25.375	315	25.001	38.2
8	4.528	-10.933	-25.375	292.5	25.001	49.2
9	0	-11.833	-25.375	270	25.001	50.1
10	-4.528	-10.933	-25.375	247.5	25.001	48.9
11	-8.367	-8.367	-25.375	225	25.001	39.8
12	-10.933	-4.528	-25.375	202.5	25.001	31.7
13	-11.833	0	-25.375	180	25.001	18.7
14	-10.933	4.528	-25.375	157.5	25.001	18.8
15	-8.367	8.367	-25.375	135	25.001	16.4
16	-4.528	10.933	-25.375	112.5	25.001	16.2

75

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average = 24.28

Maximum = 41.0

Minimum = 16.0

Avg/Min = 1.52

Max/Min = 2.56

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point No.	X-Coord	Y-Coord	Meter Z-Coord	Orient	Tilt	Value
1	0	7.247	-27.047	90	14.999	16.2
2	2.773	6.695	-27.047	67.5	14.999	18
3	5.124	5.124	-27.047	45	14.999	18.7
4	6.695	2.773	-27.047	22.5	14.999	16
5	7.247	0	-27.047	0	14.999	19.3
6	6.695	-2.773	-27.047	337.5	14.999	26.8
7	5.124	-5.124	-27.047	315	14.999	31.3
8	2.773	-6.695	-27.047	292.5	14.999	36.1
9	0	-7.247	-27.047	270	14.999	41
10	-2.773	-6.695	-27.047	247.5	14.999	35.7
11	-5.124	-5.124	-27.047	225	14.999	34.5
12	-6.695	-2.773	-27.047	202.5	14.999	24.5
13	-7.247	0	-27.047	180	14.999	18.4
14	-6.695	2.773	-27.047	157.5	14.999	17.9
15	-5.124	5.124	-27.047	135	14.999	17.5
16	-2.773	6.695	-27.047	112.5	14.999	16.5

85

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average =	21.24
Maximum =	25.6
Minimum =	17.4
Avg/Min =	1.22
Max/Min =	1.47

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point No.	X-Coord	Y-Coord	Z-Coord	Meter Orient	Tilt	Value
1	0	2.44	-27.8958	90	5	17.6
2	.934	2.255	-27.8958	67.5	5	18
3	1.726	1.726	-27.8598	45	5.006	19.7
4	2.255	.934	-27.8598	22.5	5.006	19.5
5	2.44	0	-27.8598	0	5.006	18
6	2.255	-.934	-27.8598	337.5	5.006	23.4
7	1.726	-1.726	-27.8598	315	5.006	25.3
8	.934	-2.255	-27.8598	292.5	5.006	25.6
9	0	-2.44	-27.8598	270	5.006	24.9
10	-.934	-2.255	-27.8598	247.5	5.006	25.4
11	-1.726	-1.726	-27.8598	225	5.006	24.9
12	-2.255	-.934	-27.8598	202.5	5.006	21.4
13	-2.44	0	-27.8598	180	5.006	19.6
14	-2.255	.934	-27.8598	157.5	5.006	19.9
15	-1.726	1.726	-27.8598	135	5.006	17.4
16	-.934	2.255	-27.8598	112.5	5.006	19.3

90

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average = 18.50

Maximum = 18.5

Minimum = 18.5

Avg/Min = 1.00

Max/Min = 1.00

Calculation Points

Coordinates in Feet

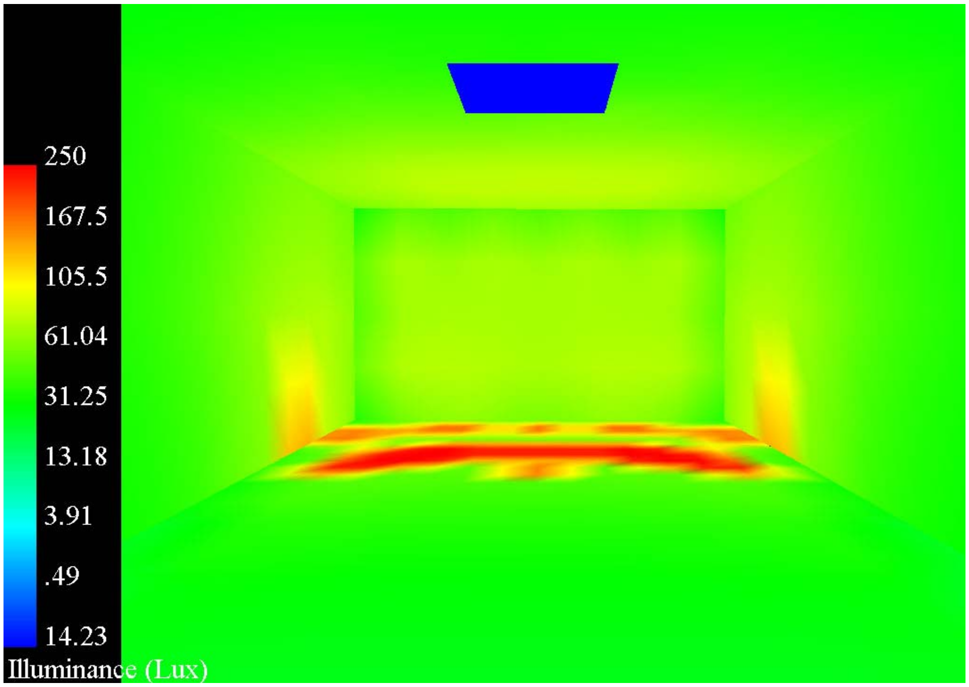
Illuminance Values (Lux)

Point No.	X-Coord	Y-Coord	Meter Z-Coord	Orient	Tilt	Value
1	0	0	-28	0	0	18.5

IESNA Electronic Format Photometric File Created with Daylighted Goniophotometer Illuminance Values:

```
s_135_cloudy
IESNA:LM-63-1995
[TEST] S35-3.21-12PM
[LUMINAIRE] Unglazed Louver Control
[OTHER] No
[_SKYLIGHT] Control
[_NOTE] Header angles are in degrees counterclockwise looking down;
[_MORE] 0 = North for major axis and 0 = South for solar azimuth
[_MAJOR_AXIS] 0
[_GLAZING_VT] NA
[_GLAZING_HAZE] NA
[_GLAZING_CLARITY] NA
[_UNITS_TYPE] Feet
[_GLAZING_AREA] 16
[_INCLUDE_FILE] None
[_WELL] No
[_WELL_HEIGHT] 0
[_WELL_WIDTH] 0
[_WELL_LENGTH] 0
[_WELL_REFL] 0.82
[_REFL_TYPE] Diffuse Louvers 85% Reflect
[_BOTTOM_DIFFUSER] No
[_DIFFUSER_VT]
[_DIFFUSER_HAZE]
[_DIFFUSER_CLARITY]
[_SOLAR_ELEVATION] 54.54
[_SOLAR_AZIMUTH] -78.39
[_SKY_RATIO] 0.0
[_SKY_CONDITION] overcast
[_TEST_LONG] 78.39
[_TEST_LAT] 35.46
[_TEST_ELEV] 0
[_TEST_DATE] 3/21/06
[_TEST_TIME]12:00PM
[_TEST_TZ]
TILT=NONE
1 1000 0.823 11 17 1 1 4 4 0
1 1 0
0 5 15 25 35 45 55 65 75 85 90
0 22.5 45 67.5 90 112.5 135 157.5 180 202.5 225 247.5 270 292.5 315 337.5 360
 645 614 565 603 415 387 317 241 143 91 0.
 645 627 627 523 509 380 345 265 153 70 0.
 645 689 652 565 572 418 328 220 188 87 0.
 645 680 558 547 485 352 345 254 157 80 0.
 645 627 673 472 443 457 390 265 178 112 0.
 645 816 934 976 1063 1035 962 858 551 146 0.
 645 882 1091 1332 1509 1604 1520 1196 446 146 0.
 645 892 1258 1715 1879 1924 1882 1116 394 122 0.
 645 868 1429 1746 2018 2109 2039 1067 495 164 0.
 645 885 1244 1704 1851 1970 1868 1126 415 112 0.
 645 868 1203 1387 1548 1680 1572 1192 495 139 0.
 645 746 854 1105 1119 1105 1004 847 579 171 0.
 645 683 641 652 669 519 443 282 167 101 0.
 645 694 624 655 488 439 307 237 167 87 0.
 645 607 610 571 537 394 356 244 178 105 0.
 645 673 575 565 457 352 345 234 153 94 0.
 645 614 565 603 415 387 317 241 143 91 0.
```

False Color Illuminance of IESNA File Input:



Goniophotometer Illuminance with IESNA File Source:

Luminaire Definition(s)

----

s_135_cloudy

Filename = s_135_cloudy

Lumens per Lamp = 1000

Number of Lamps = 1

Lamp Lumen Depreciation (LLD) = 1

Lamp Dirt Depreciation (LDD) = 1

Ballast Factor (BF) = 1

Total Light Loss Factor (LLDxLDDxBF) = 1.000

Luminaire Watts = 0

Total Watts = 0

Luminaire Effective Projected Area = 0 Sq.Ft.

Total Effective Projected Area = 0 Sq.Ft.

Normal Mode Symbol = BOX RECESSED
Normal Mode Symbol Scaling = (X= 4 Y= 4 Z= 4)
Render Mode Symbol = BOX RECESSED
Render Mode Symbol Scaling = (X= 4 Y= 4 Z= 1)
Housing Color = (R= 51 G= 51 B= 51)
Luminous Color = (R= 255 G= 255 B= 255)
Arrangement = SINGLE
Arm Length = 0
Offset = 0

Photometric File
Filename : s_135_cloudy

[Test] S35-3_21-12PM
[IssueDate]
[Manufac]
[Lumcat]
[Lampcat]
[Lamp]

Road Classification: Type I, Very Short, Non-Cutoff
Indoor Classification: Direct
Flood NEMA Type: N.A.

Numeric Summary
----
el_0

Project: Project_1
Scattered points
Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average = 7.30

Maximum = 7.3

Minimum = 7.3

Avg/Min = 1.00

Max/Min = 1.00

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point				Meter		
No.	X-Coord	Y-Coord	Z-Coord	Orient	Tilt	Value
1	0	0	-28	0	0	7.3

el_85

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average =	1.30
Maximum =	1.9
Minimum =	0.8
Avg/Min =	1.63
Max/Min =	2.38

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point No.	X-Coord	Y-Coord	Meter Z-Coord	Orient	Tilt	Value
1	0	27.911	-2.443	90	84.998	1
2	10.681	25.786	-2.443	67.5	84.998	1.1
3	19.736	19.736	-2.443	45	84.998	1.2
4	25.786	10.681	-2.443	22.5	84.998	1
5	27.911	0	-2.443	0	84.998	1.2
6	25.786	-10.681	-2.443	337.5	84.998	1.9
7	19.736	-19.736	-2.443	315	84.998	1.6
8	10.681	-25.786	-2.443	292.5	84.998	1.3
9	0	-27.911	-2.443	270	84.998	1.9
10	-10.681	-25.786	-2.443	247.5	84.998	1.4
11	-19.736	-19.736	-2.443	225	84.998	1.6
12	-25.786	-10.681	-2.443	202.5	84.998	1.6
13	-27.911	0	-2.443	180	84.998	1.3
14	-25.786	10.681	-2.443	157.5	84.998	.9
15	-19.736	19.736	-2.443	135	84.998	1
16	-10.681	25.786	-2.443	112.5	84.998	.8

el_75

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average = 3.42

Maximum = 6.2

Minimum = 1.6

Avg/Min = 2.14

Max/Min = 3.88

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point			Meter			
No.	X-Coord	Y-Coord	Z-Coord	Orient	Tilt	Value
1	0	27.046	-7.25	90	74.994	1.6
2	10.35	24.987	-7.25	67.5	74.994	1.8
3	19.124	19.124	-7.25	45	74.994	2
4	24.987	10.35	-7.25	22.5	74.994	1.9
5	27.046	0	-7.25	0	74.994	1.9
6	24.987	-10.35	-7.25	337.5	74.994	6.2
7	19.124	-19.124	-7.25	315	74.994	5.6
8	10.35	-24.987	-7.25	292.5	74.994	4.8
9	0	-27.046	-7.25	270	74.994	5.6
10	-10.35	-24.987	-7.25	247.5	74.994	4.6

11	-19.124	-19.124	-7.25	225	74.994	5.1
12	-24.987	-10.35	-7.25	202.5	74.994	5.9
13	-27.046	0	-7.25	180	74.994	2
14	-24.987	10.35	-7.25	157.5	74.994	1.8
15	-19.124	19.124	-7.25	135	74.994	2.1
16	-10.35	24.987	-7.25	112.5	74.994	1.8

el_65

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average = 6.76

Maximum = 13.1

Minimum = 2.6

Avg/Min = 2.60

Max/Min = 5.04

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point				Meter		
No.	X-Coord	Y-Coord	Z-Coord	Orient	Tilt	Value
1	0	25.377	-11.833	90	65.001	2.7

2	9.711	23.445	-11.833	67.5	65.001	2.7
3	17.944	17.944	-11.833	45	65.001	2.8
4	23.445	9.711	-11.833	22.5	65.001	2.7
5	25.377	0	-11.833	0	65.001	3.2
6	23.445	-9.711	-11.833	337.5	65.001	9.4
7	17.944	-17.944	-11.833	315	65.001	13.1
8	9.711	-23.445	-11.833	292.5	65.001	12.7
9	0	-25.377	-11.833	270	65.001	12.1
10	-9.711	-23.445	-11.833	247.5	65.001	12.6
11	-17.944	-17.944	-11.833	225	65.001	13.1
12	-23.445	-9.711	-11.833	202.5	65.001	9.5
13	-25.377	0	-11.833	180	65.001	3
14	-23.445	9.711	-11.833	157.5	65.001	2.9
15	-17.944	17.944	-11.833	135	65.001	2.6
16	-9.711	23.445	-11.833	112.5	65.001	3

el_55

Project: Project_1
Scattered points
Coordinates in Feet

Meter Type = Variable (aimed at a point)
Meter Aimed at X = 0
Meter Aimed at Y = 0
Meter Aimed at Z = 0

Illuminance Values (Lux)
Average = 9.86
Maximum = 23.0
Minimum = 3.6
Avg/Min = 2.74

Max/Min = 6.39

Calculation Points
Coordinates in Feet
Illuminance Values (Lux)

Point No.	X-Coord	Y-Coord	Z-Coord	Meter Orient	Tilt	Value
1	0	22.936	-16.063	90	54.995	3.6
2	8.777	21.19	-16.063	67.5	54.995	3.9
3	16.218	16.218	-16.063	45	54.995	4
4	21.19	8.777	-16.063	22.5	54.995	3.6
5	22.936	0	-16.063	0	54.995	5
6	21.19	-8.777	-16.063	337.5	54.995	11.3
7	16.218	-16.218	-16.063	315	54.995	17.5
8	8.777	-21.19	-16.063	292.5	54.995	21
9	0	-22.936	-16.063	270	54.995	23
10	-8.777	-21.19	-16.063	247.5	54.995	21.1
11	-16.218	-16.218	-16.063	225	54.995	17
12	-21.19	-8.777	-16.063	202.5	54.995	10.9
13	-22.936	0	-16.063	180	54.995	4.4
14	-21.19	8.777	-16.063	157.5	54.995	3.9
15	-16.218	16.218	-16.063	135	54.995	3.7
16	-8.777	21.19	-16.063	112.5	54.995	3.9

el_45

Project: Project_1
Scattered points
Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average = 10.68

Maximum = 23.9

Minimum = 4.0

Avg/Min = 2.67

Max/Min = 5.98

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point No.	X-Coord	Y-Coord	Z-Coord	Meter Orient	Tilt	Value
1	0	19.799	-19.797	90	45.003	4.4
2	7.577	18.292	-19.797	67.5	45.003	4
3	14	14	-19.797	45	45.003	4.5
4	18.292	7.577	-19.797	22.5	45.003	5
5	19.799	0	-19.797	0	45.003	5.9
6	18.292	-7.577	-19.797	337.5	45.003	12.5
7	14	-14	-19.797	315	45.003	18.8
8	7.577	-18.292	-19.797	292.5	45.003	22.2
9	0	-19.799	-19.797	270	45.003	23.9
10	-7.577	-18.292	-19.797	247.5	45.003	21.7
11	-14	-14	-19.797	225	45.003	17.9
12	-18.292	-7.577	-19.797	202.5	45.003	11.7
13	-19.799	0	-19.797	180	45.003	5.2
14	-18.292	7.577	-19.797	157.5	45.003	4.1
15	-14	14	-19.797	135	45.003	4.7

16	-7.577	18.292	-19.797	112.5	45.003	4.3

el_35

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average = 10.96

Maximum = 22.8

Minimum = 4.7

Avg/Min = 2.33

Max/Min = 4.85

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point No.	X-Coord	Y-Coord	Z-Coord	Meter Orient	Tilt	Value
1	0	16.06	-22.937	90	34.999	4.7
2	6.146	14.838	-22.937	67.5	34.999	5.2
3	11.356	11.356	-22.937	45	34.999	6
4	14.838	6.146	-22.937	22.5	34.999	5.7
5	16.06	0	-22.937	0	34.999	7.6
6	14.838	-6.146	-22.937	337.5	34.999	12.6

7	11.356	-11.356	-22.937	315	34.999	17.4
8	6.146	-14.838	-22.937	292.5	34.999	20.9
9	0	-16.06	-22.937	270	34.999	22.8
10	-6.146	-14.838	-22.937	247.5	34.999	21.1
11	-11.356	-11.356	-22.937	225	34.999	17
12	-14.838	-6.146	-22.937	202.5	34.999	11.9
13	-16.06	0	-22.937	180	34.999	5
14	-14.838	6.146	-22.937	157.5	34.999	5.5
15	-11.356	11.356	-22.937	135	34.999	6.3
16	-6.146	14.838	-22.937	112.5	34.999	5.7

el_25

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average = 10.66

Maximum = 19.8

Minimum = 5.3

Avg/Min = 2.01

Max/Min = 3.74

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point			Meter			
No.	X-Coord	Y-Coord	Z-Coord	Orient	Tilt	Value
1	0	11.833	-25.375	90	25.001	6.8
2	4.528	10.933	-25.375	67.5	25.001	6.4
3	8.367	8.367	-25.375	45	25.001	6.5
4	10.933	4.528	-25.375	22.5	25.001	7.4
5	11.833	0	-25.375	0	25.001	7.4
6	10.933	-4.528	-25.375	337.5	25.001	12.4
7	8.367	-8.367	-25.375	315	25.001	15.7
8	4.528	-10.933	-25.375	292.5	25.001	19.1
9	0	-11.833	-25.375	270	25.001	19.8
10	-4.528	-10.933	-25.375	247.5	25.001	19.2
11	-8.367	-8.367	-25.375	225	25.001	15.1
12	-10.933	-4.528	-25.375	202.5	25.001	10.9
13	-11.833	0	-25.375	180	25.001	5.3
14	-10.933	4.528	-25.375	157.5	25.001	6.1
15	-8.367	8.367	-25.375	135	25.001	6.4
16	-4.528	10.933	-25.375	112.5	25.001	6

el_15

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average = 9.58
Maximum = 16.2
Minimum = 6.4
Avg/Min = 1.50
Max/Min = 2.53

Calculation Points
Coordinates in Feet
Illuminance Values (Lux)

Point No.	X-Coord	Y-Coord	Z-Coord	Orient	Tilt	Meter Value
1	0	7.247	-27.047	90	14.999	6.4
2	2.773	6.695	-27.047	67.5	14.999	6.5
3	5.124	5.124	-27.047	45	14.999	6.9
4	6.695	2.773	-27.047	22.5	14.999	7.1
5	7.247	0	-27.047	0	14.999	7.3
6	6.695	-2.773	-27.047	337.5	14.999	9.7
7	5.124	-5.124	-27.047	315	14.999	13.4
8	2.773	-6.695	-27.047	292.5	14.999	14.2
9	0	-7.247	-27.047	270	14.999	16.2
10	-2.773	-6.695	-27.047	247.5	14.999	14.2
11	-5.124	-5.124	-27.047	225	14.999	12.4
12	-6.695	-2.773	-27.047	202.5	14.999	10.5
13	-7.247	0	-27.047	180	14.999	7.6
14	-6.695	2.773	-27.047	157.5	14.999	6.4
15	-5.124	5.124	-27.047	135	14.999	7.3
16	-2.773	6.695	-27.047	112.5	14.999	7.1

el_05

Project: Project_1

Scattered points

Coordinates in Feet

Meter Type = Variable (aimed at a point)

Meter Aimed at X = 0

Meter Aimed at Y = 0

Meter Aimed at Z = 0

Illuminance Values (Lux)

Average = 8.39

Maximum = 10.1

Minimum = 7.0

Avg/Min = 1.20

Max/Min = 1.44

Calculation Points

Coordinates in Feet

Illuminance Values (Lux)

Point				Meter		
No.	X-Coord	Y-Coord	Z-Coord	Orient	Tilt	Value
1	0	2.44	-27.8958	90	5	7
2	.934	2.255	-27.8958	67.5	5	7.5
3	1.726	1.726	-27.8598	45	5.006	7
4	2.255	.934	-27.8598	22.5	5.006	7.8
5	2.44	0	-27.8598	0	5.006	7.8
6	2.255	-.934	-27.8598	337.5	5.006	8.5
7	1.726	-1.726	-27.8598	315	5.006	9.8
8	.934	-2.255	-27.8598	292.5	5.006	10
9	0	-2.44	-27.8598	270	5.006	9.9
10	-.934	-2.255	-27.8598	247.5	5.006	10.1
11	-1.726	-1.726	-27.8598	225	5.006	10

12	-2.255	-.934	-27.8598	202.5	5.006	9.2
13	-2.44	0	-27.8598	180	5.006	7.1
14	-2.255	.934	-27.8598	157.5	5.006	7.7
15	-1.726	1.726	-27.8598	135	5.006	7.8
16	-.934	2.255	-27.8598	112.5	5.006	7.1

APPENDIX G:

Typological classification of toplighting controls.

Control and Treatment Designs:

The treatments are the independent variable in the performance characterization tests. There are (5) treatments, (2) static and (3) dynamic that have been derived for architectural toplighting applications. All treatments will use planar control elements, and have been designed as components that may be added to daylighting systems with little or no modification. The treatment configurations have been designed to represent typological classifications with a progression in physical complexity. There is less to be gained from testing actual configurations, than by scaling the configurations to a common line of evaluation. Since the designs are based on actual installations it might be possible to test the entire daylighting system in situ, but that may not provide the most useful information to future designer's intent on improving application performance. The ability to compare outputs from the different configurations is necessary to support development. Therefore, the configurations have been scaled as treatments for the same setting. The performance characterization results will, thereby, be much more informative to designers.

The treatments will be comprised of louver elements that are all nominally 6" wide by ¼" thick to allow performance comparisons. The heights of the treatments vary based on louver configuration. I have attempted in each case to keep the curb height to a minimum and to be open where possible to minimize the shading effect on performance.

In practice louver components are frequently modified to enhance performance. It is common, for example, to design exterior edges of a louver to overhangs the aperture to shade it from higher angle beam sunlight. I have not made this or any similar modification to the treatments to keep the *basic* idea consistent. The louvers will be rendered as white painted aluminum. Aluminum is a common material for louvers, and most of the applications the treatments are modeled on are white painted aluminum. The white paint will be 85% reflective.

Static defines a control element that is designed to perform in a fixed position. A *dynamic* control has one or more degrees of rotational freedom, that are used to respond to the variability of the solar resource.

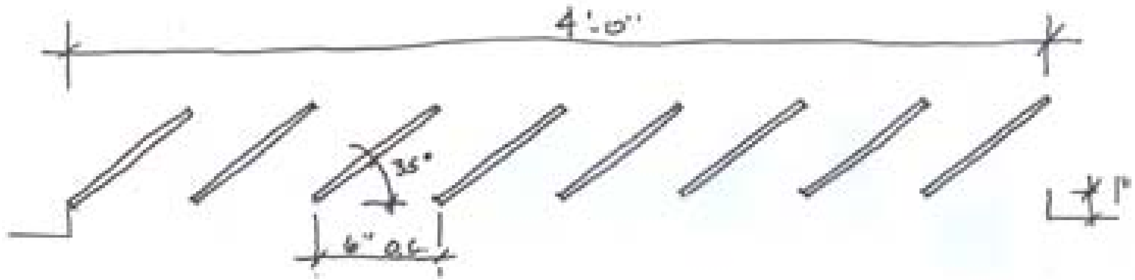
Parametric Control Design:

The control will be a 4’ x 4’ aperture in a flat opaque and horizontal plane. It will have no treatment. The plane will be ¼” thick and 30’ x 30’. It will be painted flat black on all surfaces to prevent reflections. The transmission of this assembly will be 100%.

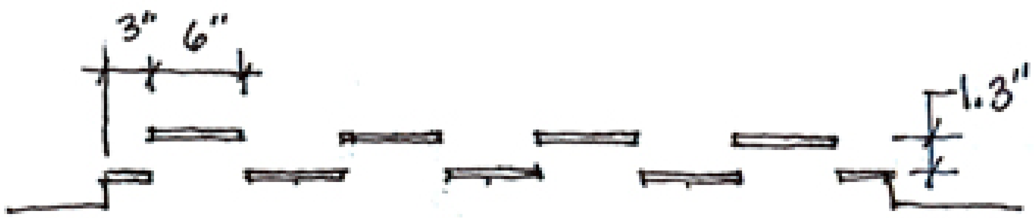
The treatments are each designed to completely cover the 4’ x 4’ aperture in the control. 4’ x 4’ was chosen as a standard building product unit. The principle of superimposition allows daylighting performance data to be extrapolated for various aperture patterns and for components with different aperture size.

Static Control Designs:

The static louvers have been selected to present two basic louver arrangements. The first treatment (S-1) is a louver capable of selecting light from one part of the sky. The second treatment (S-2) is capable of admitting light from two parts of the sky. Numerous architectural applications, particularly in factory buildings, have been variations on these configurations.



Treatment S-1:



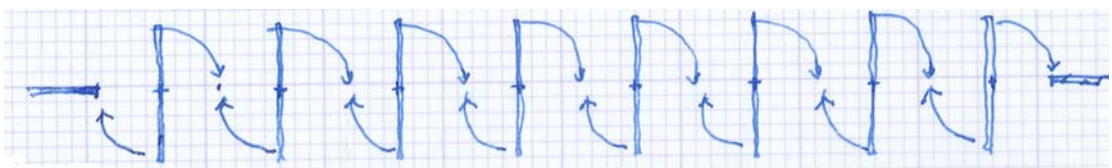
Treatment S-2

Treatment S-1 is analogous to the 'saw tooth' roof. It represents a primary approach to sky selectivity with single layer angled planar components to select light from *one* quadrant of the sky. There are eight equal apertures facing the same direction. This treatment is identical to the upper layer of Treatment D-2.

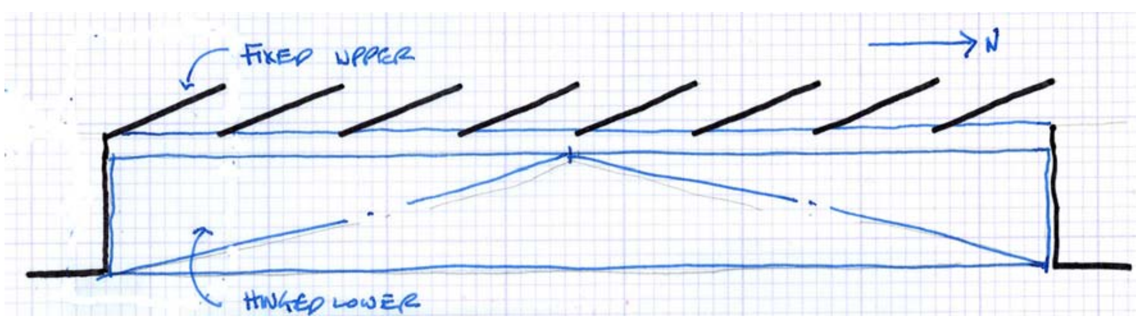
The design of treatment S-2 is analogous to the linear roof monitors seen on industrial buildings. The louvers are traditionally oriented east-west to form north and south facing apertures. There are eight equal apertures, which admit light from *two* quadrants of the sky, which may increase thermal gain in winter.

Dynamic Control Designs:

Treatment D-1 is comprised of a single layer of 6" wide louvers with rotational movement. It is based upon Richard Meier's design for the Getty Museum in Malibu, California. Lawrence Berkeley Laboratories Daylight Group consulted on the project, although I have been unable to find performance data.

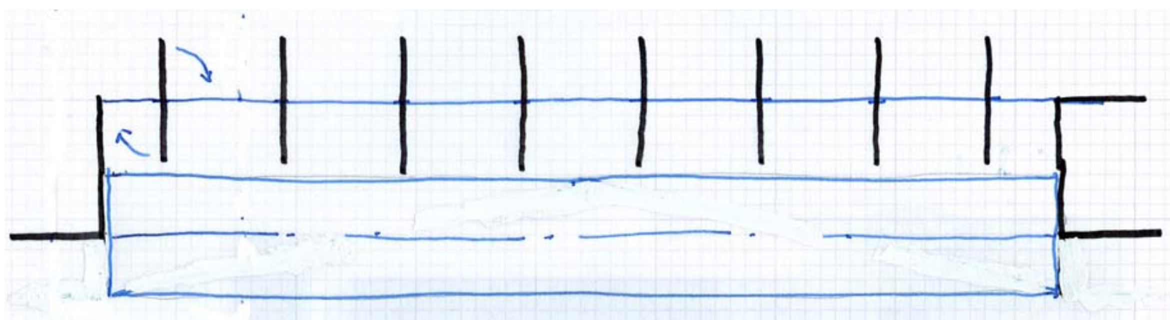


Treatment D-1



Treatment D-2

Treatment D-2 is based upon Renzo Piano's design for the Cy Twombley Museum in Houston, Texas. It has two layers of louvers at 6" on center. The upper layer is static to select light from one quadrant of the sky, similar to S-1. This layer manages light quality as north light is generally uniform. The lower layer of louvers manages light quantity through aperture adjustment. The lower layer operates rotationally on a pivot and is oriented at 90 degrees to the upper louvers. The proportion of the space between the louver layers and the relative orientation of the louvers to each other has been changed from Piano's concept for the purposes of this experiment. The change in orientation allows the louvers to be located with little separation without affecting performance. This decision minimizes the overall height of the component curb and related shading.



Treatment D-3

Treatment D-3 is derived from Llewellyn Davies' design for the Tate Museum in London. It has two layers of louvers with rotational movement. The layers are disposed at 90 degrees to each other. The movement of the louvers will be synchronized so that the layers rotate simultaneously and equally.