1-1-2008

Mathematical model to simulate a hybrid lighting system

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MATHEMATICAL MODEL TO SIMULATE A HYBRID LIGHTING SYSTEM

by

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Bachelor of Science
University of Alexandria, Egypt
2004

A thesis submitted in partial fulfillment
of the requirements for

Master of Science Degree in Engineering
Department of Mechanical Engineering
Howard R. Hughes College of Engineering

Graduate College
University of Nevada, Las Vegas
December 2008

UNLV
UNIVERSITY OF NEVADA LAS VEGAS

Thesis Approval
The Graduate College
University of Nevada, Las Vegas

NOVEMBER 10, 2008

The Thesis prepared by

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Entitled

MATHEMATICAL MODEL TO STIMULATE A HYBRID LIGHTING SYSTEM

is approved in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

Examination Committee Chair

Dean of the Graduate College

Examination Committee Member

Examination Committee Member

Graduate College Faculty Representative

1017-53

Abstract

Mathematical Model to Simulate a Hybrid Lighting System

by

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Hybrid solar lighting (HSL) technology is a relatively new technology to utilize natural sunlight along with the traditional electric lighting to light the interior spaces. HSL systems concentrate the sunlight onto a bundle of optical fibers. The optical fibers are routed into the interior space and coupled with cylindrical rods to diffuse the light. A lighting sensor modulates the amount of electric energy depending on the amount of natural light available.

This study presents a simplified mathematical model to predict the output of the HSL system based on the amount of the available solar radiation. The model is verified via real-time measurement of the output of the system. The monthly savings on electric energy are estimated. The break-even cost of the system is estimated based on the electricity saving. The effect of the length of the fibers on the output and the savings is also investigated.

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NOMENCLATURE

I	Solar irradiance (W/m^2)
G	Irradiance ($W/nm\ m^2$)
P	Power of light (Watt)
η	Optical efficiency
λ	Wavelength (nm)
ν	CIE visibility curve
ξ	Efficacy (lumens/Watt)
ρ	Reflectivity
τ	Transmissivity

ACKNOWLEDGEMENT

I appreciate the financial support from the US Department of Energy on the contract number “RF-06-PRD-003”, project “Photonics Research and Development”. I would also like to thank my advisor, Robert F. Boehm, and my colleagues Rik Hurt and Marc Campbell for their help.

CHAPTER 1

INTRODUCTION

1.1. Technology overview

Hybrid solar lighting technology is an innovative way to utilize the sunlight along with the electric light to illuminate the interior of the buildings. The system collects the sunlight and distributes it through optical fibers to hybrid luminaires that blend the light from the two sources harmoniously.

The idea of routing the sunlight through fibers into the interior space dates back to the early 1970's when Himawari, in Japan (Figure 1.1), marketed a fiber-coupled solar collection system, but it never developed a significant impact on the lighting market. The hybrid solar lighting system (HSL) was conceived at the Oak Ridge National Laboratory (ORNL) in the mid 1990's. The concept of fiber-coupled solar collecting daylighting system wasn't new. However, HSL was the first system to integrate the electric lighting as a fundamental part of the system.

HSL is composed of four main components: 2-axis tracking system, solar collector, plastic fiber optic bundle, and hybrid luminaires (Figure 1.2) The HSL tracking enclosure houses a sun tracking control board used to calculate the position of the sun based on latitude, longitude, and coordinated universal time (UTC.) The control board uses a microprocessor to compute the U.S. Naval Observatory's astronomical equations, which are good to one-sixtieth of a degree for the next 300 years. This precision allows the system to track at 0.1° accuracy. The calculations determine the positions in the azimuth and zenith Earth-based coordinate system using latitude, longitude, and UTC from a global positioning system (GPS) receiver. Figure 1.3 illustrates the HSL tracking system. The positions are then converted to units of encoder counts for the two encoders used to detect the location of the collector on each axis. The controller compares the actual direction in which it is pointed to the computed position of the sun. Then the controller determines if the collector needs to be moved in a positive or negative direction to match its position with that of the sun. The motors then move at a speed proportional to the difference in the actual and computed positions. This process is performed continuously throughout the day to track the sun accurately. The control board operates on a 12-V or 24-V dc supply and uses less than 2 watts average power. A small photovoltaic (PV) solar cell may be used to charge a battery to power the entire system.

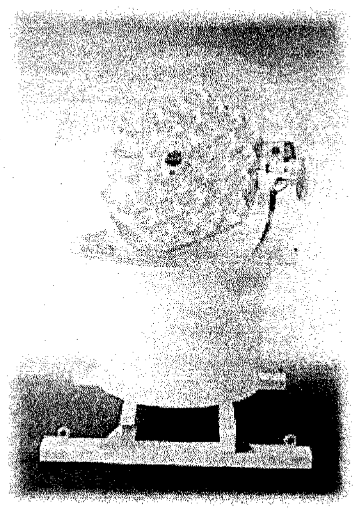

Figure 1.1. Himawari solar collector.

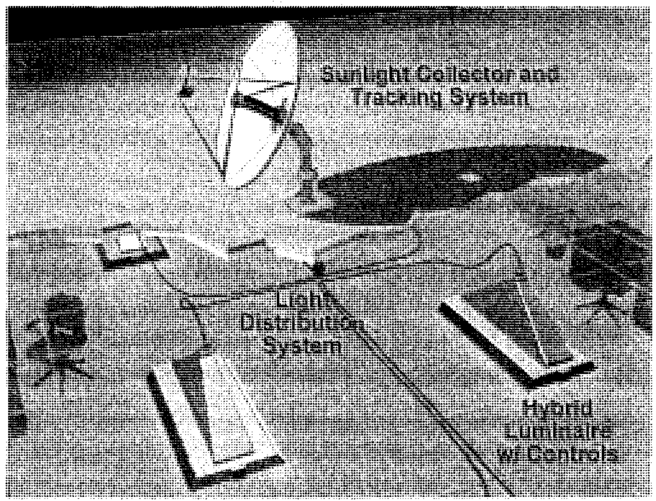

Figure 1.2. Illustration of the major components of the system (http://www.ornl.gov/sci/solar/applications.htm)

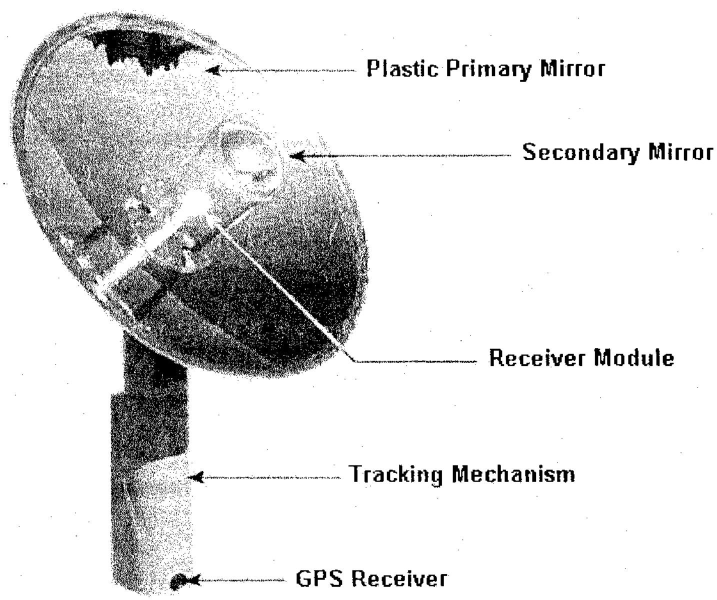

Figure 1.3. Illustration of the HSL tracking system.

Sunlight is captured and concentrated by a roof-mounted, two-mirror solar collector. The parabolic primary mirror captures the sunlight and directs it to an elliptical secondary mirror. The secondary mirror is covered with a wavelength selective coating (giving it a pink tint), which allows the infrared (IR) and ultraviolet (UV) wavelengths to pass through. Only the visible wavelengths are focused onto the bundle of plastic optical fibers. The bundle of fibers contains 127 individual plastic optical fibers. Each optical fiber is 6mm in diameter. The bundle of plastic fibers penetrates the roof and distributes the sunlight to multiple "hybrid" luminaires within the building. These hybrid luminaires contain clear plastic diffusing rods that blend the natural light with artificial light (both of variable intensity) to maintain a constant level of room illumination. The system uses a lighting harvesting sensor and dimmable fluorescent ballasts to control the illumination level inside the room. The sensor is used to dim or brighten the fluorescent ballasts depending on how much illumination the HSL is providing. Thus, this enables seamless operation.

1.2. System advantages

Electric lighting is estimated to account for 2.35 quadrillion Btu or 11.3% of the residential electricity consumption and for 3.66 quadrillion Btu or 20.4% in commercial buildings per year in the USA (Annual Energy Outlook 2008, DOE). With the cost of power continuously increasing, especially at today's escalating oil prices, HSL can result in considerable savings by cutting the dependence on electricity. Moreover, using HSL reduces the HVAC loads by 15% (Muhs, 2000) as the IR gets filtered out before being transmitted into the interior. By reducing the electricity consumption, and in turn the use of fossil fuels, HSL helps reduce the greenhouse effect.

Savings on the electricity cost are not the only benefits of the HSL. The lighting quality of the HSL far exceeds that of the typical electric lighting. This is attributed to the spectrum of the light output of each source. Almost all of the artificial light sources emit light that is more reddish than natural light (i.e. their emission is peaked at wavelengths greater than 500 nm). The spectrum in Figure 1.4 is typical of what is seen in many commonly used fluorescent lamps. The majority of light is emitted in a band that is centered around 575 nm and falls off rapidly on either side of that peak. There are also substantial spikes in the spectrum at other wavelengths. HSL light on the other hand is spread more uniformly over the visible spectrum, making the light so much whiter than the fluorescent one. Figure 1.5 shows a comparison between the light output of the HSL system and the sunlight. It is obvious how the HSL output closely mimics the natural sunlight.

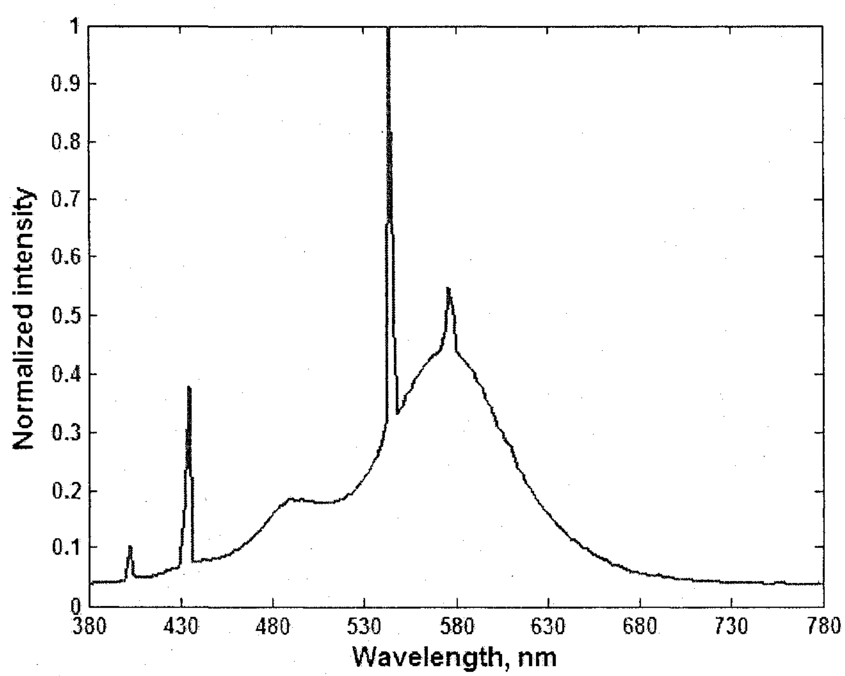

Figure 1.4. Spectral normalized output of typical fluorescent lamps.

HSL light output, being almost natural light, has a CRI of 100 (Lapsa, 2007). CRI, or the Color Rendering Index, is a measure of the degree to which a light source affects the apparent color of objects relative to the perceived color of the same objects when illuminated by a reference source for specified conditions. The higher the index, the better is the color rendering.

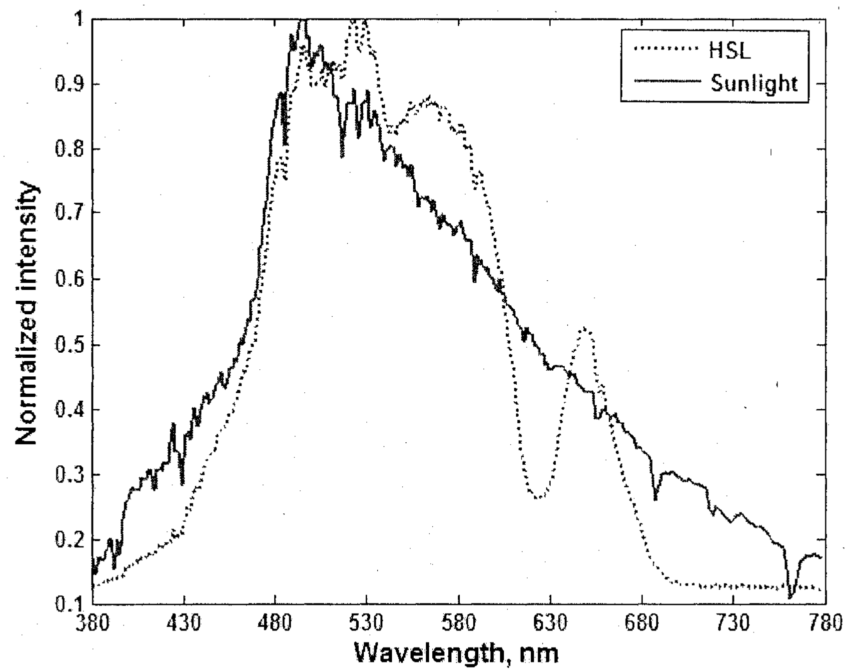

Figure 1.5. Natural normalized solar spectrum compared to HSL output.

Natural light, also, has been associated with improved mood, enhanced morale, lower fatigue, and reduced eyestrain. It has been shown also that natural lighting increased the productivity in offices and academic achievement in school (Edwards and Torcellini, 2002). And also it has helped increase the profit in retail stores (Lapsa et al., 2007).

1.3. Literature review

Edwards and Torcellini (2002) introduced a literature review of the effects of natural light on building occupants. The paper discusses the effects of natural light on the occupants of offices, schools, retails, and health care facilities. According to the paper, natural light had proved to be beneficial for the health, productivity, and safety of building occupants. Natural light helped maintain good health and could cure some medical ailments. The pleasant environment created by natural light decreased stress levels for office workers. Students also performed better with natural light. Across the nation, studies had shown students in daylight rooms achieved higher test scores than students in windowless or poorly lit classrooms. Along with better test scores, students' health also improved from the increase in vitamin D intake. Students had fewer dental cavities and grew more under full-spectrum lighting. Daylighting also benefits retail stores because of more even light that provided better color rendering. In health care facilities, natural light improved patient recovery rates. Productivity increased in industrial environments because of improved color rendering and the better quality of light provided by natural light.

Schlegel et al. (2004) developed a TRNSYS model of the HSL system. The simulation incorporates the spectral properties of the hybrid lighting components as well as the spectral distribution of the incoming solar radiation that is based upon output from the SMARTS atmospheric transmittance model. The model assumed that the system used a thermal photovoltaic array to generate electricity using the IR portion of the solar irradiance. An office building model was coupled with the simulation to predict the annual energy impact upon lighting, heating, and cooling loads. The simulation was done for six locations within the United States. The paper also presented an economic analysis based on the savings to estimate the break-even capital cost of the HSL system in each of the six locations. Muhs (2000) presented full-spectrum analysis of the HSL system. The paper discusses the conceptual design of the different components of the HSL system. It also presents a projected performance of the system in which an estimation of the savings on the electricity is presented. The economic analysis was done for different scenarios for the collector area and different electricity rates. The cost of the system was estimated to be $3000 based on a 2-m collector area, illuminating 12 luminaires, covering about 1000 ft^2. The paper expected the cost of the system to be reduced by 50% once the system is fully commercialized. A comparison between the HSL system and its alternatives, mainly skylights since it is the most promising daylighting technology, was also made and was presented in the paper. Several factors were mentioned as to why the HSL system would have less pay-back period than skylights. The paper also introduces a synopsis of some the possible uses of solar energy in the United States.

Kandili and Ulgen (2007) presented a review of the previous studies done on the transmission of concentrated solar energy via optical fibers for various purposes (TCSEvOF). Previous studies of TCSEvOF were grouped into six categories; characterization of the system, solar lighting, solar surgery, photo-bio reactors, hydrogen generation and photochemical reactions, solar power generation, and solar pumped lasers. A mathematical model was presented for the coupling of symmetrical dishes with fibers. A modified model was also presented for the optimum coupling of an offset parabolic dish with the fibers. The optimal geometrical parameters for the coupling were also analyzed. The amount of energy collected by each dish design was calculated and compared to measurements of an actual system. A comparison was made between symmetric and offset concentrating dishes. The advantages and the disadvantage of each configuration were discussed.

Cates et al. (2003) experimentally studied the transmission properties of the optical fibers used in the HSL system. The investigated properties included the total transmission per unit length, transmission as a function of input angle and wavelength, transmission as a function of bend radius, and transmission through two bends. The experimental methodology used to study the light guide properties was presented in the paper in detail.

Maxey et al. (2007) studied the spectral transmission of the HSL system. Spectral transmission properties of the hot mirror, the secondary mirror, and the optical fibers were measured using a spectrometer. The paper characterized the ultraviolet, visible, and near infrared spectral transmission. The UV and NIR performance of the system is crucial since optical fiber damage can be caused by both UV and NIR light; thus, optimal system design maximizes the collection and transmission of visible light while minimizing the transmission of the UV and NIR light.

Earl and Muhs (2001) reported on the design of two hybrid luminaire designs for use in the HSL system. The two designs under question were multiple dispersing elements or cylindrical emitting rods. Both designs involve the retrofit of commercially available recessed fluorescent luminaires. ZEMAX software was used to compare the spatial intensity distribution of the two designs. Various factors that affect the performance of each design were discussed. According to the results concluded in the paper the multiple dispersing elements configuration was slightly more efficient than the cylindrical rods one. The paper also concluded that significant amount of modeling and testing was still required to more accurately study the performance characteristics of each configuration. Earl et al. (2003) reported on an experimental investigation of a new hybrid lighting luminaire design. The design utilized a cylindrical rods with grooves precisely machined into them to disperse the light. Quantitative measurements of the optical efficiency and the special intensity distribution were discussed. ZEMAX was used to simulate the optical performance of the luminaire under various configurations. The simulations showed that the natural conic intensity distribution of an optical fiber was highly incompatible with the distribution of fluorescent 4-tube luminaire designed for large-area lighting. It was determined that a long uniform cylindrical source distribution would permit the most effective blending of fiber optic lighting with fluorescent lighting. Experimental measurements showed that this luminaire design had an optical efficiency of 58%. A significant amount of losses, estimated to be 20%, were attributed to the coupling between the fibers and the rods. An improved method for coupling the fibers with the rods was claimed in the paper to cut the coupling losses to only 3% and to increase the optical efficiency of the luminaire to 75%. The paper also concluded that a significant amount of modeling and testing were still required to be done on the new design before its physical implementation realized its full potential.

Muhs (2000) presented an overview of the HSL technology and a historical background about the use of natural light for lighting. The paper also discussed some of the technical difficulties that needed to be addressed in order for the system to become a reality. The paper presented some of the anticipated outcomes of the system, such as the saving on electricity and reduction of HVAC load. The paper also presented a comparison between the HSL system and its alternatives, and also presented an estimation of the system cost based on the location of the system.

Lapsa et al. (2007) presented a historical background about utilizing natural sunlight for illuminating interior spaces. Then, the paper reported on the results of field trials of the HSL system at three sites: a retail space located at Wal-Mart in McKinney, Texas; an open office area and a hallway at San Diego State University; and the new Multifunctional Research Facility at ORNL in Oak Ridge, Tennessee. Extensive non-energy assessment of the benefits of using natural light was done by Wal-Mart. It concluded among other things that the store was perceived by the customers to be cleaner, the products are more appealing, and customers prefer and are attracted to areas illuminated by natural light. Preliminary results from San Diego State University showed that HSL could have a significant impact on energy savings. Measurements of electric energy consumption were taken and reported for an entire day (21/6/06). It was shown that during the course of the day the reduction of electric energy consumption was 41%, while the reduction during the peak hours was 63%.

Lapsa et al. (2006) presented an overview of the technology and discussed the way the system works. The paper also mentioned some of the HSL advantages. The original price of the product offering Sunlight Direct was $24,000. The company has a development plan the aggressively targets the commercialization cost goal of $3 per foot illuminated. Energy savings of approximately 6,000 kWh per year are due to the reduced lighting needs. About 2,000 kWh per year is estimated to be saved due to reducing the cooling load. The paper estimates that by the year 2011 the HSL should be saving 50 million kWh per year. The paper also shows comparisons between the sunlight, HSL light, and fluorescent light spectra. The graphs show how the HSL light spectrum closely mimics the natural sunlight while the fluorescent light is completely different and spiky. Hence HSL light quality far exceeds that of the fluorescent. The paper concludes that a significant market exists for hybrid solar lighting.

Beshears et al. (2003) evaluated the performance of two potential candidate tracking systems for HSL solar collector. The first system, the Wattsun Solar Tracker, bui;t by Array Technologies, utilizes a patented closed-loop optical sun sensor to sense the sun's position and track it. The second tracking system, SolarTrak, built by Enhancement Electronics Inc., is a microcontroller-based tracking system. The sun's position is determined by computing the celestial bearing of the sun with respect to the earth using the local time, date, latitude, longitude, and time zone. A ZEMAX model was developed to determine the permissible alignment tolerances on each axis. Based on experimental observations, SolarTrak computerized controller had many advantages when compared to Wattsun's. The paper also suggests some enhancement that could enhance the performance of the SolarTrak controller.

CHAPTER 2

SYSTEM COMPONENTS

2.1. Primary mirror

The primary mirror is the element used to collect and concentrate the sunlight. It consists of 50 in. (1.27 meter) diameter mirror that has a concave parabolic profile, that is silver-coated on the back. It is mounted on a 2-axis tracking system that enables it to gather the direct normal incident radiation. The mirror increases the power density of the incident radiation by focusing it on a small receiver area. The receiver penetrates the center of the collector.

Figure 2.1 shows the spectral reflectivity of the collector over the visible portion of the sunlight. The coating used for the collector has an average reflectivity of approximately 93%.

The optical performance of the dish is sensitive to the surface characteristics. Imperfections in the surface (surface errors) greatly impair the optical efficiency of the dish and in turn the light output of the system. The parabolic dish installed at Taylor Hall has an optical efficiency of 30%. The optical efficiency is the ratio of the lumens incident on the dish to the lumens reflected from the dish. The light output of the system will be proportioned by this efficiency. The efficiency was measured by a special tool provided by Sunlight-Direct. (See Appendix A).

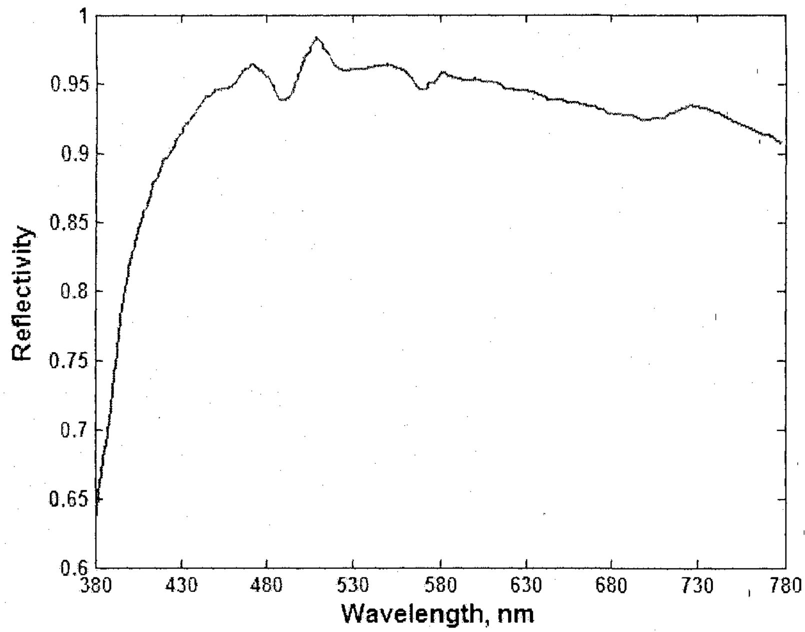

Figure 2.1. The spectral reflectivity of the primary dish.

2.2. Secondary mirror

The secondary mirror is sometimes referred to as Secondary Optical Element (SOE) as well. It is the element onto which the concentrated sunlight reflected from the primary mirror falls. The mirror lies near the focal point of the primary collector. It is a small elliptical mirror coated with a selective material. This coating allows the ultraviolet (UV) and the infrared (IR) portions of the spectrum to pass through and reflects only the visible portion of the light (from 380 to 780 nm) onto the fibers receiver tube. By getting rid of the IR and the UV, the SOE reduces the heat input to the space, and increases the luminous efficacy of the HSL output light. The efficacy of the light is a measure of how well the power in the light is used to illuminate, and its units are lumen/Watt. The higher the efficacy of the light is, the less power is needed to give the same illumination level. Luminous efficacy will be discussed in detail later.

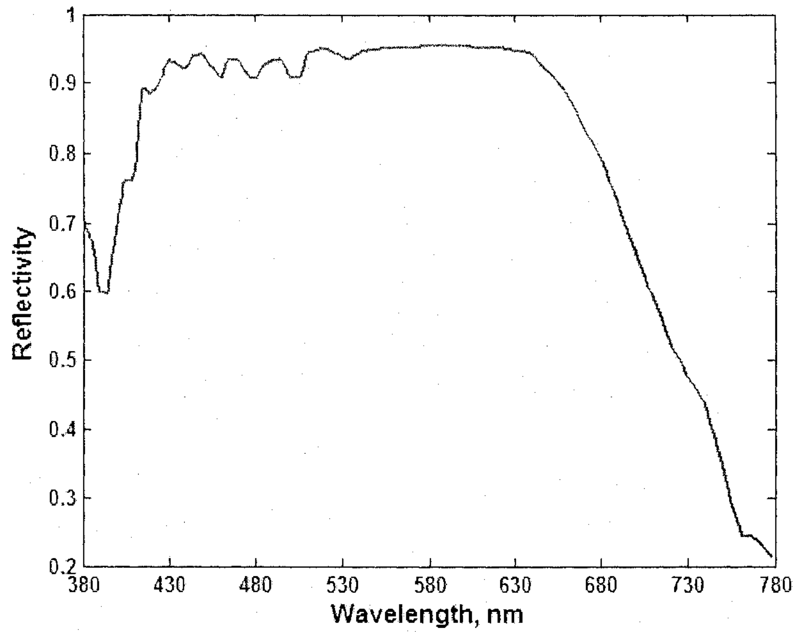

Figure 2.2. The spectral reflectivity of the secondary mirror.

Figure 2.2 shows the spectral reflectivity of the SOE over the visible spectrum. The coating has a low reflectivity near the IR which is not important as the human-eye doesn't respond well to the light at high wavelength. The coating has a poor reflectivity near the IR portion (650~780 nm). The inefficiency from 650-780 nm is relatively insignificant due to the standard CIE visibility curve, which represents the spectral sensitivity of the human eye. The eye does not see visible light very well at longer visible wavelengths, so the reflectance losses at longer visible wavelengths are not as significant as they appear to be. The average reflectivity of the secondary mirror is 85% over the visible portion.

2.3. IR filter

Although the secondary mirror filters out the IR, a small residual remains in the light reflected onto the fiber optics. This residual, though small, could damage the fiber optics at such a high concentration ratio. To protect the fibers, an additional IR filtering should be provided at the entrance of the light onto the fibers' receiver to get rid of any residual IR. Two types of filters had been investigated. The first suggestion was to use an IR filter. Figure 2.3 shows the spectral transmissivity of the IR filter. The average transmissivity of the IR filter over the visible portion of the spectrum is 72%, which represents a fairly high loss. The second suggestion was to use a fused quartz glass. This is a more economic alternative as the losses associated with it do not exceed 3%.

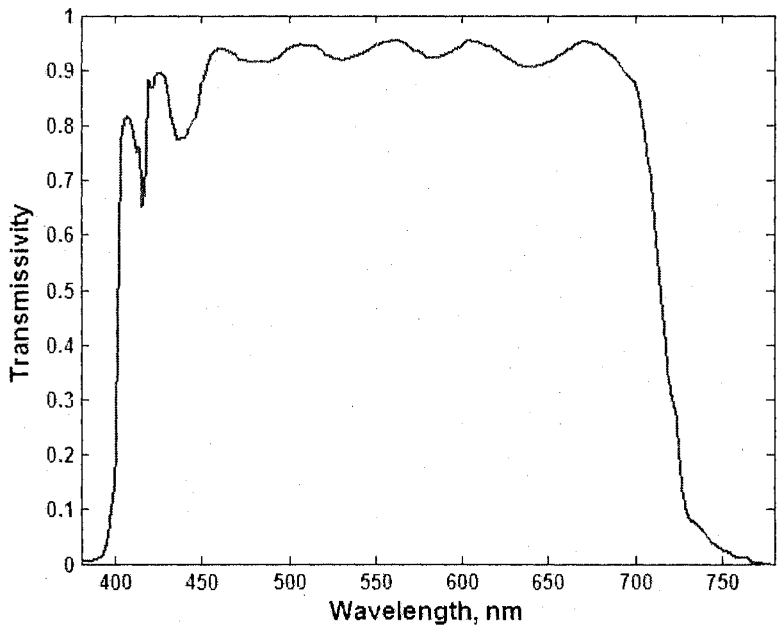

Figure 2.3. The spectral transmissivity of the IR filter.

2.4. Optical fibers

The optical fibers transmit the light, collected by the primary mirror and filtered and reflected by the SOE, into the interior space. The current material being used is a high luminance light fiber manufactured by 3M. The light fiber is made of polymethacrylate which is flexible and resistant to fatigue, elongation, and vibration. At one end, the fibers are bundled into a receiver tube that penetrates the primary mirror, and onto which the SOE reflects the light.

Figure 2.4 shows the spectral attenuation characteristics of the fibers. The graph shows little attenuation for the most part of the visible spectrum except for a spike at around 740 nm. Fibers are the weakest link in the system. They comprise the component where most of the losses take place. The average attenuation for this type of fiber over the visible range is 14% per meter. For this reason, fibers length is recommended to be kept at less than 10 meters. The ends of the fibers should be properly finished since a poor finishing would increase the light losses.

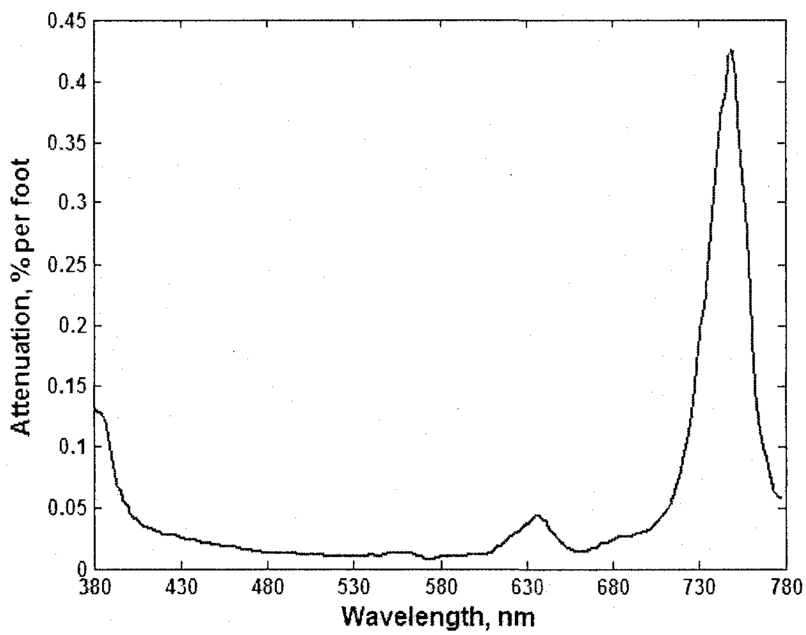

Figure 2.4. The spectral transmissivity of the optical fibers.

2.5. Hybrid luminaires and controls

Hybrid luminaires are fixtures that contain the natural light dispersing elements as well as the electric light bulbs. Luminaires should be designed to provide uniform light distribution using the natural light, the electric light, or both. They also should be capable of blending the two sources harmoniously. This ensures seamless operation specially that the intensities of both of the light sources change depending on the available sunlight. Two designs are available for the dispersing elements. In the first one, the ends of the fibers individually penetrate the top of the fixture and are distributed in rows. Figure 2.5 shows such an arrangement. The light is emitted down to the space from those ends.

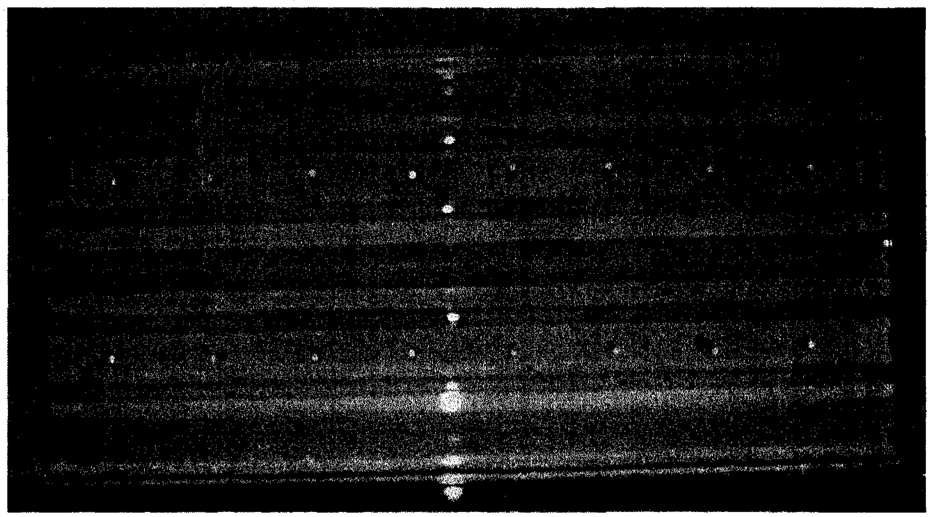

Figure 2.5. Illustration of the first arrangement; the ends of the fiber optics penetrate the fixture.

The other design is the side emitting one. In this, bundles of 14 fibers each are coupled with acrylic rods. Figure 2.6 shows the side emitting rods. The rods are mounted in the fixtures. Each rod has precisely machined grooves to control scattering along the length of the rod. At the other end of each rod is a reflecting surface. This surface is to reflect back the light that would have otherwise escaped through this end of the rod and been lost. Figure 2.7 shows a hybrid luminaire with the dispersing rods installed and shining.

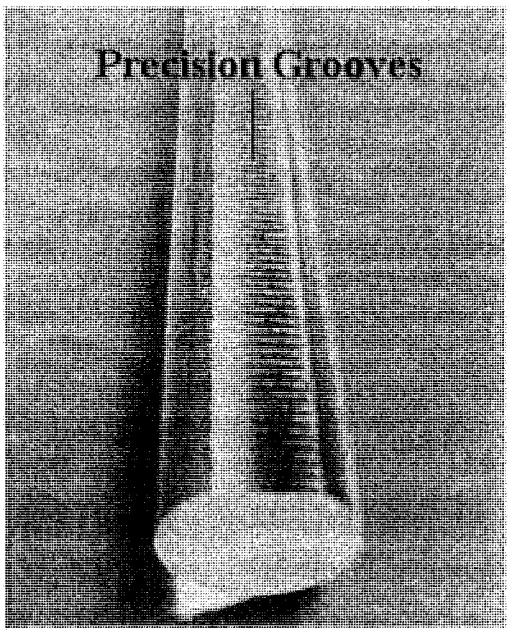

Figure 2.6. Illustration of side emitting rod.

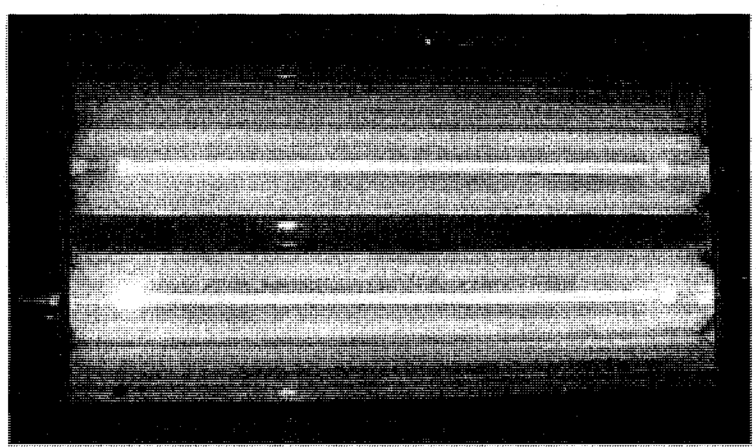

Figure 2.7. Hybrid luminaire with side emitting rods installed (the second design)

No spectral data is available for the luminaries. However, according to the work of Earl et al., (2001) the overall optical efficiency of this design was initially 58%. The optical efficiency is defined as in equation 2.1,

$$\text{Optical efficiency} = \frac{\text{lumens output from the luminaire}}{\text{lumens input to the luminaire from the fibers}} \tag{2.1}$$

This low performance was attributed to the coupling losses between the fibers and the rod. Coupling losses were estimated to account for 20%. An improved design has been suggested to cut these losses down to only 3%, increasing the overall optical efficiency of the luminaire to 75%, but it hasn't been verified yet. Of the four hybrid fixtures at UNLV's Taylor Hall, three are of the latter design and only one is of the former one.

A lighting harvesting sensor is mounted inside the space to monitor the illumination level and compare it to a preset value. Based on the sensed illumination level, the control system dims the electric ballasts or brightens them up. This is accomplished by controlling the amount of electrical power supplied to the ballasts. The control system however never dims the fluorescent ballasts below 20% of their nominal power. Below this value, the efficacy of the fluorescent bulbs greatly deteriorates, which renders it impractical to keep it on.

CHAPTER 3

SIMULATION

3.1. Luminous efficacy and the lumen

The human eye perception of light depends on the distribution of the light power over the different wavelengths. So, in order to estimate how much illumination the HSL could provide, the collected sun power should be weighted using response characteristics of the typical human eye. These response characteristics are defined by the CIE visibility curve. Figure 3.1 shows the 1924 CIE visibility curve. There are two different ways in which the eye processes the light; photopic under high illumination levels and scotopic under low illumination levels. The difference between the two modes lies in which part of the eye responds to the excitation of the light; the rods or the cones. The shown figure is for the photopic mode.

Luminous flux is an important quantity when studying the illumination. It is defined as the radiant power weighted by the visibility curve. The lumen is the unit of the luminous flux. One lumen is equal to the light per unit area on a surface of a sphere that has a radius of one meter and a light source at its center equal to one candela.

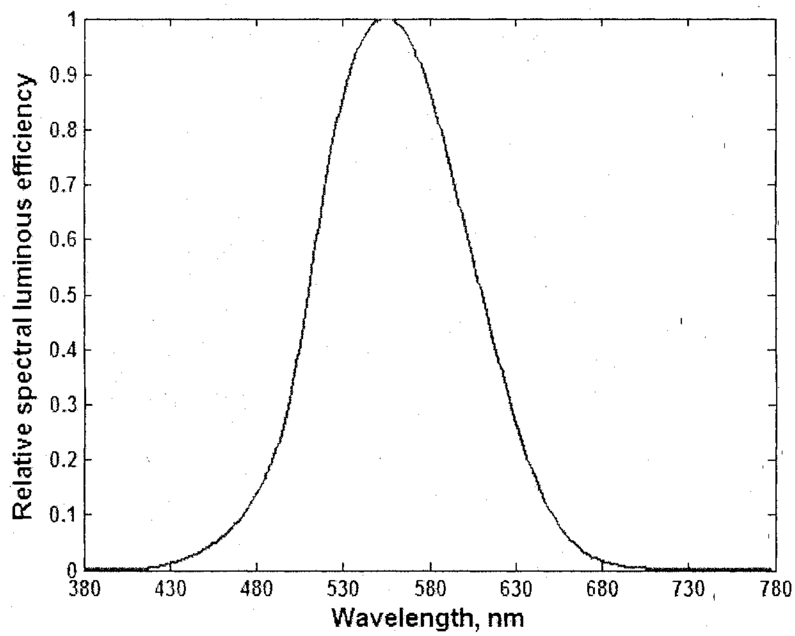

Figure 3.1. CIE 1924 visibility curve (wavelength characteristics of typical human eye.)

Luminous efficacy is the ratio of the luminous flux to the total power input. In other words, luminous efficacy is a measure of how much illumination the human eye would perceive that results from a certain amount of power. Luminous efficacy is an important factor to compare different sources of lighting. The higher the efficacy, the more efficient the source is. Luminous efficacy is calculated by integrating the spectral distribution of the light multiplied by the visibility curve (the luminous flux) and divide that by the integral of the spectral distribution of the light (the power input) as in equation 3.1,

$$\xi = 683 \cdot \frac{\int_0^\infty G(\lambda)v(\lambda)d\lambda}{\int_0^\infty G(\lambda)d\lambda} (lumens / Watt) \tag{3.1}$$

where v = CIE 1924 visibility curve

G= Irradiance (W/nm m^2)

ξ = efficacy (lumens/Watt)

The range of integration of the numerator is reduced to the limits of the visible portion (380 to 780 nm) since this is the range over which the human eye responds to the light. An ideal light source, defined as one that emits monochromatic light over the visible portion, has a luminous efficacy of 683 lumens/Watt. The luminous efficacy of the sunlight is approximately 220 lumens/Watt (varies depending on the atmospheric conditions.) Modern fluorescent light has a luminous efficacy of approximately 100 lumens/Watt. Incandescent light sources have a luminous efficacy of 60 lumens/Watt. Since the HSL filters out the IR and UV portions and emits only over the visible portion, the power input is reduced and the efficacy in turn is increased dramatically.

3.2. Solar irradiance

The sun is a huge nuclear reactor. Energy is generated at its interior at extremely high temperatures, estimated at many millions degrees. This energy is transferred to the surface through a series of convective and radiative processes. It is then radiated into the space. Energy is radiated with different intensities at different wavelengths. Solar radiation is believed to have a nearly fixed value outside the earth's atmosphere. Although fixed, this constant has different estimates. Recent studies estimate this constant to be approximately 1367 W/m^2 (Duffie and Beckman, 2006.) The amount of energy that reaches a specific location on earth however depends on the location atmospheric conditions.

Solar radiation is emitted over a wide range of wavelengths ranging approximately from 0.28 nm to 4 nm. Figure 3.2 shows the extraterrestrial spectral irradiance. Slight variation might occur in the spectral distribution of the solar radiation due to the periodic variation of the energy generated in the sun and the variation of the sun-earth distance.

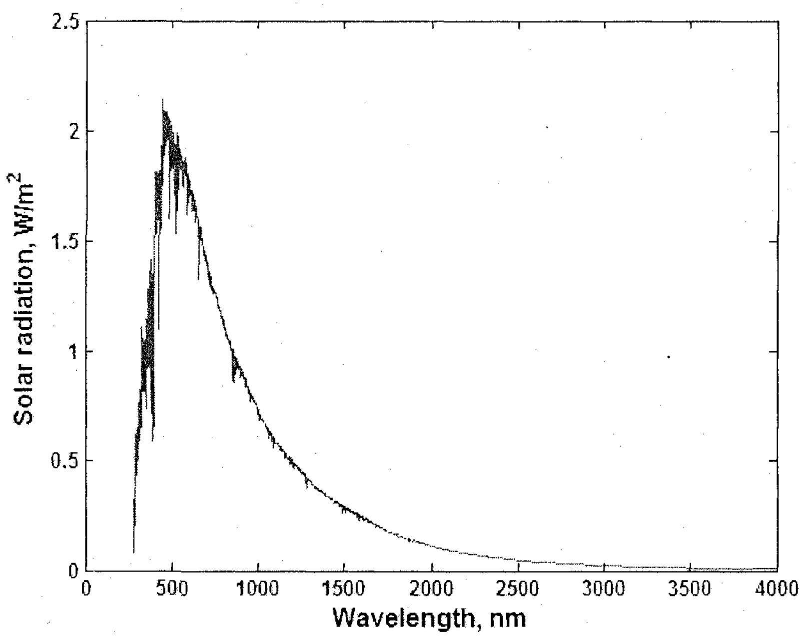

Figure 3.2. Extraterrestrial solar radiation.

As solar radiation travels through the atmosphere it gets attenuated. These attenuation characteristics depend on the local atmospheric conditions. The amount of attenuation also is different for different wavelengths. Spectral irradiance distribution was measured locally to be used in the calculations. Figure 3.3 shows a comparison between the spectral distribution of the extraterrestrial radiation and the locally measured solar radiation over the visible range of the spectrum.

Total incident solar radiation is composed of two main components; diffuse and beam radiation. Diffuse radiation is the radiation received from the sun after being scattered by the atmosphere. Beam radiation is the radiation received from the sun without being scattered i.e., its direction hasn't been changed. The amount of incident radiation on a surface depends on the available solar radiation as well as on the orientation of the surface with respect to the sun, which determines the incidence angle. For 2-axis tracking collectors, the incidence angle is normally zero. The incident solar radiation in this case is given the name "Direct Normal." This value can be calculated based on the available beam radiation and the zenith angle.

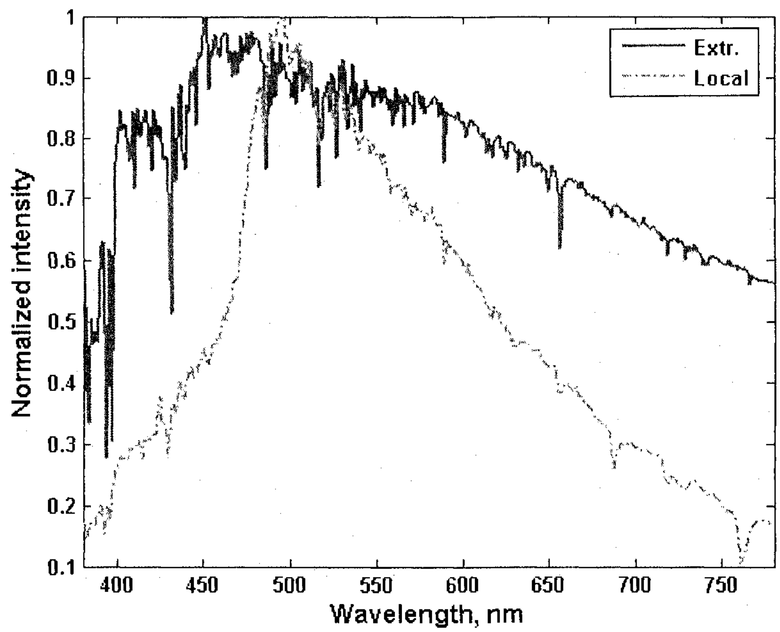

Figure 3.3. Spectral distribution of extraterrestrial versus locally measured solar radiation.

For predictive estimation purposes, values of TMY2 data should be used. TMY is a data set of hourly values of solar radiation and meteorological elements for a 1-year period. It consists of months selected from individual years and concatenated to form a complete year. The TMY2s were derived from hourly values of measured or modeled solar radiation and meteorological data for 239 stations for the 30-year period from 1961-1990. TMY2 files can be downloaded free of charge at the National Renewable Energy Laboratory (NREL) website.

3.3. The hybrid lighting model

The purpose of modeling the HSL is to predict the illumination the system can provide at a certain solar irradiance level, and hence the savings on the electric light can be estimated. To do so, the spectral distribution of the output light as well as the power level of the light should be identified. The former determines the luminous efficacy of the light. When multiplied by the power input, luminous efficacy yields the available amount of lumens.

The spectral distribution of the output light is determined based on the spectral characteristics of the various components and the spectral distribution of the solar irradiance. The effect of the luminaires is not taken into account here since no spectral data are available for them. Thus, the spectral distribution is calculated for the light at the outlet of the fiber just before entering the luminaires. The spectral distribution is calculated as in equation 3.2,

$$H(\lambda) = I(\lambda)\rho_{conc}(\lambda)\rho_{soe}(\lambda)\tau_{fibers}(\lambda) \qquad (3.2)$$

where $H(\lambda)$ = spectral distribution of the output light from the fibers (Watt)

$I(\lambda)$ = spectral distribution of the solar irradiance (Watt)

$\rho_{conc}(\lambda)$ = spectral reflectivity of the concentrating collector

$\rho_{soe}(\lambda)$ = spectral reflectivity of the secondary mirror

$\tau_{fibers}(\lambda)$ = spectral transmissivity of the fibers, i.e. *1-attenuation*

Efficacy is then calculated as in equation 3.1.

Power of the output light is determined based on how much is lost of the power of the incident radiation while being transmitted through the different components of the system. Thus, light power is calculated as in equation 3.3,

$$P = I\rho_{conc}\rho_{soe}\tau_f\tau_{fibers} \tag{3.3}$$

where P = power of the output light at the fibers end (Watt)

ρ_{conc} = average reflectivity of the concentrating collector

ρ_{soe} = average reflectivity of the secondary mirror

τ_f = average transmissivity of the IR filter

τ_{fibers} = average transmissivity of the fibers

Average reflectivities are calculated as in equation 3.4,

$$\rho = \frac{\int_{380}^{780} \rho(\lambda)d\lambda}{\int_{380}^{780} 1d\lambda} \tag{3.4}$$

Average transmissivities are calculated using the same concept.

Now that the efficacy of the light as well as the light power is known, illumination (lumens) can be calculated by simply multiplying them. The result is how much lumens are input into the luminaires. Effect of the luminaires on the illumination is taken into account by the optical efficiency. Illumination output of the luminaires is calculated as in equation 3.5,

$$illum(lumens) = PH\eta \tag{3.5}$$

where η = optical efficiency of the luminaires

The illumination sensor dims the electric light by almost the same amount of lumens provided by the HSL system. Thus, electricity savings are related to the efficacy of the electric bulbs used as in equation 3.6,

$$\text{Savings} = \text{HSL - provided lumens x electric light efficacy} \quad (3.6)$$

MATLAB code was written to predict the annual HSL output using TMY data (Appendix C). The code reads the spectral properties of the different component, spectral solar irradiance, and the CIE visibility curve directly from excel sheets that contain these sets of data. Different sets of data were taken at different wavelength increments. The code interpolates the data and uniforms all the sets on a unit wavelength increment over the range of 380 nm to 780 nm.

CHAPTER 4

RESULTS AND VERIFICATION

4.1. Introduction

In order to verify the proposed model, measurements of the actual system output were taken to be compared with the predicted values. Measurements include the spectral characteristics of the output light, as well as the illumination level. All measurements were done on the system installed at Taylor Hall. In the following sections, the methodology and the findings of the measurements will be discussed in detail.

4.2. Actual measurements

Spectral characteristics of the output light from the fibers and before the luminaires were measured using a spectrometer[1] (Figure 4.1). A spectrometer is an instrument used to measure the properties of light over some portion of the electromagnetic spectrum. The used spectrometer has a measurement range of 218nm to 1066 nm. The spectrometer connects to a computer via USB port. Software provides the necessary interface to read the measured data and manipulate it. The procedure to measure the spectrum is a simple one. The end of one optical fiber was put directly in front of the spectrometer. The lens lies inside a groove, so no disturbances from other light sources could affect the accuracy of the measurement. The spectrum of the light was output on two forms; a graph of the

[1] Manufactured by Edmund Ind. Optics, Model number BRC111A-USB-VIS/NIR

intensity versus the wavelength, and a table of these values. The table is exported as an Excel sheet.

Figure 4.1. A picture of the used spectrometer showing the light input port.

Illumination measurement on the other hand is much more sophisticated. The value of the illumination at a certain point depends on the position of the point relative to the source. Different sources' geometries have different distribution patterns, as well. Another complicating factor was the distribution of the hybrid luminaires. Only four out of 17 luminaires in the room incorporate HSL light. Figure 4.2 shows the layout of the luminaires at Taylor Hall. The procedure was to measure the illumination at each of several points. These points were chosen such that they constitute a uniform grid that covers the area over which the hybrid luminaires were distributed. The grid consists of 7x4 points.

Only 14 light meters were available. The illumination measurement would have to be carried out on two times. For that purpose, a 12x4 ft metal frame was manufactured on which the illumination measurement elements will be mounted. After measuring the illumination for one half of the grid, the frame is then moved to cover the other half. The light meters used are EXTECH Pocket Foot Candle Light Meters[2]. The measurement can be done in two ranges; 0.0 ~ 200.0 Fc or 0 ~ 2000 Fc. Figure 4.3 shows an illustration of the light meter.

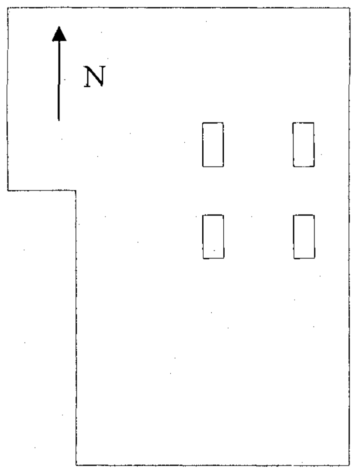

Figure 4.2. Layout showing the distribution of the hybrid luminaires at Taylor Hall.

The solar irradiance at which the measurement took place will be input to the model to predict the illumination at each point and compare these results with the measured values.

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[2] Manufactured by EXTECH Instruments, Model 401027.

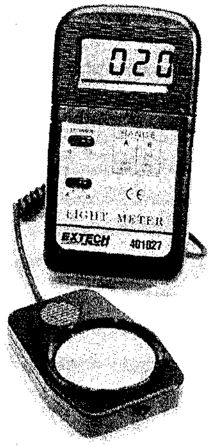


Figure 4.3. Illustration of the light meter used to measure the illumination.

The proposed model, however, doesn't consider the spatial distribution of the light. It rather predicts the total amount of lumens provided by the system. In order to compare the predicted illumination to the actual measurements, illumination at each of the measurement points should be calculated based on the predicted available lumens. Identifying the illumination pattern inside a certain space is a complex process. It depends on many factors, mainly

- The material and the color of the ceiling, walls, and floor.
- The furniture; its material, shape, color, and orientation.
- Type of light bulbs.
- Type of luminaire.

DIALux computer software was used to model the interior space of Taylor Hall to predict the illumination at each of the measuring points based on the total lumens provided by the HSL system. DIALux is a free software developed by DIAL GmbH. It performs lighting analysis, daylighting analysis, and energy performance of buildings. DIALux can be downloaded free of charge at www.dial.de. Figure 4.4 is a screen shot of the model of the modeled space in DIALux showing the furniture, the hybrid luminaires, and the calculation points.

The steps below summarize the procedure to compare the predicted lighting to the actual measurements,

- Direct solar irradiance at the time of the lighting measurement was measured.
- This irradiance value was input into the MATLAB code, and the code was run to predict the amount of lumens provided to the luminaires.
- The space was modeled in DIALux. The amount of lumens available was supplied into the program to determine the spatial distribution of the light.
- Contour plot is obtained for the measured values and the predicted ones.

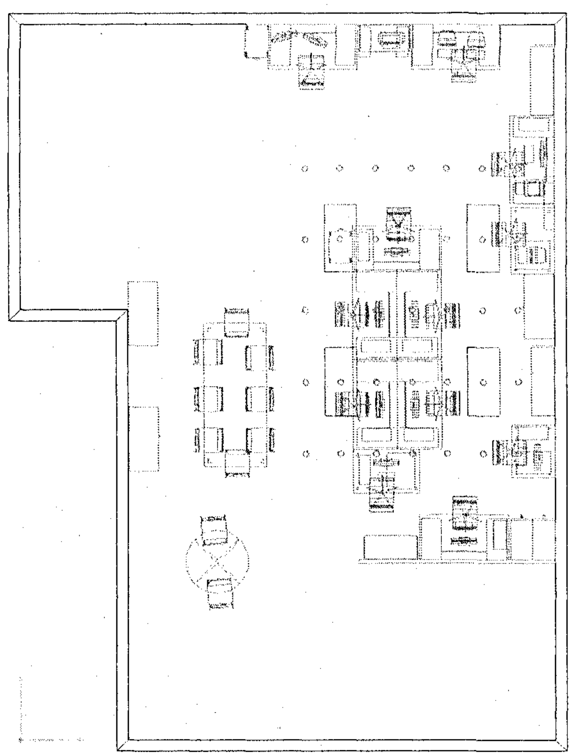


Figure 4.4. Drawing of Taylor Hall used as an input into DIALux.

4.3. Verification

The illumination measurement was done on July 20, 2008 at around 1:20 pm. The available Direct Normal Irradiance at this time was input into the MATLAB model to predict how many lumens were available at each luminaire. Figure 4.5 and Figure 4.6 show contour maps of the predicted and the measured illumination respectively. The values from DIALux seem to be slightly higher than the measured values but generally the two figures seem to be in good agreement.

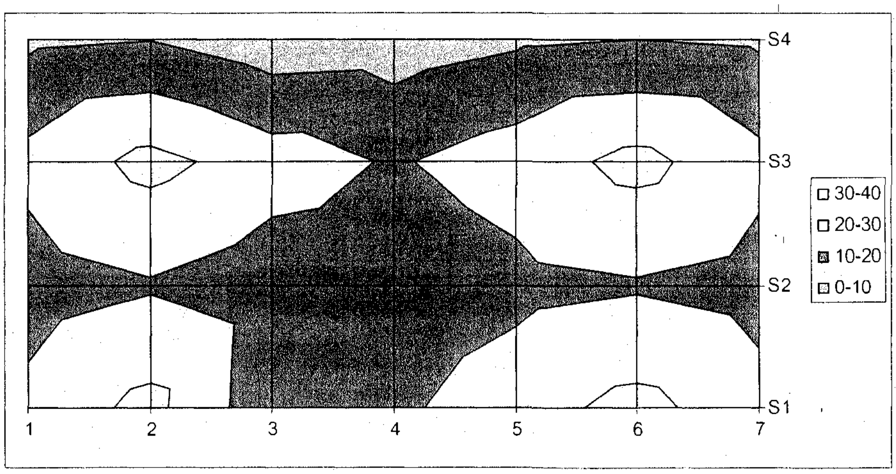


Figure 4.5. Contour map of the DIALux-predicted illumination pattern (in fc).

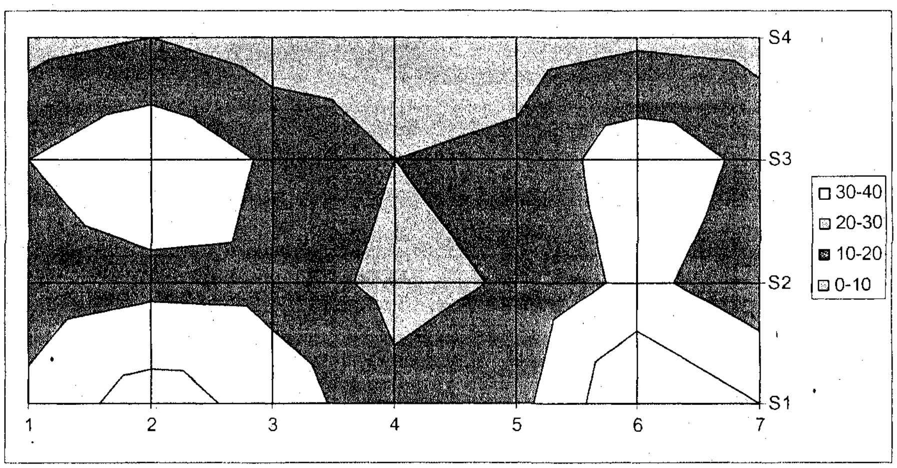


Figure 4.6. Contour map of the measured illumination values (in fc).

Figure 4.7 shows the normalized predicted spectrum of the HSL light and the measured one on the same graph for comparison. The two spectrums seem to be in a very good agreement. The efficacy calculated from the measured spectrum is 360 lumens/Watt and the efficacy of the predicted one is 351 lumens/Watt.

In summary the model could predict the spectral characteristics of the output light as well as the amount of lumens available to a reasonable accuracy.

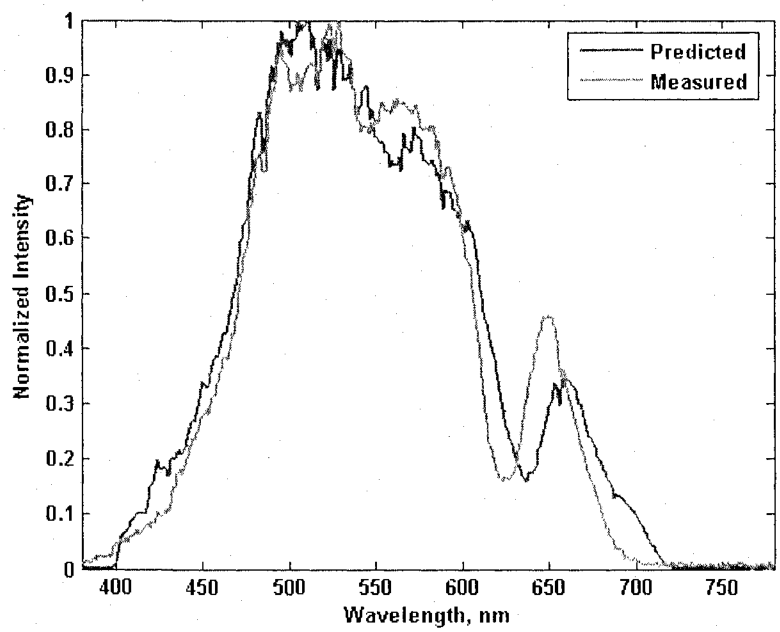


Figure 4.7. The normalized predicted versus the measured spectrum of the HSL output.

4.4. Results

Table 4-1 summarizes the losses of the light power in each component of the system. These numbers are based on how much power (Watts) is lost of the total amount of power incident on the certain component. The luminaires are not included as there was no spectral data available for them. The largest power loss occurs when the light goes through the fibers. For 10 meters the loss in power is 45% which is quite high. This is the reason why HSL is limited to one-story-installations. The second highest loss in power occurs secondary mirror with 20% loss. Such low average reflectivity is because the secondary mirror has a low reflectivity over the near IR (640nm and above) and the near UV (420nm and below) portions of the visible spectrum. The primary dish comes in the third place with 8% loss of power. The least amount of losses occurs in the hot mirror with only 3% loss. It should be noted that the luminaires were not mentioned in the table as there was no data available to calculate the loss in the power in the luminaires. However the luminaires account for a considerable loss in the available lumens.

Table 4-1. Summary of the losses in the different components.

Component	Loss (%)
Primary dish	8
Secondary mirror	20
Hot mirror	3
Optical fibers	45

The efficacy of the HSL light was calculated to be 351 lumens/Watt. The HSL drastically increased the efficacy of the natural light (sunlight efficacy is 220 lumens/Watt). This was accomplished through getting rid of the portions of the spectrum that the human-eye doesn't respond to, namely the IR and UV. Increased efficacy means lower wattage for the same level of illumination. This helps reduce the cooling load.

The amount of electric energy that the HSL system could save depends on the efficacy of the displaced electric bulbs. The lower the efficacy, the higher will be the saving. The efficacy depends on the light source. The incandescent bulbs have an efficacy of about 16 lumens/Watt while the fluorescent bulbs have an efficacy of about

85 lumens/watt. In turn, the electricity savings depend on the type of bulbs used along with the system. Figure 4.8 shows a bar plot of the electric energy saved each month of the year based on fluorescent bulbs being used. The total annual electric energy saving is 0.45 MWh. It is important to notice that such low savings is because of the low optical efficiency of the parabolic concentrator.

Figure 4.9 shows the savings on electric energy if the concentrator had a 100% optical efficiency. In such case, the annual saving will increase to 1.54 MWh.

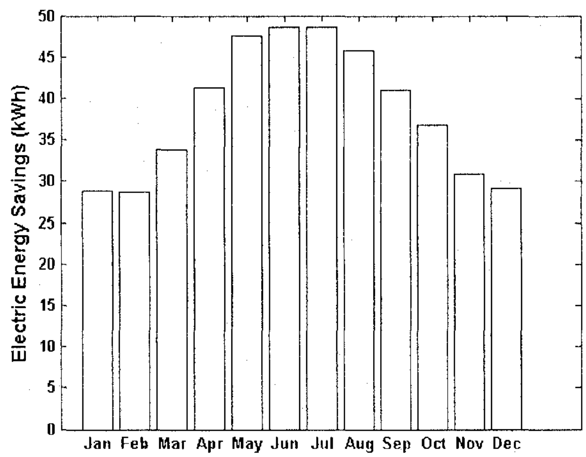


Figure 4.8. Monthly electricity saving (30% optical efficiency of the concentrator).

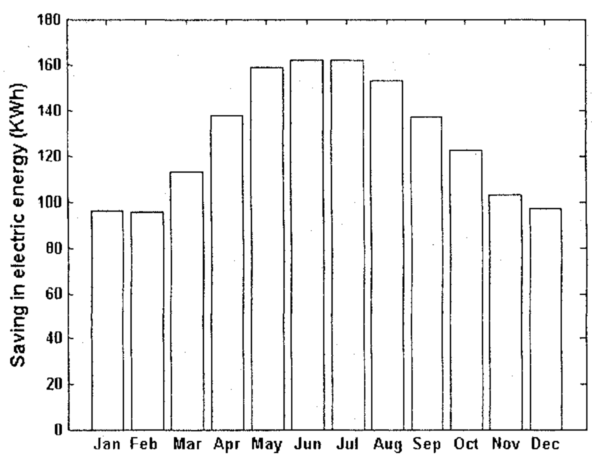


Figure 4.9. Monthly electricity savings (100% optical efficiency of the concentrator).

The other very important factor that affects the output of the system is the length of the optical fibers. Figure 4.10 shows the total annual electric energy savings versus the optical fibers length. The electricity savings decrease exponentially with the increasing the length of the fibers. The total annual electric energy savings decreased from 1.8 MWh with 5-meters long fibers to 1 MWh with 14-meters long fibers.

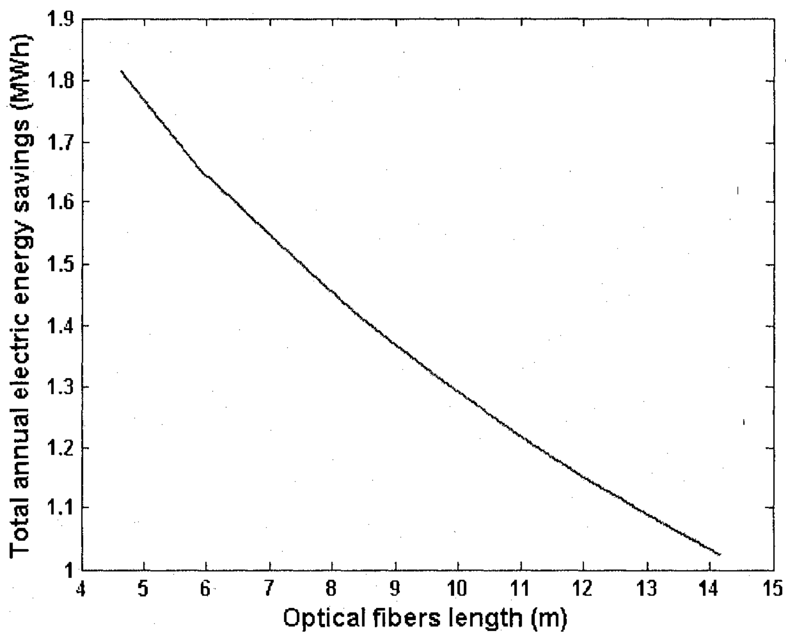


Figure 4.10. Annual total electricity saving versus fibers length.

The break-even cost of the HSL system is calculated based on the annual savings on electric energy consumed for lighting. The calculations were based on a 0.11 $/kWh (Nevada Power, 2008), 10 years pay-back period, and 3% inflation rate. The break-even cost was calculated for various interest rates. It was also calculated for various fiber lengths, since the length of the fibers affects the amount of energy savings. Figure 4.11 shows the break-even cost of the system for three different lengths of the fibers over an interest rate range of 4~7%. For any length of the fibers, the cost is inversely proportional to the interest rate, e.g. for fiber length of 7 meters the cost drops from $1523 at an interest rate of 4% to $1310 at an interest rate of 7%. For fiber length of 10 meters and an interest rate of 4%, the break-even cost of the HSL is $1306.

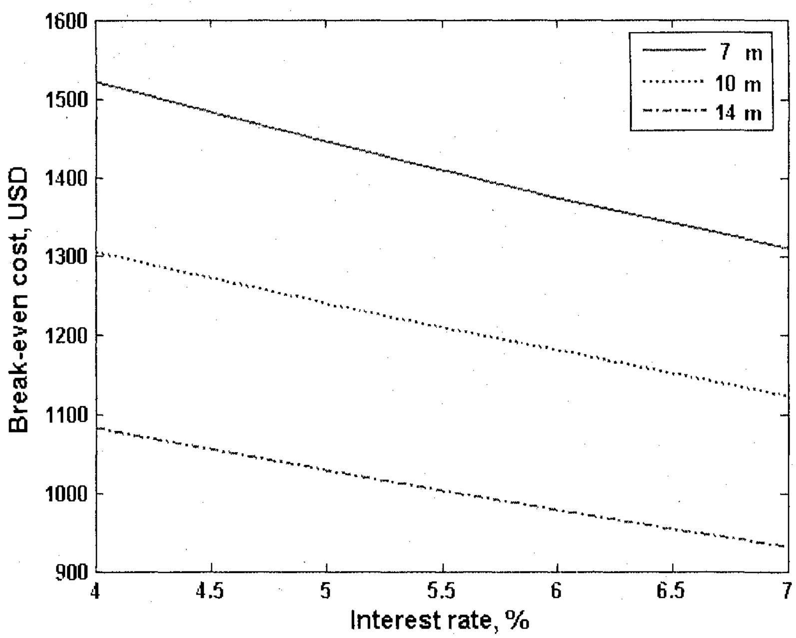


Figure 4.11. Break-even cost of the HSL system as a function of the interest rate for various fiber lengths.

CHAPTER 5

CONCLUSION

This thesis studies a new lighting technology that separates the sunlight and uses the visible portion to light buildings. The hybrid lighting technology consists of a two-axis concentrating collector that gathers direct normal solar radiation throughout the day. The direct normal solar radiation is reflected onto a secondary element which divides the solar radiation into the visible and infrared spectra. The visible light is reflected off of the secondary element and focused onto a bundle of optical fibers which transport the light into a space where it is needed. On some units, the infrared portion is used to generate electricity using a thermal photovoltaic (TPV) array. There are two major benefits from hybrid lighting. The first benefit is the reduction in electricity needed to light the building, and the second benefit is a reduced cooling load due to the high efficacy of natural light.

A model of the HSL system was developed in MATLAB to predict the illumination output of the system based on the spectral characteristics of each of the individual components of the system. An economic analysis was also conducted to estimate the break-even cost of the system.

Based on the predicted annual savings for Las Vegas climate, the break-even cost of the system is about $1300. Bringing the cost down to this point is extremely challenging for the research and design team. The target price they had set was $3000 by the year 2011. It should be noted however that the cost estimated here is based only on the savings on lighting. The impact of the HSL on reducing the cooling load was not taken into consideration.

Besides the direct savings on electricity, studies have shown that additional monetary benefits are associated with natural lighting. Increased productivity, enhanced morale, and better quality of lighting are all examples of benefits that eventually lead to increased profit or decreased loss. These effects however, although having been discussed in detail in the literature, have never been quantified. This is probably one thing that should be done, to quantitatively identify the impact of natural lighting on the inhabitants, towards the commercialization of the system.

APPENDIX A

EFFICIENCY MEASUREMENT TOOL[3]

Sunlight Direct HSL Optical Efficiency Measurement Instructions

The following is meant to be a method of testing the optical efficiency of Sunlight Direct's Hybrid Solar Lighting (HSL) solar collection optics. The user is advised to follow directions precisely so as to avoid damaging the sensitive test equipment.

Measurements will be most accurate on clear days with minimal cloud cover. However, since the complete measurement operation only requires about 30 minutes to perform, accurate results are possible as long as clear sky conditions can be maintained for this short period of time. Measurements made between two hours after sunrise and two hours before sunset will provide the greatest stability of natural light levels during the measurement process.

Required Equipment:

- SunlightDirect Sensing Receiver Module
- Thor Labs data acquisition unit
- Almond receiver attenuation disk.

[3] This tool was provided by SunlightDirect, and so is this document.

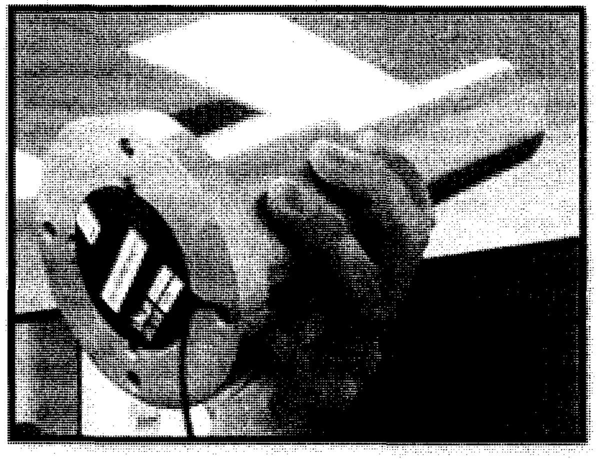


Fig.1 Sensing Receiver Module

Fig. 2 Thor Labs data acquisition unit

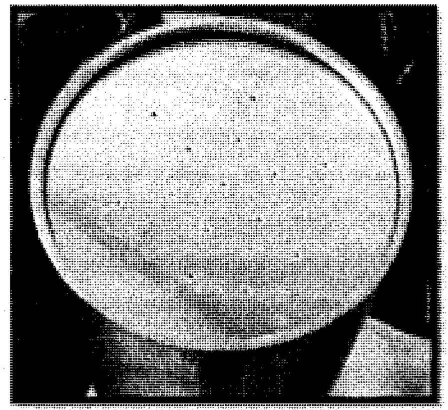


Fig. 3 Alanod receiver disk installed in Sensing Receiver module

Procedure:

1. Take tracker off-sun and allow receiver to cool.
2. Rotate tracker down and away from direction of sunlight. The tracker will have to be directed away from the path of direct sunlight for the following procedure, as any incident light can result in a highly concentrated beam of light which can cause serious burns.
3. If necessary, remove any existing optical fiber receivers from the solar collector by removing the four bolts that retain the HSL receiver to the collector hub as indicated in Figure 4. Gently remove the HSL receiver, with fiber bundle attached, and set aside on a stable surface.
4. If the primary mirror is dirty, it is a good idea to clean the surface of the primary mirror by using a low-pressure water spray. Let the mirror air-dry for about twenty minutes.

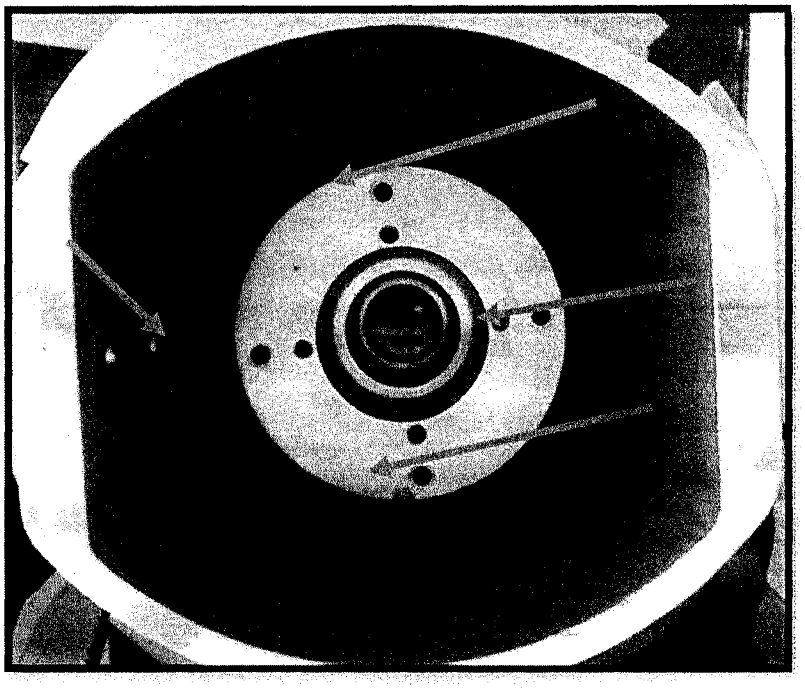


Fig. 4 Rear view of collector hub showing 4 retaining bolt holes on receiver to be removed (note: fiber optic cable bundle not attached)

5. While the tracker is still off-sun, install the Sensing Receiver using the reverse method of step #3.
6. Remove the secondary mirror by unscrewing the three bolts around its rim. Be careful not to lose the washer spacers, or lose track of how many were stacked under each post. Be careful not to touch the surface of the mirror, as this may harm the coating. Gently set the secondary mirror aside.
7. With the Sensing Receiver installed and the secondary mirror removed, connect the Sensing Receiver to the Thor Labs data acquisition unit and turn it on by pressing the button on the upper left-hand corner of the data acquisition unit.
8. Press the arrow buttons to highlight "Start" on the bottom menu, then press the center button to begin collecting data.

9. Note that the unit should be recording a small value of wattage from ambient light.
10. Ensure that the Alanod receiver disk (Figure 3) is **not** attached to the end of the receiver.
11. Return tracker to "On-sun" operation.
12. Once the tracker is on-sun, move the arrow keys on the data acquisition unit to "Reset" and press the center button to reset the data readings.
13. Adjust the east-west and north-south alignment of the tracker to optimize the maximum signal measured by the Sensing Receiver. This usually take a couple of minutes to find the optimal position. A good technique for finding the maximum signal is to optimize in one direction first (say east-west) and then optimize in the other direction (north-south) and then repeat. Collect data for a minute or two at the optimal position and then observe and record the "Maximum value" reading. This will be the "Sensor reading without attenuator" value to be used in final calculations.
14. Return the tracker to "off-sun" using methods described in step 2 above.
15. Replace the secondary mirror using the reverse method of step 6.
16. Before putting tracker on-sun, **insert** the Alanod test disk into the receiver as pictured in figure 3, with the reflective side facing outwards (toward the sun). **Failing to do so may permanently damage the data acquisition hardware.**
17. Return the tracker to on-sun.
18. Reset the data acquisition unit as in step 12.
19. Again, adjust the east-west and north-south alignment of the tracker to optimize the maximum signal measured by the Sensing Receiver. Optimize in one

direction first (east-west) and then optimize in the other direction (north-south) and then repeat. Collect data for a minute or two at the optimal position and then observe and record the "Maximum value" reading. This will be the "Sensor reading with attenuator" value to be used in final calculations.

20. Let the unit collect data for one or two minutes, then observe and record the "Maximum value" reading. This will be the "Sensor reading with attenuator" value used in final calculations.
21. You may now place tracker off-sun, remove test receiver and return HSL receiver and fiber bundle.
22. The efficiency of the collection optic system is computed using the following equation:

$$Efficiency = \left(\frac{\text{Sensor Reading with Attenuator}}{\text{Sensor Reading without Attenuator}} \right)$$

23. The efficiency value is meant to be used for comparison and calibration purposes. Please consult a Sunlight Direct engineer for application.

APPENDIX B

INPUT DATA

The following table contains the spectral reflectance of the secondary object element (cold mirror), the concentrator, the spectral attenuation data of the fibers, and the spectral transmissivity of the hot mirror

Wavelength, nm	SOE	Wavelength, nm	Conc	Wavelength, nm	Fiber	Wavelength, nm	Hot Mirror
380.41	0.702	380.15	0.635	380.15	0.261	301.779	0.000
380.821	0.698	380.71	0.637	380.71	0.267	308.897	0.000
381.641	0.695	380.968	0.638	380.968	0.270	314.235	0.003
382.051	0.692	381.376	0.644	381.376	0.275	319.573	0.000
382.872	0.689	381.781	0.654	381.781	0.280	326.69	0.003
383.692	0.685	381.784	0.648	381.784	0.280	333.808	0.003
384.513	0.679	381.934	0.650	381.934	0.282	337.367	0.001
385.333	0.675	382.599	0.658	382.599	0.291	342.705	0.003
385.744	0.672	383.417	0.662	383.417	0.303	349.822	0.003
386.154	0.656	383.825	0.667	383.825	0.308	355.16	0.001
386.154	0.656	383.971	0.668	383.971	0.310	362.278	0.001
386.564	0.652	384.233	0.671	384.233	0.313	369.395	0.001
386.974	0.637	385.051	0.677	385.051	0.322	372.954	0.005
386.974	0.637	385.195	0.679	385.195	0.323	380.071	0.005
387.385	0.633	385.458	0.682	385.458	0.325	385.409	0.005
387.795	0.629	386.682	0.695	386.682	0.333	388.968	0.008
387.795	0.629	387.239	0.700	387.239	0.336	392.527	0.016
388.205	0.620	388.316	0.710	388.316	0.345	394.306	0.030
388.615	0.603	388.873	0.716	388.873	0.349	396.085	0.052
388.615	0.603	389.54	0.723	389.54	0.353	397.865	0.098
389.436	0.600	390.763	0.737	390.763	0.361	399.644	0.184
389.846	0.599	390.917	0.738	390.917	0.362	401.423	0.489
390.667	0.600	392.398	0.750	392.398	0.374	403.203	0.772
391.487	0.599	392.551	0.752	392.551	0.375	404.982	0.812

392.308	0.599	393.621	0.764	393.621	0.388	406.762	0.815
393.538	0.597	393.775	0.766	393.775	0.389	408.541	0.812
393.949	0.597	394.845	0.777	394.845	0.398	412.1	0.747
394.769	0.599	395.254	0.780	395.254	0.401	413.879	0.765
395.179	0.606	395.409	0.782	395.409	0.402	415.658	0.640
395.179	0.606	395.662	0.786	395.662	0.404	417.438	0.701
395.59	0.622	396.479	0.792	396.479	0.411	419.217	0.887
395.59	0.622	397.043	0.794	397.043	0.415	420.996	0.858
396	0.633	397.297	0.796	397.297	0.418	422.776	0.894
396.821	0.642	397.705	0.800	397.705	0.423	424.555	0.894
397.231	0.649	398.113	0.805	398.113	0.428	428.114	0.891
397.231	0.649	398.267	0.806	398.267	0.430	429.893	0.873
398.051	0.669	398.52	0.810	398.52	0.432	431.673	0.830
398.462	0.681	398.928	0.816	398.928	0.435	433.452	0.794
398.872	0.685	399.336	0.820	399.336	0.438	435.231	0.773
398.872	0.685	399.747	0.818	399.747	0.441	438.79	0.776
399.282	0.694	399.901	0.819	399.901	0.443	440.569	0.780
399.692	0.702	400.564	0.825	400.564	0.448	445.907	0.816
400.513	0.714	401.382	0.828	401.382	0.454	447.687	0.837
400.513	0.714	401.535	0.829	401.535	0.455	449.466	0.877
401.333	0.725	401.79	0.832	401.79	0.457	451.246	0.887
401.333	0.725	402.201	0.829	402.201	0.461	454.804	0.923
402.154	0.731	403.019	0.835	403.019	0.467	456.584	0.934
402.564	0.734	403.169	0.835	403.169	0.468	460.142	0.938
402.974	0.741	404.246	0.839	404.246	0.478	461.922	0.938
402.974	0.741	404.654	0.843	404.654	0.481	465.48	0.934
403.385	0.757	404.802	0.844	404.802	0.483	469.039	0.927
404.205	0.760	405.473	0.846	405.473	0.490	470.819	0.916
404.615	0.760	406.026	0.848	406.026	0.496	474.377	0.916
405.846	0.760	406.291	0.849	406.291	0.497	477.936	0.913
406.667	0.760	406.701	0.851	406.701	0.500	479.715	0.913
407.487	0.760	407.11	0.852	407.11	0.503	483.274	0.913
407.897	0.760	407.928	0.855	407.928	0.508	486.833	0.913
408.718	0.761	408.07	0.856	408.07	0.509	490.391	0.917
409.538	0.771	408.337	0.858	408.337	0.511	493.95	0.924
409.538	0.771	409.565	0.862	409.565	0.520	499.288	0.938
409.949	0.776	409.704	0.861	409.704	0.522	502.847	0.942
410.359	0.781	410.383	0.865	410.383	0.526	506.406	0.946
410.769	0.794	411.202	0.868	411.202	0.531	511.744	0.942
411.179	0.796	411.748	0.870	411.748	0.534	515.302	0.942
411.179	0.796	412.02	0.871	412.02	0.536	518.861	0.935
411.59	0.822	412.429	0.872	412.429	0.538	520.641	0.928
412	0.836	412.838	0.875	412.838	0.541	525.979	0.921
412.41	0.845	413.656	0.879	413.656	0.545	529.537	0.917
412.821	0.856	413.793	0.879	413.793	0.546	534.875	0.921

413.231	0.862	414.885	0.881	414.885	0.551	540.214	0.928
413.641	0.875	415.704	0.882	415.704	0.555	543.772	0.932
414.051	0.889	416.247	0.883	416.247	0.557	549.11	0.943
414.051	0.889	416.932	0.885	416.932	0.561	552.669	0.950
415.692	0.894	417.342	0.886	417.342	0.563	558.007	0.954
416.513	0.891	418.16	0.889	418.16	0.566	563.345	0.954
417.744	0.888	418.701	0.891	418.701	0.569	568.683	0.947
418.974	0.885	418.979	0.892	418.979	0.570	572.242	0.936
419.795	0.885	419.387	0.895	419.387	0.572	575.801	0.932
420.615	0.889	421.435	0.898	421.435	0.581	579.359	0.922
421.436	0.892	421.565	0.898	421.565	0.582	584.698	0.922
422.667	0.895	422.254	0.899	422.254	0.584	590.036	0.929
423.487	0.898	423.073	0.901	423.073	0.587	593.594	0.933
424.308	0.902	423.202	0.901	423.202	0.588	598.932	0.943
425.538	0.907	424.303	0.901	424.303	0.592	602.491	0.954
426.359	0.911	424.43	0.902	424.43	0.592	604.27	0.954
426.769	0.917	424.711	0.905	424.711	0.593	609.609	0.951
427.179	0.920	425.531	0.905	425.531	0.597	614.947	0.944
428.41	0.925	425.657	0.906	425.657	0.598	616.726	0.944
428.821	0.930	425.939	0.908	425.939	0.599	620.285	0.936
429.641	0.931	426.758	0.909	426.758	0.602	623.843	0.926
430.051	0.933	427.168	0.909	427.168	0.603	629.181	0.919
431.282	0.933	427.294	0.910	427.294	0.603	632.74	0.908
432.103	0.931	427.987	0.912	427.987	0.605	639.858	0.905
433.744	0.930	428.522	0.913	428.522	0.606	645.196	0.908
434.564	0.928	428.931	0.913	428.931	0.609	650.534	0.915
435.385	0.927	430.035	0.914	430.035	0.612	657.651	0.930
435.795	0.925	430.159	0.914	430.159	0.612	662.989	0.941
436.205	0.927	430.854	0.917	430.854	0.613	668.327	0.952
437.026	0.925	431.672	0.920	431.672	0.615	671.886	0.952
437.846	0.924	431.797	0.920	431.797	0.615	679.004	0.945
438.256	0.923	433.026	0.922	433.026	0.616	684.342	0.934
439.487	0.921	433.31	0.922	433.31	0.617	687.9	0.923
440.308	0.923	433.845	0.923	433.845	0.619	691.459	0.909
441.128	0.924	434.949	0.925	434.949	0.622	693.238	0.902
441.949	0.931	435.073	0.925	435.073	0.622	696.797	0.887
442.359	0.931	436.178	0.927	436.178	0.624	700.356	0.873
443.179	0.935	437.53	0.928	437.53	0.626	702.135	0.852
444	0.938	437.816	0.928	437.816	0.627	703.915	0.812
444.821	0.941	439.044	0.932	439.044	0.629	705.694	0.784
445.641	0.941	440.683	0.934	440.683	0.631	707.473	0.730
446.051	0.941	441.216	0.935	441.216	0.632	709.253	0.712
446.462	0.941	442.321	0.937	442.321	0.635	711.032	0.608
447.282	0.943	443.14	0.938	443.14	0.636	712.811	0.551
447.692	0.943	444.368	0.941	444.368	0.639	714.591	0.486

448.923	0.943	444.492	0.941	444.492	0.639	716.37	0.443
449.744	0.943	445.598	0.941	445.598	0.642	718.149	0.372
450.974	0.938	446.418	0.941	446.418	0.643	719.929	0.318
451.795	0.937	448.056	0.944	448.056	0.646	721.708	0.300
452.205	0.936	448.178	0.944	448.178	0.647	723.488	0.264
453.026	0.933	449.285	0.945	449.285	0.649	725.267	0.178
453.436	0.930	449.695	0.945	449.695	0.651	727.046	0.132
454.256	0.927	450.514	0.945	450.514	0.653	728.826	0.103
455.077	0.924	451.334	0.945	451.334	0.655	730.605	0.085
455.897	0.923	451.453	0.945	451.453	0.655	734.164	0.074
456.308	0.920	452.154	0.945	452.154	0.657	737.722	0.064
457.128	0.917	453.792	0.947	453.792	0.660	739.502	0.056
457.538	0.914	454.612	0.947	454.612	0.661	743.06	0.042
457.949	0.913	455.138	0.947	455.138	0.662	746.619	0.031
458.769	0.911	456.251	0.947	456.251	0.665	750.178	0.024
459.179	0.908	458.3	0.948	458.3	0.669	755.516	0.017
460.41	0.907	458.414	0.948	458.414	0.670	759.075	0.010
460.821	0.913	458.71	0.948	458.71	0.670	762.633	0.010
461.641	0.915	460.348	0.950	460.348	0.675	764.413	0.010
462.051	0.918	461.577	0.951	461.577	0.678	767.972	0.003
462.872	0.925	461.689	0.951	461.689	0.678	775.089	0.000
463.282	0.928	462.396	0.953	462.396	0.680	778.648	0.000
463.692	0.930	463.625	0.955	463.625	0.682	780.427	0.003
464.513	0.933	464.854	0.957	464.854	0.684	785.765	0.000
464.923	0.934	465.375	0.958	465.375	0.685	792.883	0.000
465.333	0.934	466.082	0.960	466.082	0.687	798.221	0.004
465.744	0.934	466.083	0.958	466.083	0.687	805.338	0.000
466.564	0.934	466.902	0.960	466.902	0.689	812.456	0.000
466.974	0.934	467.422	0.960	467.422	0.690	816.014	0.000
467.385	0.934	468.54	0.961	468.54	0.691	821.352	0.000
468.615	0.934	468.651	0.961	468.651	0.691	826.69	0.000
469.436	0.934	469.769	0.964	469.769	0.694	833.808	0.000
469.846	0.934	469.88	0.964	469.88	0.694	839.146	0.001
470.256	0.934	470.179	0.964	470.179	0.694	846.263	0.001
470.667	0.933	470.998	0.964	470.998	0.696	851.601	0.001
471.077	0.931	471.518	0.964	471.518	0.697		
471.487	0.930	471.818	0.964	471.818	0.697		
471.897	0.928	472.638	0.964	472.638	0.698		
472.308	0.926	473.458	0.963	473.458	0.700		
472.718	0.923	473.566	0.963	473.566	0.700		
473.128	0.921	473.868	0.963	473.868	0.700		
473.949	0.917	474.688	0.961	474.688	0.701		
474.359	0.917	474.795	0.961	474.795	0.701		
475.179	0.915	475.508	0.961	475.508	0.702		
476	0.914	476.024	0.960	476.024	0.703		

476.41	0.911	476.328	0.960	476.328	0.703
476.821	0.910	477.252	0.960	477.252	0.704
477.231	0.908	477.557	0.960	477.557	0.704
477.641	0.908	477.558	0.958	477.558	0.704
478.051	0.908	478.481	0.958	478.481	0.705
478.462	0.908	478.788	0.958	478.788	0.706
478.872	0.908	479.608	0.955	479.608	0.707
479.282	0.908	479.71	0.955	479.71	0.707
479.692	0.908	480.529	0.954	480.529	0.708
480.103	0.910	480.839	0.954	480.839	0.709
480.923	0.911	481.249	0.953	481.249	0.709
481.744	0.915	481.758	0.952	481.758	0.710
482.154	0.917	482.069	0.951	482.069	0.710
482.564	0.918	482.987	0.950	482.987	0.711
483.385	0.923	483.299	0.950	483.299	0.712
483.795	0.924	484.12	0.947	484.12	0.713
484.615	0.926	484.216	0.947	484.216	0.713
485.846	0.928	484.531	0.945	484.531	0.713
486.667	0.928	485.445	0.943	485.445	0.714
487.487	0.930	485.761	0.943	485.761	0.714
487.897	0.930	486.674	0.940	486.674	0.716
489.128	0.933	486.992	0.940	486.992	0.716
489.538	0.934	487.812	0.938	487.812	0.717
489.949	0.934	487.903	0.939	487.903	0.717
490.359	0.934	488.221	0.940	488.221	0.717
490.769	0.934	489.042	0.938	489.042	0.718
491.59	0.934	489.132	0.938	489.132	0.718
492	0.934	489.861	0.938	489.861	0.719
492.821	0.934	490.361	0.939	490.361	0.720
493.231	0.934	491.09	0.940	491.09	0.720
494.051	0.936	491.5	0.940	491.5	0.721
494.872	0.934	491.999	0.941	491.999	0.721
495.282	0.934	493.138	0.943	493.138	0.723
495.692	0.930	493.228	0.943	493.228	0.723
496.103	0.928	494.776	0.945	494.776	0.724
496.513	0.926	494.867	0.945	494.867	0.724
496.923	0.923	495.186	0.945	495.186	0.725
497.744	0.920	495.595	0.948	495.595	0.725
498.154	0.917	495.686	0.949	495.686	0.726
498.564	0.914	496.413	0.951	496.413	0.726
498.974	0.913	496.915	0.952	496.915	0.727
499.385	0.911	497.642	0.954	497.642	0.728
500.205	0.908	498.554	0.957	498.554	0.728
501.026	0.908	498.87	0.958	498.87	0.729
501.846	0.908	499.783	0.960	499.783	0.730

502.667	0.908	500.098	0.961	500.098	0.730
503.487	0.908	500.916	0.964	500.916	0.731
504.308	0.908	501.012	0.964	501.012	0.731
504.718	0.908	501.735	0.967	501.735	0.732
505.128	0.910	502.241	0.969	502.241	0.733
505.949	0.913	502.553	0.970	502.553	0.733
506.359	0.916	503.47	0.971	503.47	0.734
506.769	0.918	503.879	0.972	503.879	0.736
507.179	0.921	504.192	0.973	504.192	0.736
508	0.930	505.01	0.976	505.01	0.736
508.41	0.933	505.829	0.978	505.829	0.737
508.821	0.937	505.927	0.979	505.927	0.737
509.641	0.940	506.648	0.980	506.648	0.738
510.051	0.941	507.467	0.980	507.467	0.738
510.462	0.944	507.566	0.981	507.566	0.739
511.282	0.946	507.876	0.983	507.876	0.739
512.513	0.946	508.286	0.983	508.286	0.740
513.333	0.946	508.385	0.983	508.385	0.740
514.154	0.946	509.515	0.983	509.515	0.741
514.564	0.947	510.024	0.982	510.024	0.741
514.974	0.947	510.745	0.981	510.745	0.742
515.385	0.947	511.155	0.981	511.155	0.743
516.205	0.949	511.253	0.981	511.253	0.743
517.026	0.949	511.662	0.981	511.662	0.744
517.846	0.949	511.975	0.981	511.975	0.745
518.256	0.950	513.206	0.977	513.206	0.746
519.487	0.950	513.301	0.977	513.301	0.746
520.308	0.950	514.026	0.976	514.026	0.748
521.128	0.950	514.119	0.975	514.119	0.749
521.538	0.950	514.847	0.974	514.847	0.749
521.949	0.950	514.939	0.974	514.939	0.749
522.769	0.950	515.257	0.973	515.257	0.749
523.179	0.949	516.077	0.971	516.077	0.750
523.59	0.947	516.578	0.970	516.578	0.750
524	0.947	516.898	0.968	516.898	0.750
524.821	0.946	518.128	0.967	518.128	0.751
525.231	0.946	518.217	0.967	518.217	0.751
526.051	0.944	518.949	0.964	518.949	0.751
526.872	0.943	519.036	0.964	519.036	0.751
527.692	0.942	519.769	0.963	519.769	0.752
528.513	0.942	520.265	0.963	520.265	0.753
529.333	0.939	520.999	0.963	520.999	0.753
529.744	0.939	521.819	0.961	521.819	0.753
530.564	0.939	521.905	0.961	521.905	0.753
531.385	0.937	523.049	0.961	523.049	0.753

532.615	0.936	523.134	0.961	523.134	0.753
533.436	0.936	524.363	0.960	524.363	0.754
534.667	0.936	524.689	0.960	524.689	0.754
535.077	0.937	525.592	0.960	525.592	0.754
535.897	0.939	525.918	0.960	525.918	0.754
536.718	0.940	526.822	0.960	526.822	0.754
537.538	0.940	528.052	0.961	528.052	0.754
537.949	0.943	529.281	0.961	529.281	0.754
538.769	0.943	530.016	0.961	530.016	0.753
539.59	0.944	530.101	0.961	530.101	0.753
540	0.946	530.921	0.961	530.921	0.753
540.821	0.947	532.561	0.961	532.561	0.751
541.641	0.947	533.79	0.961	533.79	0.751
542.872	0.947	534.114	0.961	534.114	0.751
543.692	0.949	535.02	0.961	535.02	0.750
544.513	0.949	536.251	0.961	536.251	0.749
545.333	0.949	537.481	0.961	537.481	0.747
546.154	0.949	537.803	0.961	537.803	0.747
546.974	0.949	538.711	0.962	538.711	0.746
548.615	0.949	539.941	0.962	539.941	0.744
549.846	0.950	541.171	0.963	541.171	0.743
550.667	0.950	541.491	0.963	541.491	0.742
551.077	0.952	542.402	0.963	542.402	0.740
551.897	0.952	543.632	0.963	543.632	0.739
552.718	0.952	544.862	0.963	544.862	0.737
553.538	0.952	545.589	0.963	545.589	0.735
554.359	0.952	546.093	0.963	546.093	0.734
555.179	0.952	547.323	0.963	547.323	0.733
556.41	0.953	548.553	0.964	548.553	0.731
557.641	0.953	549.687	0.964	549.687	0.730
558.872	0.953	550.193	0.964	550.193	0.730
560.103	0.953	551.423	0.963	551.423	0.728
561.744	0.953	553.062	0.963	553.062	0.728
562.564	0.953	553.376	0.963	553.376	0.728
563.795	0.953	554.292	0.962	554.292	0.727
564.615	0.952	555.426	0.961	555.426	0.728
566.256	0.952	555.521	0.961	555.521	0.728
567.897	0.953	556.655	0.961	556.655	0.728
568.718	0.952	556.751	0.961	556.751	0.728
569.538	0.953	557.475	0.961	557.475	0.729
570.769	0.953	557.98	0.960	557.98	0.730
572.821	0.953	558.295	0.960	558.295	0.730
574.051	0.953	559.209	0.960	559.209	0.730
575.282	0.953	559.525	0.960	559.525	0.730
576.923	0.953	560.345	0.958	560.345	0.732

578.974	0.953	560.847	0.958	560.847	0.733
580.205	0.953	561.575	0.957	561.575	0.735
581.846	0.953	561.666	0.957	561.666	0.736
583.897	0.953	562.894	0.955	562.894	0.739
585.128	0.953	563.216	0.954	563.216	0.739
587.179	0.953	564.123	0.952	564.123	0.740
589.231	0.953	564.856	0.951	564.856	0.742
590.872	0.953	565.351	0.950	565.351	0.743
591.692	0.953	566.087	0.948	566.087	0.744
594.154	0.953	566.17	0.948	566.17	0.744
595.385	0.953	566.906	0.948	566.906	0.745
597.846	0.953	567.809	0.946	567.809	0.746
600.308	0.953	568.137	0.945	568.137	0.747
602.769	0.953	568.627	0.945	568.627	0.750
604.821	0.953	569.036	0.945	569.036	0.751
606.051	0.952	569.367	0.945	569.367	0.752
607.282	0.952	570.186	0.945	570.186	0.754
607.692	0.952	570.265	0.945	570.265	0.754
608.513	0.952	571.006	0.945	571.006	0.756
609.744	0.952	571.902	0.946	571.902	0.759
611.385	0.952	572.645	0.947	572.645	0.759
613.436	0.952	573.131	0.949	573.131	0.760
614.667	0.952	573.463	0.950	573.463	0.761
616.308	0.952	574.359	0.950	574.359	0.763
618.359	0.952	575.103	0.950	575.103	0.764
619.59	0.952	575.588	0.950	575.588	0.764
621.231	0.952	576.817	0.952	576.817	0.766
623.282	0.952	577.56	0.953	577.56	0.767
624.513	0.951	578.046	0.953	578.046	0.767
626.564	0.951	579.686	0.956	579.686	0.767
628.615	0.949	580.018	0.957	580.018	0.767
630.256	0.948	580.505	0.957	580.505	0.767
631.487	0.946	581.325	0.957	581.325	0.767
633.128	0.946	582.067	0.957	582.067	0.767
634.359	0.946	582.145	0.957	582.145	0.767
636	0.946	583.374	0.957	583.374	0.767
636.821	0.946	584.116	0.957	584.116	0.766
637.641	0.946	584.604	0.956	584.604	0.766
638.872	0.946	585.346	0.955	585.346	0.766
639.692	0.945	586.244	0.955	586.244	0.766
640.513	0.943	586.986	0.954	586.986	0.765
641.333	0.941	587.474	0.954	587.474	0.764
642.154	0.939	587.806	0.954	587.806	0.764
642.974	0.936	589.035	0.954	589.035	0.763
643.795	0.933	589.934	0.954	589.934	0.761

644.615	0.932	591.084	0.954	591.084	0.760
645.026	0.929	591.904	0.954	591.904	0.759
645.436	0.926	591.984	0.954	591.984	0.759
646.256	0.926	593.625	0.953	593.625	0.754
647.487	0.922	594.364	0.953	594.364	0.752
648.718	0.920	595.266	0.953	595.266	0.750
649.949	0.916	595.593	0.953	595.593	0.749
650.769	0.913	596.908	0.953	596.908	0.746
651.59	0.910	598.052	0.953	598.052	0.743
652.821	0.907	598.138	0.953	598.138	0.743
654.462	0.903	599.691	0.954	599.691	0.737
655.282	0.900	599.78	0.954	599.78	0.737
656.923	0.896	601.012	0.953	601.012	0.731
658.154	0.892	601.741	0.953	601.741	0.728
659.795	0.889	602.244	0.953	602.244	0.726
661.026	0.883	603.79	0.953	603.79	0.720
661.436	0.880	603.885	0.953	603.885	0.720
662.667	0.874	604.707	0.952	604.707	0.714
663.897	0.869	605.43	0.951	605.43	0.709
665.128	0.863	605.529	0.951	605.529	0.708
666.359	0.859	606.762	0.951	606.762	0.701
667.59	0.851	607.479	0.951	607.479	0.696
668.821	0.844	607.584	0.951	607.584	0.695
670.051	0.838	608.406	0.951	608.406	0.688
671.282	0.833	609.938	0.951	609.938	0.676
672.923	0.826	610.051	0.951	610.051	0.675
674.154	0.820	611.577	0.951	611.577	0.663
675.795	0.814	611.696	0.951	611.696	0.662
676.615	0.808	613.341	0.951	613.341	0.648
677.846	0.804	613.627	0.951	613.627	0.645
679.077	0.798	614.576	0.950	614.576	0.635
680.718	0.791	615.676	0.950	615.676	0.625
681.538	0.784	616.221	0.949	616.221	0.621
682.769	0.778	617.456	0.948	617.456	0.608
683.179	0.774	618.137	0.947	618.137	0.601
684	0.768	618.691	0.947	618.691	0.595
684.41	0.762	619.926	0.947	619.926	0.580
685.641	0.756	620.186	0.947	620.186	0.578
686.462	0.751	621.161	0.947	621.161	0.568
687.282	0.745	621.983	0.947	621.983	0.560
688.513	0.738	622.235	0.947	622.235	0.558
689.333	0.731	622.806	0.947	622.806	0.553
690.154	0.723	623.218	0.946	623.218	0.549
690.974	0.718	623.63	0.946	623.63	0.543
692.205	0.709	624.041	0.946	624.041	0.540

693.436	0.700	624.454	0.946	624.454	0.532
694.667	0.693	624.695	0.945	624.695	0.530
695.897	0.687	625.276	0.945	625.276	0.526
696.718	0.680	625.924	0.945	625.924	0.520
697.538	0.673	626.099	0.945	626.099	0.519
698.359	0.666	626.511	0.945	626.511	0.513
700	0.657	626.923	0.945	626.923	0.507
700.821	0.650	627.745	0.945	627.745	0.501
701.231	0.644	627.973	0.945	627.973	0.500
702.462	0.640	628.156	0.946	628.156	0.499
703.692	0.631	628.978	0.946	628.978	0.494
704.923	0.624	629.612	0.947	629.612	0.490
705.744	0.618	629.8	0.947	629.8	0.489
706.564	0.611	629.801	0.947	629.801	0.486
707.795	0.604	630.622	0.946	630.622	0.481
709.436	0.597	631.443	0.946	631.443	0.478
710.667	0.585	631.662	0.945	631.662	0.477
711.897	0.578	631.854	0.945	631.854	0.476
712.718	0.572	632.675	0.945	632.675	0.473
713.538	0.565	633.302	0.944	633.302	0.472
714.769	0.558	633.495	0.944	633.495	0.471
716	0.551	633.906	0.944	633.906	0.468
717.231	0.541	634.317	0.944	634.317	0.467
718.462	0.534	634.727	0.944	634.727	0.466
719.692	0.526	635.351	0.944	635.351	0.466
720.923	0.519	635.547	0.944	635.547	0.466
722.154	0.513	636.365	0.943	636.365	0.468
722.974	0.508	637.184	0.943	637.184	0.471
724.615	0.502	638.002	0.943	638.002	0.474
725.846	0.496	638.22	0.943	638.22	0.476
727.487	0.489	638.411	0.943	638.411	0.477
728.718	0.482	639.23	0.943	639.23	0.480
730.769	0.473	640.047	0.943	640.047	0.484
732.41	0.466	640.269	0.943	640.269	0.486
733.641	0.462	640.456	0.942	640.456	0.487
735.282	0.455	641.274	0.941	641.274	0.491
736.513	0.450	642.092	0.940	642.092	0.496
737.333	0.446	642.32	0.940	642.32	0.499
737.744	0.442	642.499	0.939	642.499	0.501
738.974	0.440	643.55	0.938	643.55	0.511
740.205	0.433	644.133	0.938	644.133	0.516
740.615	0.430	644.779	0.938	644.779	0.523
741.026	0.427	645.357	0.938	645.357	0.529
741.846	0.423	646.581	0.938	646.581	0.542
742.256	0.417	647.648	0.938	647.648	0.554

742.667	0.411	647.805	0.938	647.805	0.556
743.077	0.407	649.029	0.938	649.029	0.569
743.897	0.404	649.288	0.938	649.288	0.572
744.308	0.398	650.253	0.938	650.253	0.583
744.718	0.391	650.927	0.938	650.927	0.589
745.538	0.385	651.747	0.938	651.747	0.596
745.949	0.378	651.886	0.938	651.886	0.598
746.359	0.371	653.11	0.937	653.11	0.611
747.179	0.365	653.387	0.937	653.387	0.614
748	0.360	653.518	0.937	653.518	0.615
749.231	0.352	653.926	0.937	653.926	0.621
749.641	0.345	654.335	0.937	654.335	0.624
750.462	0.337	654.742	0.937	654.742	0.629
751.692	0.327	655.026	0.937	655.026	0.633
752.513	0.319	655.15	0.937	655.15	0.635
753.333	0.311	655.846	0.937	655.846	0.638
754.154	0.302	655.968	0.937	655.968	0.638
754.974	0.292	656.786	0.937	656.786	0.642
755.795	0.285	657.485	0.937	657.485	0.645
756.205	0.276	657.604	0.937	657.604	0.645
758.256	0.265	658.013	0.937	658.013	0.649
759.077	0.259	658.714	0.937	658.714	0.654
759.487	0.252	658.83	0.937	658.83	0.655
759.897	0.246	659.648	0.937	659.648	0.658
760.718	0.245	659.944	0.937	659.944	0.660
761.538	0.243	660.466	0.937	660.466	0.662
762.769	0.243	661.173	0.937	661.173	0.663
764.41	0.243	662.105	0.936	662.105	0.664
765.641	0.243	662.924	0.936	662.924	0.665
766.462	0.243	663.223	0.935	663.223	0.666
767.282	0.242	664.043	0.935	664.043	0.667
768.513	0.240	664.153	0.935	664.153	0.667
769.333	0.239	665.793	0.934	665.793	0.665
770.154	0.236	666.093	0.934	666.093	0.665
770.974	0.235	666.613	0.934	666.613	0.664
772.205	0.230	667.433	0.934	667.433	0.662
773.436	0.227	667.732	0.934	667.732	0.661
774.667	0.223	668.255	0.934	668.255	0.658
775.897	0.220	669.075	0.934	669.075	0.657
777.128	0.217	669.486	0.934	669.486	0.655
777.949	0.214	669.781	0.934	669.781	0.654
779.179	0.212	670.306	0.934	670.306	0.652
779.59	0.210	670.601	0.934	670.601	0.651
780	0.209	671.127	0.933	671.127	0.649
		671.539	0.933	671.539	0.645

671.831	0.932	671.831	0.644
672.241	0.932	672.241	0.643
672.36	0.932	672.36	0.642
672.77	0.932	672.77	0.641
673.592	0.932	673.592	0.636
674.291	0.931	674.291	0.633
674.413	0.931	674.413	0.632
674.824	0.931	674.824	0.629
675.646	0.931	675.646	0.624
675.93	0.931	675.93	0.623
676.877	0.929	676.877	0.619
677.288	0.929	677.288	0.616
677.98	0.928	677.98	0.613
678.11	0.928	678.11	0.612
678.932	0.928	678.932	0.606
679.342	0.928	679.342	0.605
679.62	0.928	679.62	0.603
680.029	0.928	680.029	0.601
680.164	0.928	680.164	0.601
680.986	0.928	680.986	0.595
681.259	0.928	681.259	0.594
681.807	0.928	681.807	0.592
682.628	0.928	682.628	0.588
683.45	0.928	683.45	0.582
683.718	0.928	683.718	0.581
683.86	0.928	683.86	0.580
685.092	0.928	685.092	0.576
685.357	0.928	685.357	0.575
686.324	0.928	686.324	0.569
686.587	0.928	686.587	0.568
687.556	0.928	687.556	0.563
687.816	0.928	687.816	0.562
688.226	0.928	688.226	0.560
688.788	0.928	688.788	0.557
689.866	0.928	689.866	0.552
690.02	0.928	690.02	0.552
691.252	0.928	691.252	0.546
691.915	0.928	691.915	0.542
692.073	0.928	692.073	0.542
692.734	0.928	692.734	0.539
692.894	0.928	692.894	0.539
693.715	0.927	693.715	0.534
694.537	0.927	694.537	0.530
694.784	0.927	694.784	0.528
694.948	0.927	694.948	0.527

695.77	0.927	695.77	0.522
696.014	0.927	696.014	0.520
696.591	0.926	696.591	0.517
697.244	0.925	697.244	0.514
697.413	0.925	697.413	0.513
698.235	0.925	698.235	0.507
698.883	0.925	698.883	0.504
699.056	0.925	699.056	0.503
699.468	0.924	699.468	0.497
699.703	0.924	699.703	0.496
700.29	0.924	700.29	0.493
700.702	0.925	700.702	0.487
701.342	0.925	701.342	0.483
701.524	0.925	701.524	0.481
701.936	0.925	701.936	0.477
702.758	0.925	702.758	0.470
702.981	0.925	702.981	0.467
703.801	0.925	703.801	0.459
703.993	0.925	703.993	0.457
705.228	0.925	705.228	0.443
705.44	0.925	705.44	0.440
706.463	0.925	706.463	0.430
707.49	0.925	707.49	0.418
707.699	0.925	707.699	0.415
707.899	0.925	707.899	0.412
708.524	0.926	708.524	0.401
709.759	0.926	709.759	0.388
710.358	0.927	710.358	0.378
710.585	0.927	710.585	0.374
711.82	0.928	711.82	0.359
711.997	0.928	711.997	0.356
712.646	0.929	712.646	0.345
713.471	0.929	713.471	0.332
714.296	0.930	714.296	0.318
714.455	0.930	714.455	0.315
715.122	0.930	715.122	0.303
715.685	0.930	715.685	0.293
715.947	0.930	715.947	0.289
716.772	0.931	716.772	0.276
717.323	0.931	717.323	0.266
717.598	0.931	717.598	0.261
718.423	0.931	718.423	0.247
718.963	0.931	718.963	0.241
719.659	0.932	719.659	0.233
719.782	0.932	719.782	0.231

720.484	0.932	720.484	0.218
720.601	0.932	720.601	0.217
721.309	0.933	721.309	0.205
721.83	0.934	721.83	0.196
722.135	0.934	722.135	0.191
722.96	0.934	722.96	0.177
723.06	0.934	723.06	0.175
723.786	0.934	723.786	0.162
723.88	0.934	723.88	0.161
724.611	0.935	724.611	0.149
725.108	0.935	725.108	0.144
725.846	0.935	725.846	0.135
725.928	0.935	725.928	0.134
726.672	0.935	726.672	0.121
727.567	0.935	727.567	0.110
727.907	0.935	727.907	0.106
728.732	0.934	728.732	0.093
728.798	0.934	728.798	0.093
729.968	0.934	729.968	0.079
730.847	0.934	730.847	0.070
731.202	0.934	731.202	0.066
731.666	0.934	731.666	0.062
732.848	0.933	732.848	0.052
733.67	0.933	733.67	0.045
733.716	0.932	733.716	0.044
734.082	0.932	734.082	0.039
734.536	0.932	734.536	0.036
734.904	0.932	734.904	0.034
735.316	0.932	735.316	0.029
735.765	0.932	735.765	0.027
736.137	0.932	736.137	0.026
736.958	0.932	736.958	0.022
737.779	0.931	737.779	0.019
737.815	0.931	737.815	0.018
738.601	0.930	738.601	0.014
739.422	0.930	739.422	0.010
739.455	0.930	739.455	0.010
740.243	0.930	740.243	0.007
741.094	0.930	741.094	0.006
741.473	0.930	741.473	0.006
742.324	0.930	742.324	0.005
742.703	0.929	742.703	0.004
743.554	0.928	743.554	0.003
743.933	0.928	743.933	0.003
745.163	0.927	745.163	0.001

746.393	0.926	746.393	0.001
747.622	0.925	747.622	0.001
747.654	0.925	747.654	0.001
748.852	0.924	748.852	0.001
750.081	0.923	750.081	0.001
750.9	0.923	750.9	0.004
751.343	0.922	751.343	0.006
751.718	0.922	751.718	0.007
752.537	0.922	752.537	0.009
753.356	0.922	753.356	0.011
754.174	0.921	754.174	0.014
754.994	0.921	754.994	0.016
755.403	0.921	755.403	0.017
755.442	0.921	755.442	0.018
756.22	0.920	756.22	0.023
757.038	0.920	757.038	0.027
757.856	0.919	757.856	0.032
758.263	0.919	758.263	0.037
758.672	0.919	758.672	0.040
759.49	0.918	759.49	0.045
759.542	0.918	759.542	0.045
760.716	0.918	760.716	0.053
761.532	0.917	761.532	0.062
761.94	0.917	761.94	0.068
762.757	0.917	762.757	0.073
763.161	0.917	763.161	0.086
763.164	0.917	763.164	0.080
763.231	0.917	763.231	0.081
764.387	0.916	764.387	0.095
765.612	0.915	765.612	0.108
766.835	0.914	766.835	0.122
767.33	0.914	767.33	0.127
768.059	0.914	768.059	0.135
769.283	0.913	769.283	0.149
770.097	0.913	770.097	0.164
771.321	0.912	771.321	0.177
771.429	0.912	771.429	0.178
772.545	0.911	772.545	0.191
773.359	0.911	773.359	0.204
774.583	0.910	774.583	0.218
775.119	0.909	775.119	0.224
778.254	0.907	778.254	0.260
779.219	0.907	779.219	0.271
779.478	0.906	779.478	0.274

APPENDIX C

MATLAB CODE

The following MATLAB code reads the hourly DNI values and the spectral data of the solar spectrum and the different HSL components from Excel files, and calculates the output lumens from the HSL at each hour. The code also calculates the monthly and the total annual savings on the electricity.

```
%Read the TMY solar irradiance
G=xlsread('lastmy',1,'J2:J8761');
% Read the spectral data of the hot mirror
hotr=xlsread('hot',1,'B2:B150');
wlhot=xlsread('hot',1,'A2:A150');
% Read the terresterial solar spectrum
s=xlsread('sunspectrum',1,'G2:G1996');
w=xlsread('sunspectrum',1,'B2:B1996');
% Read the measured HSL output light spectrum
hslr=xlsread('sunspectrum',2,'B2:B2049');
wlhsl=xlsread('sunspectrum',2,'A2:A2049');
% Read the CIE visibility curve
CIEr=xlsread('sunspectrum',3,'B2:B472');
wlcier=xlsread('sunspectrun',3,'A2:A472');
% Read the spectral data of the fibers
wlfibn=xlsread('fibn',1,'A2:A160');
fibnr=xlsread('fibn',1,'B2:B160');
% Read the spectral data of the secondary mirror
soer=xlsread('reflectance',1,'B1:B460');
wlsoe=xlsread('reflectance',1,'A1:A460');
% Read the spectral data of the concentrator
concr=xlsread('reflectance',2,'B1:B655');
wlconc=xlsread('reflectance',2,'A1:A655');
% Interpolates the data to generate uniform-unity-wavelength-increment sets
for i=1:401
  CIE(i)=interp1(wlcier,CIEr,wlcie(i));
  soe(i,1)=interp1(wlsoe,soer,wlcie(i));
```

```
   conc(i,1)=interp1(wlconc,concr,wlcie(i));
   fib(i,1)=interp1(wlfibn,fibnr,wlcie(i));
   hsl(i,1)=interp1(wlhsl,hslr,wlcie(i));
   hot(i,1)=interp1(wlhot,hotr,wlcie(i))/100;
   fibn(i,1)=interp1(wlfibn,fibnr,wlcie(i))/100;
   sn(i,1)=interp1(w,s,wlcie(i));
end
w=wlcie;
% The spectral chacteristics of the output light
op=sn.*conc.*soe.*hot.*(1-fibn).^L;
% Calculates the efficacy of the output light
efficacy=trapz(w,CIE'.*op)/trapz(w,op)*683;
d=ones(length(w),1);
% Average reflectances and attenuation
conc_av=trapz(w,conc)/trapz(w,d);
soe_av=trapz(w,soe)/trapz(w,d);
fib_av=trapz(w,(1-fibn).^L)/trapz(w,d);
hot_av=trapz(w,hot)/trapz(w,d);
% Illumination output
% Approximately, the visible portion of the sunlight represents only 54% of the
% sunlight. The aperture area of the collector is 1.27 m sp.
lumens=G*0.54*1.27*efficacy*conc_av*soe_av*fib_av*hot_av*.58;
% Electricity savings (KWh)
sav=lumens/90000;
% Monthly savings in electric energy (KWh)
sav_av=[sum(sav(1:744)) sum(sav(745:1416)) sum(sav(1417:2160))...
   sum(sav(2161:2880)) sum(sav(2881:3624)) sum(sav(3625:4344))...
   sum(sav(4345:5088)) sum(sav(5089:5832)) sum(sav(5833:6552))...
   sum(sav(6553:7296)) sum(sav(7297:8016)) sum(sav(8017:8760))];
% Total annual savings
ann=sum(sav_av)
```

APPENDIX D

LIGHT METER MANUAL

EXTECH INSTRUMENTS

User's Manual

Model 401027 Pocket Foot Candle Light Meter

Introduction

Congratulations on your purchase of the Extech Pocket Foot Candle Light Meter which measures and displays light intensity in foot candle units. Two ranges can be selected (200.0 and 2000 Fc). The precision color-corrected photo-diode sensor provides 5% accuracy.

Specifications

Circuit	Custom LSI microprocessor based design
Display	0.5" (13mm) 3-1/2 digit (1999 count) LCD display
Sensor	Photo-diode with color correction filter (meets CIE regulations)
Out of range indication	'1 ' is displayed
Sampling time	Approx. 0.4 seconds
Power Supply	9V battery
Power consumption	Approx. 2.7mA
Operating temperature	32°F to 122°F (0°C to 50°C)
Operating Humidity	< 80% RH
Weight	0.43 lb. (195g)
Dimensions	Meter: 5.2x2.8x1" (131x70x25mm); Probe: 3.2x2.2x0.3" (82x55x7mm)
Accessories	Probe and 9V battery

Range Specifications

Range	Resolution	Accuracy
0 to 199.9 Fc	0.1 Fc	± (5% + 4 digits) Full Scale
200 to 1999 Fc	1 Fc	

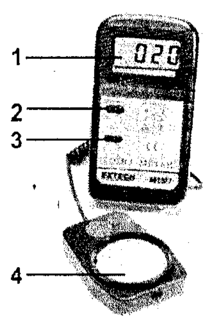
Meter Description

1. Display

2. ON/OFF switch

3. Range switch

4. Light sensor



Meter Operation

1. Slide the ON/OFF Switch to the ON position.
2. Fold out the meter's rear tilt stand and set the meter on a desktop.
3. Select range "B"
4. Hold the Light Sensor with the white lens facing the light source to be measured. The sensor can also be placed on the desktop facing in the direction of the light source.
5. Read the light measurement on the LCD display.
6. If the measurement is less than 200 fc, select the lower "A" range

Battery Replacement

The low battery indicator "LO BAT" appears on the LCD display when it is nearing the time to replace the 9V battery. Reliable readings can still be obtained for several hours after the first appearance of the low battery indicator. To replace the batteries:

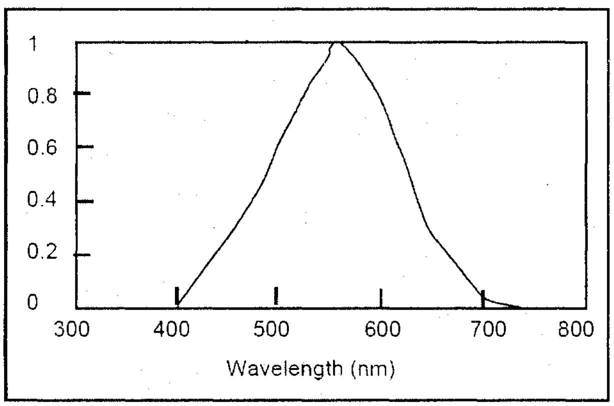
1. Slide the rear battery compartment cover off of the meter and remove the old battery
2. Replace the battery and reinstall the compartment cover

Typical Light Levels For Work Areas

		Foot Candles	Lux
Factories	Emergency Stairs, Warehouse	2 to 7	20 to 75
	Exit/Entrance Passages	7 to 15	75 to 150
	Packing Work	15 to 30	150 to 300
	Visual Work: Production Line	30 to 75	300 to 750
	Typesetting:Inspection Work	75 to 150	750 to 1500
	Electronic Assembly Drafting	150 to 300	1500 to 3000
Office	Indoor Emergency Stairs	7 to 10	75 to 100
	Corridor Stairs	10 to 20	100 to 200
	Conference, Reception Room	0 to 75	200 to 750
	Clerical Work	75 to 150	750 to 1500
	Typing Drafting	150 to 2000	1500 to 2000
Store	Indoors	7 to 15	75 to 150
	Corridor/Stairs	15 to 20	150 to 200
	Reception	20 to 30	200 to 300
	Display Stand	30 to 50	300 to 500

	Elevator	50 to 75	500 to 750
	Show Window Packing Table	75 to 150	750 to 1500
	Storefront Show Window	150 to 300	1500 to 3000
Home	Washing	10 to 15	100 to 150
	Recreational Activities	15 to 20	150 to 200
	Drawing Room Table	20 to 30	200 to 300
	Makeup	30 to 50	300 to 500
	Reading Study	50 to 150	500 to 1500
	Sewing	100 to 200	1000 to 2000
Restaurant	Corridor Stairs	7 to 15	75 to 150
	Entrance Wash Room	15 to 30	150 to 300
	Cooking Room Dining Table	30 to 75	300 to 750
	Show Window	75 to 150	750 to 1500
Hospital	Emergency Stairs	3 to 7	30 to 75
	Stairs	7 to 10	75 to 100
	Sick Room Warehouse	10 to 15	100 to 150
	Waiting Room	15 to 20	150 to 200
	Medical Examination Room	20 to 75	200 to 750
	Operating/Emergency Room	75 to 150	750 to 1500
	Eye Inspection	500 to 1000	5000 to 10000

Light Sensor Spectrum



Warranty

EXTECH INSTRUMENTS CORPORATION warrants this instrument to be free of defects in parts and workmanship for one year from date of shipment (a six month limited warranty applies on sensors and cables). If it should become necessary to return the instrument for service during or beyond the warranty period, contact the Customer Service Department at (781) 890-7440 for authorization. A Return Authorization (RA) number must be issued before any product is returned to Extech. The sender is responsible for shipping charges, freight, insurance and proper packaging to prevent damage in transit. This warranty does not apply to defects resulting from action of the user such as misuse, improper wiring, operation outside of specification, improper maintenance or repair, or unauthorized modification. Extech specifically disclaims any implied warranties or merchantability or fitness for a specific purpose and will not be liable for any direct, indirect, incidental or consequential damages. Extech's total liability is limited to repair or replacement of the product. The warranty set forth above is inclusive and no other warranty, whether written or oral, is expressed or implied.

Calibration and Repair Services

Extech offers complete repair and calibration services for all of the products we sell. For periodic calibration, NIST certification or repair of any Extech product, call customer service for details on services available. Extech recommends that calibration be performed on an annual basis to insure calibration integrity.

☎
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