NLPIP
NATIONAL LIGHTING PRODUCT INFORMATION PROGRAM

Specifier Reports

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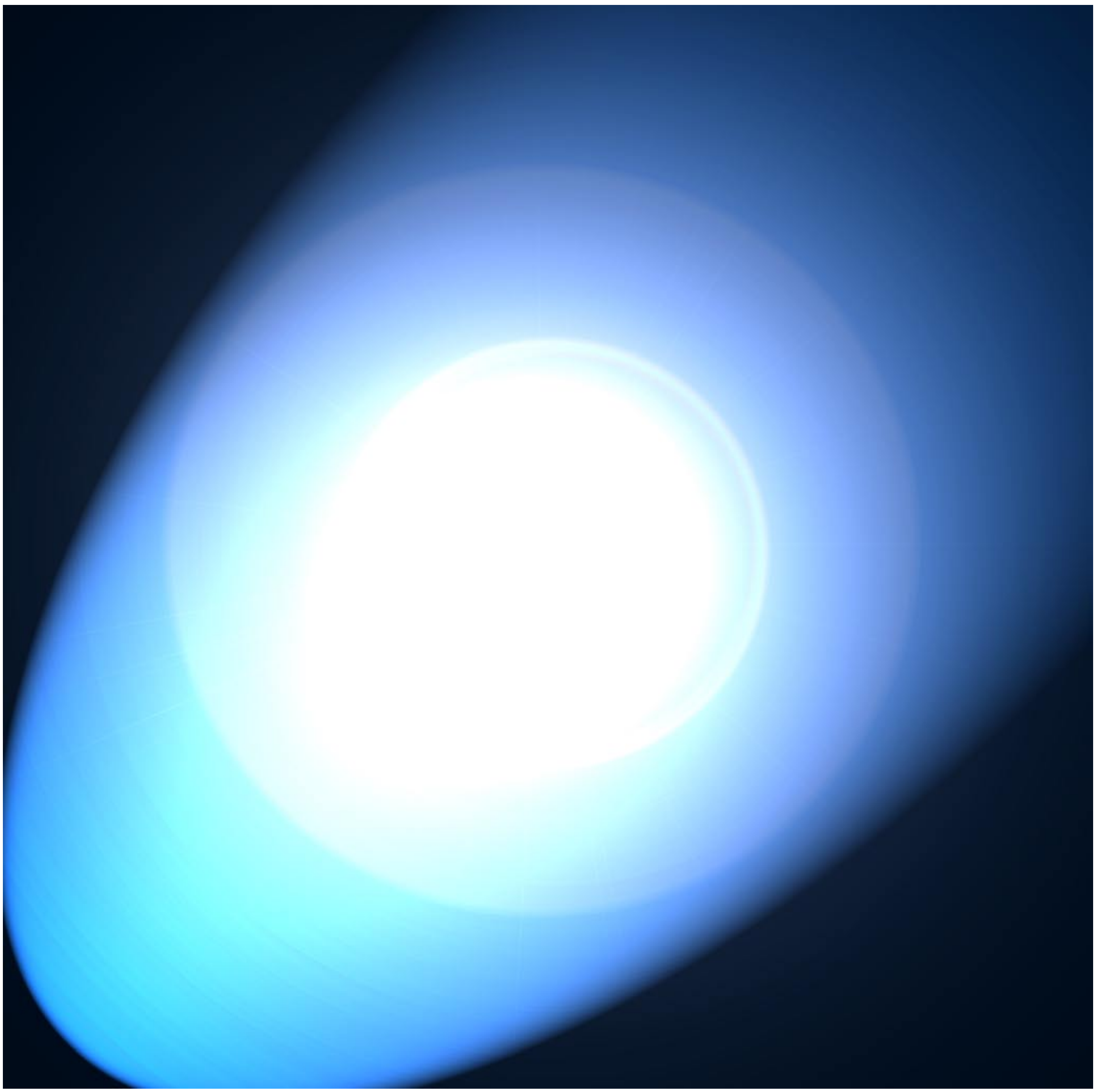
Photosensors

Dimming and Switching Systems for Daylight Harvesting

Volume 11 Number 1, October 2007



NLPIP

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About NLPIP

The National Lighting Product Information Program (NLPIP) was established in 1990. NLPIP is administered by the Lighting Research Center (LRC), the world's leading university-based center devoted to lighting excellence.

NLPIP's mission is to help lighting specifiers and other lighting decision-makers choose wisely by providing the most complete, up-to-date, objective, manufacturer specific information available on energy-efficient lighting products. Priority is given to information not available or easily accessible from other sources. NLPIP tests lighting products according to accepted industry procedures or, if such procedures are not available or applicable, NLPIP develops interim tests that focus on performance issues important to specifiers or end users.

In 1998, NLPIP Online debuted at www.lrc.rpi.edu/programs/nlpip, making the information provided by NLPIP even more accessible to lighting specifiers and other interested people. NLPIP Online includes PDF files of *Specifier Reports, Lighting Answers, Lighting Diagnostics,* and several searchable databases containing manufacturer-reported data and test results.

To ensure its continued objectivity, NLPIP does not accept funding from manufacturers.

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Contents

Introduction

Photosensors are devices often used to integrate an electric lighting system with a daylighting system so lights operate only when daylighting is insufficient. A photosensor adjusts the light output of a lighting system based on the amount of light it senses. Photosensor technology has advanced dramatically since the original National Lighting Product Information Program (NLPIP) released its *Specifier Reports: Photosensors* in March 1998. Many new photosensors have embedded digital processors that lead installers through the setup process and offer more control options than previous analog designs. Because of these dramatic changes in technology, NLPIP is updating building designers, owners, and lighting control installers on the latest photosensor products.

This report presents the findings of the testing conducted by NLPIP on these products, and information to assist in the selection, installation, setup, and general understanding of photosensors.

Along with new technology, interest in photosensors has increased since the original (1998) report. A growing desire to create sustainable buildings has led to the current trend in building design of increasing emphasis on daylit spaces that use lighting controls in order to reduce electrical energy needs. Even with this trend, however, only a small fraction of lighting installations use photosensor controls. Photosensors are seeing limited application due to three principal barriers:

1. The actual energy savings that photosensors can achieve is difficult to predict due to significant variations in building designs, weather conditions, and the occupants' needs and behaviors. Without reliable, predictable cost savings, it is often difficult to justify the purchase of photosensor controls.

2. Unlike motion sensors which do not affect the lighting when people are present, photosensors adjust the lighting when people are present. Occupants may not like the light being adjusted automatically, so adjusting the lights to save energy while people are present demands careful consideration and a high level of reliability in order to meet occupants' expectations and avoid complaints.

3. Anecdotal reports and past experiences of difficulties in installing and adjusting photosensors properly may have limited many specifiers' willingness to use them. The LRC's report, *Reducing Barriers to the Use of High-Efficiency Lighting Systems* and the *Daylight Dividends Focus Group Research Project Final Report* provide more information on this subject.

Most of the products tested in the previous *Specifier Reports: Photosensors* featured design attributes that make them difficult or impossible to use effectively for daylighting applications. Product improvements can help overcome the last two barriers listed above, and the results of NLPIP's testing look promising. In addition, new design tools, training curricula, and case studies found in the LRC's daylighting program are helping to lower the first barrier.

Technology Overview

A photosensor is an electronic control device that adjusts the light output of a lighting system based on the amount of light sensed at a particular location. Some photosensors switch lights on and off, while others, in conjunction with dimming electronic ballasts, adjust the light output of fluorescent lighting systems over a continuous range. This report examines both types of photosensors, but there are additional ways to classify types of photosensors.

Photosensors are classified based on where they are located and how their signal is used to adjust the electric lighting. This classification has two main categories referred to as either open-loop or closed-loop design. Another way to classify photosensors is by the type of application in which they will be used. Some photosensors are used to control the electric lights based on the amount of daylight entering a space, an application often called daylight harvesting. Other photosensors attempt to maintain the output of light fixtures at a constant level to, for example, compensate for lamp and dirt depreciation effects. And some simply switch lights on at dusk and off at dawn. This report discusses all of these types of photosensors and presents test results for many types.

Photosensor products are available with varying degrees of system integration; for a particular photosensor product, various amounts of additional control equipment are needed in order to implement a complete photosensor-controlled system. To switch lighting circuits on and off, for example, a line voltage relay is required in addition to the photosensor. Similarly, a dimming electronic ballast is required for dimming lighting circuits. Many photosensors are compatible with 0-10 V dimming ballasts that are available from several ballast manufacturers (see the sidebar, “0-10 V Ballasts” on page 7). Other photosensor products are designed to be specified as a complete system, including ballasts, switches, and manual dimmers with proprietary control signals that relay information between components.

Terminology

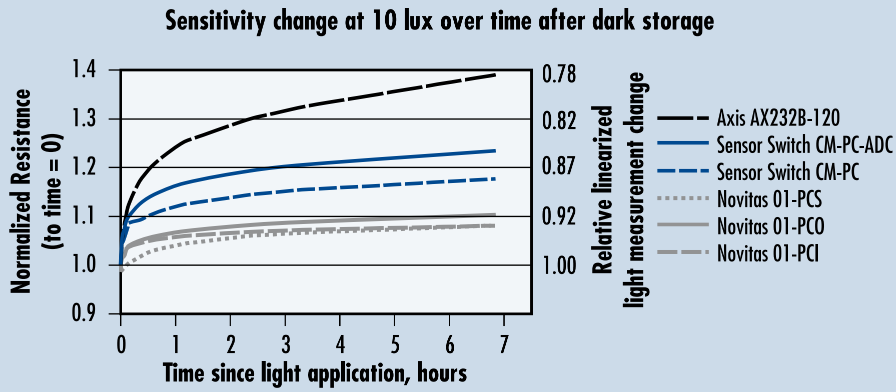
NLPIP defines a photocell as the light-responding circuit element inside the sensor that converts incident light into an electrical signal. A photosensor is defined as the complete device that includes a photocell along with a controller (the circuitry and logic control that determines the status of the lighting). The photosensor may directly interface with the lighting equipment such as when the photosensor contains line voltage relays for switching lighting circuits, or it may provide low voltage control signals for actuating contactors and other lighting control gear. The important distinction is that the term photosensor is used here to describe the controller of the whole system, including inputs and outputs, even when it all might be sold as separate components; whereas a photocell is simply a sensor providing input to such a system. The term photosensor-controlled system refers to all of the lighting components working together; the photosensors, ballasts, lamps, switches and any other control devices whose operation is controlled by the photosensor.

It is important to keep the terms photocell illuminance and photocell signal distinct. Photocell illuminance is the illuminance measured at the location of the photocell. This is often not equivalent to the signal produced by the photocell because the photocell has its particular spectral and spatial response, which often does not match that of an illuminance meter. Task illuminance refers to the illuminance on the work plane, typically the desktop in office applications.

Photocells

Two types of photocells are used in photosensors: photodiodes and photoconductive cells. Photodiodes are typically made from silicon and generate a small electrical current proportional to the number of incident photons. Silicon photodiodes offer stable performance over time and temperature and have excellent linearity over a wide range of light levels. Performance is usually limited by the additional circuitry used to amplify and condition the weak photocurrent signal. Most photosensors using photodiodes include a filter over the photocell to make the spectral response of the photocell approximate the response of the human eye (see the section, "Spectral Response" on page 16).

Photoconductive cells are light-sensitive variable resistors. Incident light lowers the resistance (resistance is the inverse of conductance) measured between two terminals on the device. This means that incident light increases the conductance of the device. The material most often used for these light sensors is cadmium sulfide (CdS) because it imparts a spectral response that is similar to the human eye and avoids the expense of added filters. CdS cells can exhibit a large change in resistance with light level, from mega-ohms in the dark, to a few kilo-ohms when illuminated to a few lux. They can also withstand several hundred volts of electric potential of either polarity across their terminals. These properties make them useful for simple, inexpensive lighting control circuits. The change in resistance is not linear with light level, however, and the cells are not as stable or repeatable as photodiodes.



Sensitivity changes over time for several CdS cells currently used in products.

One especially troubling characteristic of CdS cells is a memory effect, whereby the sensitivity is affected by its past history of illumination. Cells being exposed to light after a long period of darkness have more sensitivity than cells under constant illumination. The memory of past conditions is on the order of several hours and can change the sensitivity by over 30%, depending on the specific type of cell. The figure above shows how the resistance changes over time for several CdS cells used in current products. The implication is that a photosensor system using one of these cells will behave differently in the morning after a night of darkness than in the afternoon. The time of day and past history of the lights being on or off when such a system is commissioned will also affect the controlled lighting levels.

Photosensors monitor the amount of light only at the location of the photocell, which can be at the plane of the ceiling, a window or skylight, or outside the building. However, the main purpose of most lighting systems is to provide illumination for the tasks in a space. Therefore, understanding the relationship between task illuminance and photocell signal is important for specifying a photosensor-controlled system. Factors such as the arrangement of furniture and partitions, surface reflectance, the direction of incoming daylight, the use of task lighting, the positions of the occupants, and (for some photosensors) the location and direction that the photocell faces, all affect how the lighting will be controlled. For example, adjusting the angle of window blinds can dramatically affect how much daylight illuminates the ceiling as compared to the task. The sidebar, "Task/ceiling illuminance ratios" on page 8, further discusses the relationship between task illuminance and photocell signal.

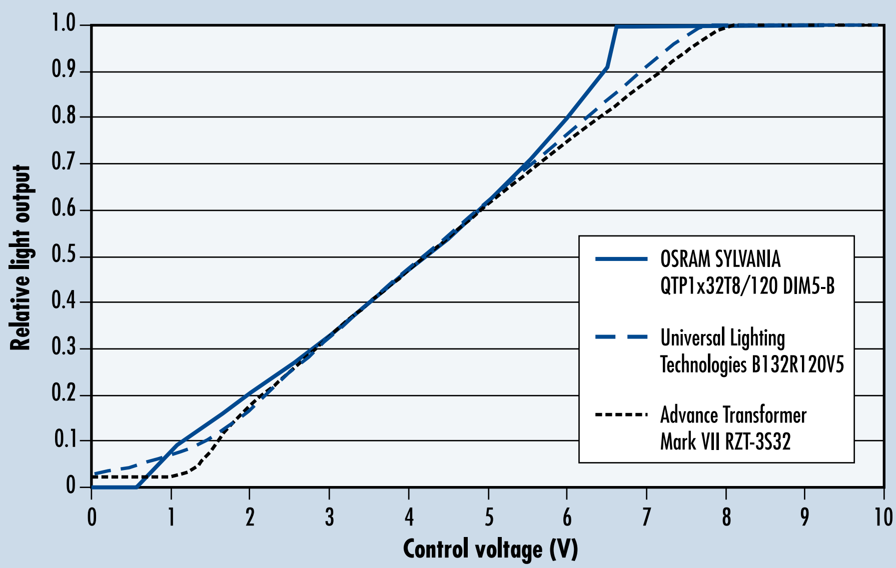
The successful operation of any photosensor system requires a setup procedure in addition to the installation of the system. This setup configures the system for the conditions unique to that particular installation. Setup procedures vary for different products, but all require some amount of user input. Conventional photosensors have slotted dials that are turned with small screwdrivers and/or switches to make adjustments for light level settings and sensitivity. Newer designs make use of digital microprocessors with push-button interfaces and text screen displays to lead users through the setup procedure. Obviously, a simple setup procedure is desirable to save time and reduce errors. Often, to obtain optimal performance requires repeated measurements and adjustments in a process that NLPIP calls tuning. Setup, tuning, and the verification of proper operation are all part of commissioning, the process of ensuring that the lighting system components interact properly and control the system as intended by the designer and the user(s).

0-10 V Ballasts

Photosensors designed to dim fluorescent lamps must interface with a dimming electronic ballast. While some manufacturers have their own proprietary system for interfacing the photosensor with the ballast, many use the 0-10 V defacto standard first introduced by Advance Transformer Company in the 1980s. Several ballast manufacturers make dimming electronic ballasts compatible with 0-10 V control devices even though no official 0-10 V standard exists for dimming ballasts. A standard does exist in the entertainment industry (ANSI E1.3 2001) for 0-10 V control of theatrical devices, but it is not specific to lighting and the typical 0-10 V ballast interface differs from this standard in important ways. The result is that different 0-10 V components will work together without damage, but not necessarily with the same signal levels or precision of control, and the support of special features like standby or shutdown modes vary from one ballast type to another.

The 0-10 V control interface works by modulating current through the input control wires of a dimming ballast. The current flow in the control wires (which are usually gray and purple) determines control voltage, which is typically in the range of 0 to 10 V. To dim the lights the photosensor allows more current to flow, which reduces the voltage in the control circuit. The lower the voltage the ballast senses across the control input wires, the more it dims the lamps. (Shorting the control wires produces the minimum light level, while an open control circuit produces full light output.) For some photosensors, the current flowing in the control wires is also used to power the photosensor. Other photosensors require a separate power supply. To control multiple ballasts from the same photosensor the 0-10 V control wires are connected in parallel. The current sourced by each ballast adds, so the photosensor must be able to sink larger amounts of current as ballasts are added to the system. The typical control current provided by a single ballast is 0.5 mA, and most photosensors can handle the current from up to 50 ballasts.

Dimming ballasts manufactured by different manufacturers may respond differently to the same control voltage level. In the past a control voltage of 5 V may dim a ballast by one manufacturer 50%, while a ballast by another manufacturer may only dim 30% with the same control signal. Therefore, if different manufacturers' dimming ballasts were used in the same control circuit, the amount of dimming may not have been uniform. Ballasts on the market today appear to be much better aligned with one another as evident in the figure below which shows the dimming response curve for three fairly recent model electronic dimming ballasts. Note how even though the range of control voltage over which the ballast dims the lamps is similar for the three types of ballasts, differences still exist near the ends of the range. Also note that the range does not extend over the entire range of 0 to 10 V for any ballast. That the dimming range doesn't extend to zero volts is important for circuit design (keeping the minimum dim level occurring above one to two transistor base-emitter voltages greatly simplifies circuitry), and having maximum light output occur at a control voltage less than 10 V is beneficial to certain proportional control algorithms (see the section, "Proportional Response" on page 13).



Task/Ceiling Illuminance Ratios

Predicting the performance of a photosensor-controlled system requires an understanding of the relationship between task illuminance and sensor signal. While the sensor signal is related to sensor illuminance, the two are not equivalent because a sensor does not necessarily have the same spectral or spatial response as an illuminance meter. Often a photosensor will have a much narrower response than an illuminance meter, or an asymmetric spatial response to reject light from certain locations in the space. Therefore, as the distribution of light in a space changes, as happens during the transition from electric light to daylight, not only does the output signal vary considerably from that of an illuminance meter, the ratio between sensor illuminance and sensor signal changes. The setup and commissioning procedures of photosensor systems should always use the actual sensor signals rather than ceiling illuminance measurements from another instrument.

Just considering illuminance measurements, the task-to-ceiling ratios for different spaces and times of the day can be quite dramatic. Concerning the differences among spaces, NLPIP measured task-to-ceiling illuminance ratios in several offices of different sizes having exposure to daylight and varying surface reflectance. Directly over the desktops the ratios ranged from 3:1 to 10:1, but clustered near 5:1. Rubenstein, et al. (1989) found task-to-ceiling illuminance ratios ranging from 5:1 to 9:1, while Choi and Mistrick (1997) estimated ratios in an office space to range from 2:1 to 5:1. Spaces with very low reflectance characteristics, such as offices with dark carpeting and walls, especially when combined with high ceilings, have ratios greater than 5:1. On the other hand, rooms with high reflectance finishes and a lot of open space have ratios closer to unity.

The type of luminaires and windows in a space also affects the task ceiling illuminance ratio. Direct luminaires such as fluorescent troffers with parabolic reflectors will illuminate the task much more than the ceiling leading to large task/ceiling ratios. On the other hand, indirect and direct/indirect luminaires will more equally illuminate the ceiling and task. Typically, the useful illumination coming in from vertical windows equally illuminates the task and ceiling; however, horizontal blinds can direct illumination up to the ceiling making the task/ceiling ratio less than one for daylight. Skylights, on the other hand, act more like ceiling mounted luminaires and illuminate the task below more so than the ceiling.

As the amount of available daylight changes throughout the day the task/ceiling illuminance ratio changes; this change can be dramatic. A room with parabolic troffers and horizontal blinds might go from a 10:1 ratio with no daylight to a 2:1 ratio when only daylight is illuminating the room. This factor-of-five change in the ratio underscores why photosensor products not designed to accommodate changes in the ratio between sensor signal and task illuminance control the electric light so poorly. (See the section, "Photosensor Response Functions" on page 11.)

Control Strategies

Before choosing a photosensor for a particular application, the specifier should decide upon a control strategy. The control strategy concerns what information is made available to the system (e.g., interior or exterior light level information) and what possible actions the system can automatically take to achieve the desired results (e.g., switching or dimming the electric lights). The major distinctions among control strategies are whether they are open-loop or closed-loop, and whether they utilize on/off switching or continuous dimming. This results in four possible combinations, as shown in Table 1.

Table 1. Control Strategies

Open-loop Switching	Open-loop Dimming
Closed-loop Switching	Closed-loop Dimming

Note that some systems might combine dimming with switching; and depending on photocell placement, the degree to which a system can be categorized as open- or closed-loop can vary. As a result, classifying control strategies according to this two-by-two matrix captures the major operating principles of the products on the market (at the time of publication).

In an open-loop control system, the photosensor is not influenced by the lighting that it is controlling. Therefore, it has zero feedback. This often means that the sensor is located outside the building or is facing the outside through a window (although facing a window may still present some feedback). Control of the electric lighting is based on the outside daylight level. Therefore, the photocell does not "see" the electric lighting.

In a closed-loop control system the photosensor is influenced by the lighting that it is controlling. The sensor makes changes based partly on its own output. Feedback is the term used to describe the loop that is created when the output influences the input to the system. The amount of feedback can vary, depending on sensor placement and its optics. Feedback is less for a sensor placed near a window where the response will be dominated by daylight, as opposed to a sensor located far from a window where the electric light being controlled is the dominant signal.

Open-loop Characteristics

Open-loop systems are conceptually simpler than closed-loop systems. This characteristic makes setup and tuning more intuitive and easier to understand than the procedures for closed-loop systems; being simpler there is less chance of improper setup and unexpected behavior.

The price paid for the simplicity of open-loop systems is their inability to react to changes other than the outside light level. Once set up, the electric light output is "programmed" to respond consistently regardless of the actual luminous conditions in the space being controlled. For example, if one closes the window blinds, an open-loop system with an outdoor sensor will not increase the electric light level to compensate for the lack of daylight entering the space. Placement of outside sensors is important so that sensor readings are representative of the amount of daylight actually entering the space. A sensor on the roof producing higher signal levels in the summer when the sun is overhead would not be representative of the light entering rooms below if large overhangs block the high-angle sun. With thoughtful placement of outside sensors and attention to daylighting design principles, open-loop systems can work effectively. The deterministic behavior of open-loop systems can be comforting in that one learns what to expect and can readily understand the behavior. This often outweighs the potentially superior performance of closed-loop systems.

Closed-loop Characteristics

Closed-loop systems are more difficult to understand and can exhibit unexpected, unintuitive behavior. For example, closed-loop systems will oscillate, continuously switch, or dim the lights up and down, if not set up correctly. However, when correctly set up and functioning they offer more precise control over interior light levels than open-loop systems. Creating a feedback loop enables the system to sense unanticipated changes in the luminous environment such as someone closing the window blinds. The system can react to the changes it senses, and it continues to sense how its own response is affecting the situation, continuing to make adjustments until the system reestablishes equilibrium. A closed-loop system also has the ability to adjust for lumen depreciation: an integral (also referred to as 'reset') control photosensor can adjust fully; while a sliding set point photosensor can adjust partially (see the section, "Lumen Maintenance Applications" on page 23).

Choosing Open- or Closed-loop

The decision to use open- or closed-loop control is based on the following considerations:

1. **How precisely does the light level need to be maintained?**

   In situations where ample daylight is present (e.g., atriums) automatic control of the lights can occur at significantly higher light levels than the required minimum while still realizing energy savings, so an open-loop system would be appropriate. However, if it is important to not dip below a minimum light level while still maximizing energy savings, closed-loop systems, which allow the system to respond to changes in interior light levels and may provide more precise control (with proper calibration), will offer better performance. This is especially true if the amount of available daylight is marginal, and the system must maintain a near constant interior light level to achieve significant energy savings.

2. **How consistent is the daylight distributed within the space?**

   In some cases, architectural design and daylighting techniques such as the use of clerestories and light shelves can provide appropriate interior light levels and light distribution throughout the day (and year) that track well with outside daylight levels. Also, in many spaces, there is no way to override or change the daylight contribution such as closing blinds or changing interior surface reflectance. In these cases, there is no need for the added complexity of closed-loop controls. Often open-loop sensors may be placed indoors in skylight wells or clerestories where they are protected from the weather and can accurately sense the amount of daylight entering a space. Daylight factor is a measure of how much of the available daylight outside makes it to the work plane inside. The more consistent the daylight factor is for all times of the day and year, the less need there is for closed-loop control.

3. **What are the ease and expense of placing sensors inside or outside?**

   The practicality of installing sensors in different places and running wires is an important consideration in many cases, especially in retrofit applications. Ceiling-mounted interior sensors are often the most practical, which then necessitates a closed-loop control strategy. Some manufacturers recommend placing their interior sensor near the window and facing outside. If the sensitivity of the sensor is confined mainly to the window, the system will be open-loop. As the sensor is moved farther from the window, it will start to take on characteristics of a closed-loop system.

The number of individual sensors and their cost differs for open- and closed-loop systems. Open-loop systems require fewer sensors, but when located outside the cost of each sensor is higher due to the need for weatherproof packaging and additional wiring expenses.

Switching vs. Dimming

The choice between switching and dimming systems also depends on the desired precision of control and the amount of available daylight. In addition, cost is a significant factor, with dimming systems being considerably more expensive to purchase and install (see the section, “Initial Costs” on page 23).

In applications with ample daylight – where annual average daylight illuminance is more than twice the minimum required illuminance produced by the electric lights – there is little or no energy benefit of a dimming system over a switching system. Dimming systems will likely require more energy than a switching system because dimming electronic ballasts are slightly less efficacious at full light output than non-dimming electronic ballasts, and they will continue to require power when fully dimmed (seven to 20 watts or more for a two-lamp ballast). Switching systems require very little power when switched-off, and if ample daylight is present the lights will remain off for the majority of the day. Under this scenario the only time a dimming system will draw less power is during the relatively brief periods of sunrise and sunset.

On the other hand, if annual average daylight illuminance is marginal – not exceeding twice the minimum required illuminance – a switching system will rarely have an opportunity to switch the lights off. Before the electric lights can be switched off, the daylight contribution must at least equal the electric light level and preferably exceed it by a significant amount (20% or more) in order to avoid frequent switching. When daylight illumination levels are approximately the same or less than the electric light levels, dimming is the only way to achieve energy savings with photosensors.

Even in situations where daylight illumination levels are high, a dimming system might be a better solution, if daylight levels vary enough, such as with climates that are typically partly cloudy, to cause frequent switching. Such frequent switching will likely annoy occupants. Combining switching with dimming permits the most energy savings and makes the on/off switching less noticeable.

Performance Characteristics

Photosensor Response Functions (Control Algorithms)

The response function describes the output of a photosensor as a function of its input. The input is the light incident on the photocell and may include other inputs such as time or occupancy, which programmatically affect how the photosensor responds to incident light. The setup/adjustment controls also are a form of input that influence the response function. However, once set they remain fixed during operation. The output of a photosensor is typically a control voltage that ultimately regulates the light output of the controlled luminaires. For photosensors that work with 0-10 V dimming ballasts, the output is a 0-10 V dc signal. For switching photosensors, the output is a binary (on/off) relay control signal. Some photosensor products are integrated directly with dimming ballasts, and NLPIP considers the output to be the relative light output of the lamp-ballast system.

NLPIP measures all response functions for open-loop operation regardless of how the photosensor is intended to be operated. Therefore, the response function does not directly indicate how the system will behave when part of a closed-loop system. While it is possible to measure the closed-loop response of systems, such results are highly dependent on the amount of feedback and other specific conditions used to make the measurement. The open-loop response, on the other hand, is a fixed characteristic of the system that contains all the information needed to describe how the system will operate for any set of external conditions.

The next few sections of this report describe the operation of the various archetypical response functions used for dimming and switching systems. Understanding these response functions will help to explain the operation of actual photosensors with similar response functions.

The three archetypical response functions for dimming, illustrated in Figure 1, are integral, proportional, and closed-loop proportional (also referred to as "sliding set point control"). One archetypical response function for switching is illustrated in Figure 2.

Integral Response

Integral photosensors are designed to maintain a constant illuminance on the photocell and must be operated in a closed-loop configuration to function properly. When operated in an open-loop configuration integral control photosensors behave as a simple high/low switch as the open-loop response function indicates. The setpoint determines at what illumination level the high-low transition occurs. When operated in a closed-loop configuration the output can take on a continuous range of intermediate values between full and minimum light output. In the graph on the left side of Figure 1, the output varies along the vertical line located at the setpoint, raising and lowering the electric light level to maintain the setpoint. The control voltage has physical high and low limits, which are indicated by the horizontal sections of the response function.

Figure 1. Three archetypical response functions for dimming photosensor

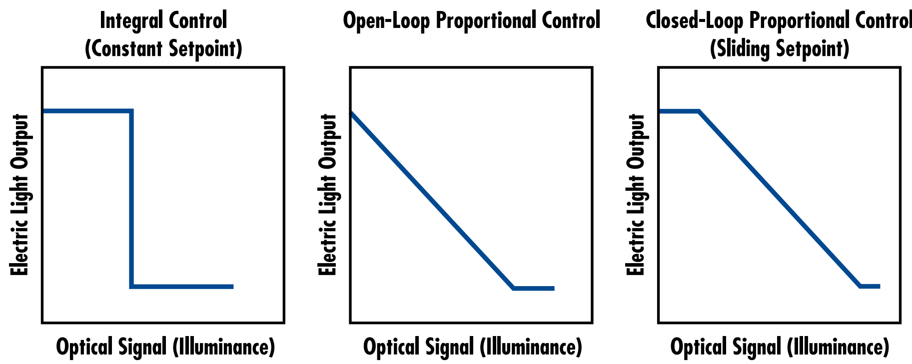
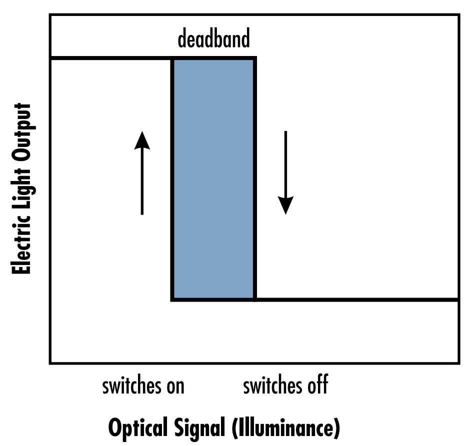


Figure 2. Archetypical response function for switching photosensor



Integral control photosensors work well for lumen-maintenance applications where the photocell responds only to the electric light output. They may not work well in lighting control systems for daylight harvesting, however, due to differences in the distribution of daylight and electric lighting. Achieving a good correlation between daylight and electric light is difficult because it is affected by room geometry and window placement. Integral control maintains a constant photocell illuminance, but since the photocell is not located on the work plane, work plane illuminance is not held constant. As daylight enters the space, the ceiling illuminance increases proportionally more than the work plane illuminance. A constant photocell illuminance causes the work plane illuminance to first overshoot the setpoint, and then, as the daylight level exceeds the level at which it was tuned, drop well below the desired amount (see the sidebar, "Task/Ceiling Illuminance Ratios" on page 8).

> ### Gain
> Gain is a multiplying factor applied to an input signal that determines how much the output will vary when the input signal changes. High gain corresponds to high sensitivity. Setting the gain on a photosensor adjusts the slope of the response function, where higher gain provides for a steeper slope. For dimming systems, higher gain causes the electric lighting level to adjust more for a given change in the photocell signal. For switching systems, higher gain causes the on/off switch points to be achieved with smaller changes in the photocell signal.

Proportional Response

Proportional response photosensors establish a constant relationship (a proportional function) between the sensor illuminance and the control voltage sent to the ballasts. These photosensors are most often used in lighting control systems associated with daylighting strategies. Figure 1 shows a sample response function for a hypothetical proportional response photosensor. The response function has a negative slope in order to reduce the electric light contribution as the photocell signal rises. The steepness of the slope is related to the daylight factor; the larger the daylight factor, the steeper the slope necessary to maintain constant work plane illuminance. For a particular daylight factor, a shallower slope produces less dimming and higher illumination levels as daylight increases.

Proportional response photosensors begin reducing the control voltage for any small amount of incident illumination. Therefore, the photocell must be in complete darkness for the control voltage to be at maximum value. This characteristic works well with open-loop systems, where the photocell is located outside; when it is dark outside the electric lights are at 100%. As the outside light level increases, a proportion of the outside light contributes to the interior illumination, allowing the electric light level to be reduced.

When used in a closed-loop system, however, a proportional response photosensor will never allow the electric lights to be at 100% because the controlled electric light that it senses will cause it to dim the electric light by some amount. In practice, when the feedback gain is low (e.g., photocell looking out of a window), this may not be a problem because the dimming ballast control function usually provides an offset of one or two volts before dimming begins (see the sidebar, " 0-10 V Ballasts" on page 7). This offset provided by the dimming ballast makes a proportional response photosensor take on similar characteristics of a closed-loop proportional photosensor. However, since the offset is not adjustable (the ballast provides a fixed amount that may vary for different ballast types) it does not provide optimal tuning for closed-loop applications.

Closed-loop Proportional

The addition of a variable offset to the proportional response control algorithm allows the full range of light output to be achieved when used in the closed-loop configuration. The offset is shown in the right graph in Figure 1 as the horizontal part of the curve before dimming starts when traced from left to right. An offset is needed in the closed-loop configuration to hold off dimming until the illuminance is greater than that due to the electric lighting being controlled. The magnitude of the offset is typically the maintained electric light level in the absence of daylight; analogous to the setpoint for integral control. The offset is typically set during a nighttime setup/tuning procedure. In fact, the offset must be equal to or greater than the nighttime photosensor signal to allow for 100% light output.

Closed-loop operation makes interpretation of the response curve's slope much different than that for the open-loop proportional response curve. As with integral control, feedback will ensure that the output follows the response curve as daylight varies. However, the control point is not fixed at one value of sensor signal. As the output signal drops, as when the electric lights dim, the control point moves to the right. As the lights are dimmed, the control point can be thought of as sliding to the right to higher photocell illuminance values. This sliding of the control point provides a means for dealing with the changing task/

ceiling illuminance ratios as daylight enters a space and gives rise to the alternate name for this control algorithm: sliding setpoint. The slope of the curve can be set to cancel the effect of changing task/ceiling illuminance ratios and thereby maintain a constant work plane illuminance as the amount of daylight varies. If desired, the slope can be set shallower than that needed for constant work plane illuminance to allow the work plane illuminance to increase by some proportion as the electric lights are dimmed.

Not only can the closed-loop proportional response function overcome the effects of changing task/ceiling illuminance ratios, it can also compensate for spectral mismatch errors of the photocell regarding its photopic sensitivity. Photosensors typically have broader spectral response curves than the ideal photopic response, which causes them to respond more strongly to daylight than to fluorescent lamp illumination of equal intensity (see section, "Spectral Response" on page 16). A shallower response function slope compensates for the increased sensitivity to daylight. This spectral mismatch compensation is established with no extra effort when the photosensor is setup and tuned.

Switching Response

A switching photosensor has two output states: on and off. The transitions from on-to-off as well as off-to-on occur at some adjustable level of the photocell signal. Figure 2 shows a sample response function for a switching photosensor. To provide stable operation and prevent frequent switching, the on-off transition must occur at a higher photocell signal than the off-on transition. This difference in photocell signal between output transitions creates a deadband, a region in which no switching takes place, and the output can be either on or off within this range. The engineering term that describes this switching behavior is hysteresis. A response function that has hysteresis traces out two different curves, depending on whether the photocell signal is increasing or decreasing. The purpose and the relative amount of hysteresis required depends on whether the switching photosensor is configured for open- or closed-loop operation.

For open-loop operation the purpose of a deadband is to prevent frequent switching due to small variations in the photocell signal near the transition level. Figures 3a and 3b show this effect. Without a deadband (Figure 3a), there may be many rapid on-off and off-on switches as the noisy signal passes through the setpoint. The noisy signals are due to changes in light level from clouds and shadows caused by trees, which change with seasons and weather conditions. With a deadband (Figure 3b), only relatively large variations in photocell signal result in an output switch. Deadbands of 10 to 25% of the setpoint level are usually sufficient to avoid rapid switching for open-loop applications, but much larger deadbands might be desirable to keep switching to a minimum.

For closed-loop operation the purpose of the deadband is to prevent continuous switching, or oscillations, resulting from optical feedback, as shown in Figure 3c. Consider a ceiling-mounted sensor with a setpoint corresponding to 500 lx on the work plane, and the electric lighting provides 400 lx on the work plane. When daylight contributes 100 lx, the photosensor will switch-off the lights. Without any electric lighting, the work plane illuminance will fall to 100 lx, and the photosensor will immediately switch-on the lights. As long as daylight is contributing between 100 and 500 lx, the system will oscillate. Time delays on the photosensor do not solve the problem, but they do slow down the rate of oscillation. The solution is to have a deadband of at least 400 lx, which prevents the lights switching-off until the work plane illuminance is 900 lx or more. When the electric lights switch-off, the daylight contribution will still be above the 500 lx lower setpoint. As shown in this example, a much larger deadband is required for closed-loop systems than for open-loop systems. For closed-loop systems a deadband of 1.1 to 2 times the lower setpoint is reasonable. Larger deadbands reduce the frequency of switching, but also reduce the energy savings because with larger deadbands, higher daylight levels are needed to switch-off the electric lights.

Figure 3a. Open-loop systems without deadband

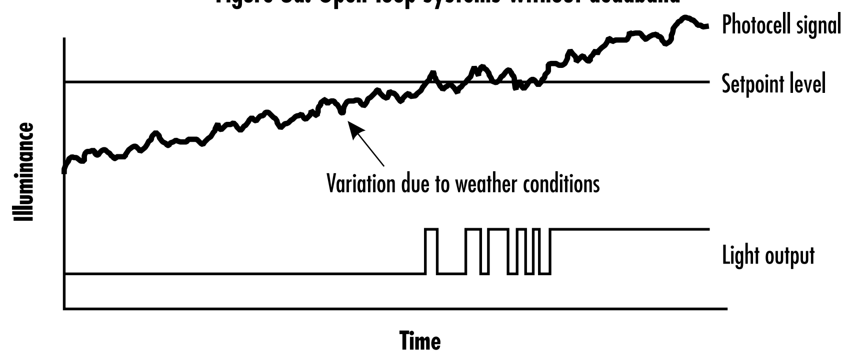


Figure 3b. Open-loop systems with deadband

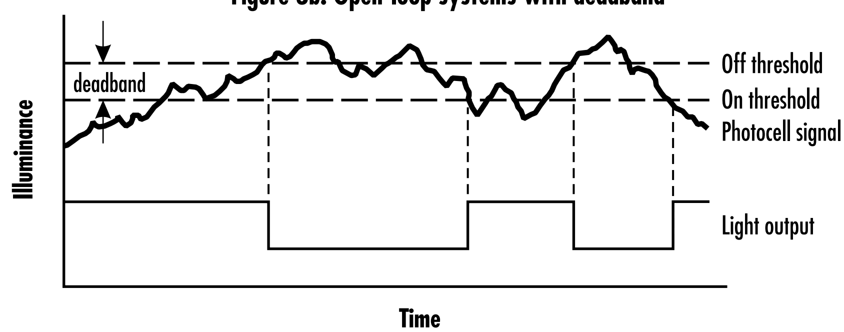
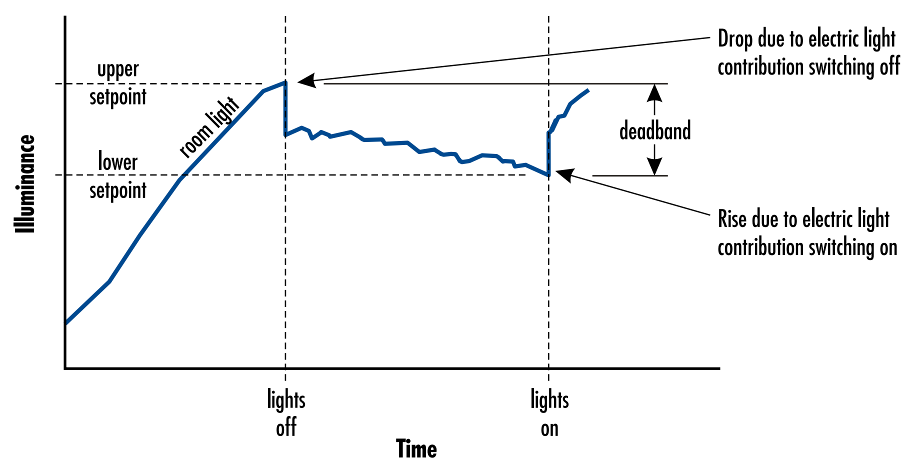


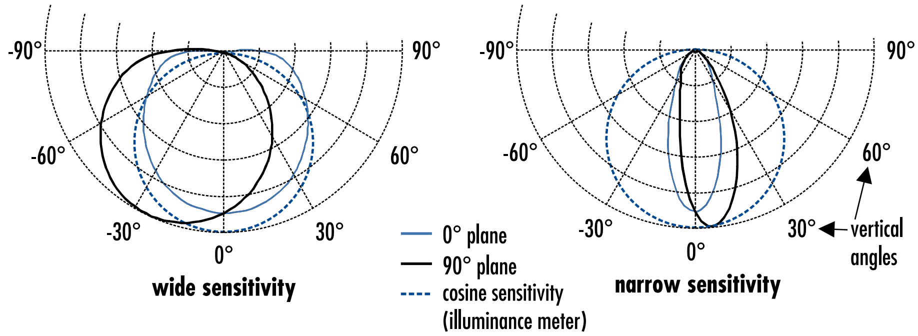
Figure 3c. Deadband for closed-loop systems



Spatial Response

The term spatial response refers to a photocell's field of view. It describes what the sensor "sees." The spatial response curve, shown in Figure 4, depicts over how wide or narrow an area the photocell is viewing light, either within a room (if it is part of a closed-loop system), or of the sky (if it is part of an open-loop system). Some photosensor spatial responses are circularly symmetrical such as a cone-shaped response, so the orientation of the photocell about the axis of symmetry is unimportant. Others, however, have asymmetric response functions and are designed to be oriented in a particular direction such as pointing toward or away from the window. Outdoor photocells often have a baffle to block direct sunlight and must be oriented accordingly.

Figure 4. Spatial response curves



These curves depict a photosensor with a wide sensitivity and a photosensor with a narrow sensitivity. The cosine sensitivity is shown to compare the sensitivity curve to that of an illuminance meter.

When installing photosensors it is helpful to know the sensor's spatial response so it can be placed and oriented to provide a signal representative of the work plane illuminance without excessive influence from windows and other light sources. For small control zones, a photosensor with a narrow spatial sensitivity is better for tracking changes in illuminance on the floor or desk below it than one with a wide sensitivity; however, its narrow field of view makes it susceptible to changes in that one area that might not be representative of the entire space being controlled. These changes can include movement of people and furniture, direct sunlight, and task lamps. For large control zones, a wide spatial sensitivity averages light over a larger area to provide a more stable representative signal. The control algorithm is then adjusted to make the photosensor respond appropriately to work plane illuminance.

Spectral Response

In daylighting controls applications, the photocell should have a spectral response similar to the human eye, responding only to the visible portion of the electromagnetic spectrum (light) and not to other forms of radiation, such as ultraviolet (UV) or infrared (IR), that might enter the room through windows and skylights. To ensure that the photocell being considered will sense the light in the space properly, look for an assurance in manufacturer's literature that the photocell has been spectrally corrected to block out UV and IR radiation or has been corrected to limit its response to UV or IR to a very small percentage of its overall response. Many manufacturers use filtering material over the photocell to block out unwanted radiation. Most manufacturers do not quantify the spectral response, and there is no standard way to report it.

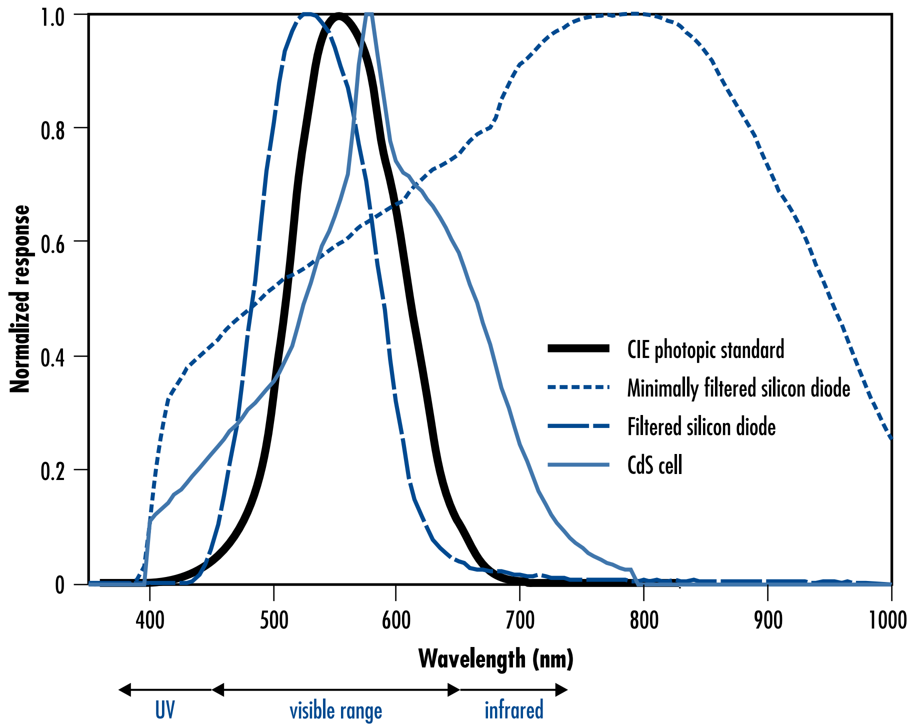
Metrics developed for characterizing illuminance meters can be applied, such as the CIE 69-1987 metric, but the level of precision for photosensors is much less than that for photometric equipment. For photocells that "see" only one type of light source, a close photopic spectral match is not important. (Some photocells "see" only fluorescent lighting for lumen maintenance or daylight for an exterior sensor.) For applications where the sensor "sees" a mixture of daylight and electric light, spectral match is important. However, even in this case certain control algorithms (see closed-loop proportional) can compensate for an imper-

Photopic vision

The term photopic refers to vision mediated essentially or exclusively by the cone photoreceptors of the human eye. Photopic vision is generally associated with adaptation to a luminance of at least 3.4 cd/m² which is achieved in well-lit environments and certainly outdoors during the daytime. The definition of light by the CIE is based on the eye's photopic spectral sensitivity and defined by a spectral weighting function known as V(λ). An accurate photopic spectral match closely represents the V(λ) function.

fect photopic spectral match. In short, a close photopic match is beneficial, but not always necessary. Figure 5 shows the spectral response of several photosensors for comparison. This type of figure is also shown in the product data sheets at the end of this report.

Figure 5. The spectral response of various photosensor products



The graph shows how the response of different detection types compare to the photopic luminous efficiency function, which defines the measurement of light. The detector types are shown in the graph legend.

Setup and Tuning Adjustments

Photosensors vary considerably in the number and type of adjustments that can be set. While some adjustment inputs relate to special features offered by particular manufacturers, commissioning a photosensor successfully requires some basic adjustment settings, which depend on the control algorithm. If the photosensor conforms to one of the archetypical types discussed earlier, make sure that it at least has the adjustments listed in Table 2. When two adjustments are necessary, they should be set independently to ensure that adjusting one does not affect the other.

Table 2. Setup and tuning adjustments

Control algorithm	Number of adjustments	Description
Integral	1	Adjustment of the setpoint
Proportional	1	Adjustment of the gain (slope) relating the output to the input
Closed-loop proportional	2	Adjustments may be the dimming start and stop set points, from which the gain (slope) is determined
Switching	2	Either separate adjustments for the high and low setpoints, or a high or low setpoint adjustment and a deadband adjustment

Microprocessor-based photosensors have the ability to execute a setup procedure that sets adjustable parameters automatically. Therefore, the parameter being adjusted may not be obvious. If uncertain, ask the manufacturer how the setup and tuning procedure is performed to ensure the device can be commissioned properly.

Time Response

Momentary fluctuations in photosensor illuminance may result from passing clouds or someone walking under the photosensor. To prevent the electric lighting from fluctuating in response to these momentary changes, most proportional response photosensors have a time-averaging filter built into the circuit design. Time constants for this filter typically range from a few seconds up to a minute. Integral type photosensors average the response over a few seconds, but longer time constants may also be used. A slow setting reduces the likelihood that occupants will be distracted by fluctuations in electric light output from sudden changes in illuminance levels. However, a time response that is too slow when the light level is low and should be increased will leave occupants in a dark environment for a longer period than would normally be the case. An asymmetrical time response for increasing and decreasing light levels can be effective for ensuring there is an adequate amount of light. For switching photosensors, a time delay is used to prevent excessive switching. Time delays typically range from two to 30 minutes. Time delays should be asymmetric, meaning they should apply only to switching-off the lights. Switching on the lights should occur immediately when the light level reaches the set point, so occupants are not left in the dark for long periods. Some manufacturers will allow for adjustments in the time response and delays. This is especially important when tuning and commissioning, so the effects of adjustments can rapidly be seen. Often the time response or time delay can be disabled temporarily while the photosensor is set up and tuned. High intensity discharge (HID) lighting may require special time delays to deal with lamp restrike time, the time required by a lamp to restart and return to at least 90% of its initial light output after being extinguished. Consult lamp and/or control equipment manufacturers for specific guidelines.

Range of Response

A photocell has a “range of response,” a limited range of output signal values that accurately measure the incident light. The lower limit is determined by detector noise and/or the resolution of the electronics involved with the sensor. The upper range is limited by the maximum output voltage recognized by the system (e.g., 10 volts for a 0-10 V dimming ballast) and/or saturation of the photocell. Different ranges can often be selected on the photocell to optimize signal resolution, minimize noise, and avoid photocell saturation.

Lighting specifiers should ensure that the selected system’s range of response matches the range of light levels likely to be found in the environment in which the photocell will be installed. For example, an open-loop system with the photocell installed outside the building will be subjected to a wider and overall much higher range of light levels than will a closed-loop system installed within the building.

Typical ranges of response for some sample applications are:

- A photocell mounted on the ceiling in an interior space with windows (such as an office or classroom): 10 to 5,000 lx
- A photocell mounted in an atrium or skylight well: 100 to 50,000 lx
- A photocell mounted on the exterior of a building: 1,000 to 100,000 lx (if unshielded; shielding will reduce these levels).

Ballast Compatibility

While some dimming photosensors may be used only with ballasts from the same manufacturer, most manufacturers of 0-10 V compatible photosensors include the Philips Advance Mark VII®, the OSRAM SYLVANIA Quicktronic® Helios™, and the Universal Lighting Ballastar® dimming electronic ballasts as approved for use with their photosensors. Other low-voltage dimming electronic ballasts, including those for T5FT lamps and compact fluorescent lamps (CFL), have 0-10 V control circuits similar to the listed products and are likely compatible with photosensors. Specifiers should consult the photosensor and ballast manufacturers if they are unsure about whether a photosensor can be used in a system with dimming electronic ballasts. Specifiers should also be aware that different ballasts respond differently to photosensor control signals (see the sidebar, "0-10 V Ballasts" on page 7).

Photosensor control systems used in switching (on/off) applications do not interact with the ballast directly, so they can be used with most types of fluorescent ballasts such as instant start, rapid start, programmed-start, dimming, magnetic, etc. If reduced lamp life due to frequent switching is a concern, consider programmed-start electronic ballasts. When executed well, programmed-start ballasts can prolong lamp life by virtually eliminating the deleterious effects of starting.

Photosensors used with switching systems usually control a relay that switches the electric lights on or off. Often, this relay is part of a device called a power pack, which contains an isolated low-voltage power supply to power the photosensor and a relay to switch the lighting circuit. To ensure long life of the relay or power pack ensure that it is compatible with the type of load (lighting) that it controls. Magnetic ballasts are highly inductive, and electronic ballasts can have large inrush current, both of which can damage relays not designed to handle such loads.

Application Considerations

Knowing and understanding a photosensor's operating characteristics is necessary in order to install it, set it up, and tune it to get the best performance. The data sheets at the end of this report provide this often hard-to-obtain information. The most important piece of information about a photosensor is its response function. The response function determines whether the photosensor is designed for switching or dimming. The response functions of most commercial dimming photosensors fall into the three archetypical types: integral, proportional, and closed-loop proportional. Knowing a photosensor's type of response function and how to adjust its necessary features such as setpoint and gain allows for a systematic approach to selection, installation, setup, and tuning (see Table 2, "Setup and Tuning Adjustments" on page 17).

Sensor Location

Much attention is paid to sensor location, which is particularly important if a photosensor has an inappropriate response function or is unable to adjust gains or setpoints correctly. When the only method available for adjusting the performance is to move the photocell to different locations, location becomes critical. However, a photosensor with easily configurable setpoints and gains and a response function that is appropriate for the application will provide some leeway on choosing a satisfactory location. In any case, it is crucial to avoid locations that cause problems.

Photosensors in open-loop systems require the sensor location to be chosen so little or no light from the controlled lighting reaches the photocell. Locations for open-loop photosensors can be within a skylight well, facing out a window, or outdoors. It is important to ensure that the photocell can handle the signal strength if exposed to direct sunlight. Otherwise, shielding may be necessary. Manufacturers often provide instructions.

Photosensors in closed-loop systems are often installed on the ceiling and should be located where changes in photocell signal relate closely to variations in work plane illuminance. Therefore, placing the photocell near the center of the control zone, or closest to the location where the lighting is most critical such as over a desk, is best. Locations to avoid are those that receive direct sunlight or sunlight reflected off shiny surfaces, very bright locations near windows, and dark, shaded areas. Light received by the photocell directly from a window, a skylight, or a luminaire may cause the photosensor to dim the electric light fully, even if there is insufficient illuminance on the work plane.

The best locations are those that receive somewhat equal amounts of electric light and daylight. In areas that use an indirect or direct-indirect electric lighting system, the sensor should be located where it is not exposed to direct light from luminaires. This may mean mounting the sensor on the bottom or side of the luminaire, suspending the sensor from the ceiling at the same height as the luminaire, or adjusting the photosensor's baffles (if so equipped) to block its view of the luminaires. It is advisable to avoid locations that are close to the movement of large objects or people; avoid locations near moveable partitions, doorways, banners, and flags.

Specifiers should check manufacturers' specifications for both open- and closed-loop systems for instructions on positioning and aiming sensors. Manufacturers often have specially designed optics to provide spatial response functions that work best for a particular location and orientation. Some manufacturers suggest placing the sensor on the ceiling near the luminaires it controls and directly above a work surface that receives a representative amount of daylight. Other manufacturers suggest aiming the sensor toward an interior wall to avoid the effect of changing reflectance on the work surface or sensing direct sunlight. Another manufacturer suggests aiming the sensor at a point near the window while shielding it from direct exposure to daylight.

As a rule of thumb, the California Energy Commission (CEC 1993) recommends that a closed-loop photosensor should be located away from the window a distance equivalent to approximately two-thirds of the depth of the area controlled by the photosensor. The CEC qualifies this recommendation by suggesting that there is rarely sufficient daylight for a photosensor-controlled system more than 5 m (15 ft) from a window. Therefore, a ceiling location approximately 3 m (10 ft) from a window is a reasonable starting point for selecting a location for a sensor.

SPOT ™

The California Energy Commission's (CEC) Public Interest Energy Research (PIER) program provided a grant to Architectural Energy Corporation to develop a photosensor location software program. This helpful program, "Sensor Placement + Orientation Tool" (SPOT), can assist lighting specifiers in properly locating photosensors and in tuning the systems control algorithm settings relative to annual daylight conditions. The software can perform annual daylighting predictions, daylight metric reports, and electric lighting analysis. Its developers say version 4.0 will include commissioning step-by-step reports. SPOT can be downloaded at no charge at www.archenergy.com/SPOT.

Zoning

The control zone established for a photosensor will also affect the sensor's location. A zone is the area within which all lighting fixtures are controlled equally. Zones are determined by space function, the size and depth of the space, height of the windows and ceiling, number of partitions in the space, configuration or layout of the electric lighting fixtures, and other factors.

In an open-loop photosensor system where the photocell is located outdoors, the single photocell can control multiple control zones for different facade exposures (e.g. north, south, east, or west), as well as different distances from the windows. However, it may be difficult to obtain satisfactory results using only one photocell. When the photocell is located within a skylight well, it may control only the lighting fixtures near that skylight. If the skylights throughout the building provide a uniform level of daylighting, a single photosensor can control all of the lighting.

For closed-loop systems, there is usually one control zone for each photocell. For effective closed-loop control, the photocell must be located within the zone that it is controlling; otherwise it would be considered open-loop control. Interior spaces where partitions separate occupied spaces along an exterior wall may require a photosensor in each individual space to provide acceptable light levels in every space as part of a closed-loop configuration.

Closed-loop dimming systems may use two or three control zones to achieve different levels of switching (step dimming), or to combine dimming with switching. In these cases, the different control zones cover the same area; one zone might control, for example, the outboard lamps in the fixtures, while a second zone controls the inboard or middle lamps.

Site Characteristics

Geometry and the reflectance characteristics of the building site, which may include plantings or nearby buildings, can also affect a specifier's decision about which photosensor(s) to install because of the effect on the availability and distribution of daylight within a space. Sites in northern regions of North America, for example, may experience significant periods of snow cover (see the sidebar "Predicting Daylight in Spaces" on page 25), and deciduous trees can create seasonal changes in shading, which can lead to significant variations in the amount of available daylight. An open-loop control scheme may not work effectively under such conditions. Contributions to interior illuminances from natural light through south-facing windows may be overestimated, for example, because occupants often use window blinds or shades to minimize sunlight (Rubin et al. 1978; Rea 1984). The specifier must consider the impact of window treatments on daylighting's contribution to photosensor and task illuminances and the resulting impact on potential energy savings with photosensor-controlled systems.

Installing, Setting, and Adjusting

Proper installation of photosensor-ballast systems requires the installer to know the system's power requirements and the number of ballasts or other devices the photosensor can control accurately. Photosensor systems may require line voltage (120 or 277 V) or low voltage (usually 24 V), being supplied to the photosensor. In the case of a low voltage system, a separate power supply may have to be purchased and installed. It is important to also know how many ballasts can be controlled on a single photosensor control system. This will allow a lighting specifier to properly specify how many separate systems will be needed for a particular building or zone. For dimming systems, the manufacturer might list the number of ballasts each photosensor can control. For switching systems, manufacturers might provide the current rating of the relay included in the photosensor system and, based on the voltage and wattage of the light fixtures, the installer or lighting specifier would need to calculate the number of ballasts or light fixtures that can be controlled.

Dimming

The setup and tuning procedures for photosensors differ greatly for different types and brands of photosensors. The manufacturer's installation instructions should be consulted to obtain the sequence and methods for properly adjusting the photosensor. Even though the procedures may differ, part of the procedure is concerned with setting either a setpoint (for integral), or a gain (for proportional), or both (for closed-loop proportional).

Setting the setpoint for integral control can be performed at any time; however, for daylight harvesting applications this should be carried out when a significant amount of daylight is present. The procedure usually involves making an adjustment that dims the light until the desired illuminance is measured on the work plane. Too much daylight may cause the measured illuminance to always be higher than the amount desired, even when the lights are fully dimmed. If this happens, the adjustment must be made when there is less daylight, preferably when daylight provides 70 to 85% of the required illuminance.

Setting the gain for a proportional response photosensor is performed when a significant amount of daylight is present. The procedure involves adjusting the gain until the desired work plane illuminance is achieved. As with integral control, if daylight provides more than the minimum illuminance required, this manual method of setting the gain will not be accurate. It must be made at a level where the electric lighting is neither fully dim nor fully bright.

Closed-loop proportional response photosensors require both a setpoint and a gain setting to be established. The setpoint is typically set a night, or with the blinds completely closed. The gain is set during the day in a fashion similar to that for open-loop proportional photosensors.

The above daytime adjustments should be made with any window treatments in their normal, or most likely to be used position. For example, window blinds should be adjusted to block direct sunlight, preferably by adjusting the angle of the blinds to reflect the sunlight up at the ceiling. Ideally, these adjustments should be performed on an average daylight condition. However, this would require checking back several times under differing sky conditions, and, given the dynamic nature of daylight, obtaining a proper adjustment would be difficult. The SPOT software can assist in setting for all design conditions and extremes throughout the year (see the sidebar, "SPOT™"on page 20).

The installer should also take care not to allow shadows to obscure the photosensor or luminaires during gain or setpoint adjustments. However, when sensitivity controls are located on the photosensor housing, avoiding blocking or casting shadows on it during installation can be difficult or impossible. Often, the installer must make repeated trips up and down a ladder, adjusting the sensitivity, walking outside the photosensor's view, and checking the resulting illuminance. More photosensors are providing means of making adjustments that are remote from the photocell. Remote adjustments make the setup and tuning task much easier, safer, and more accurate.

Switching

The setup procedure for switching photosensors involves setting two switching setpoints: the upper setpoint determines at what light level the electric lights will switch-off; and the lower setpoint determines at what daylight level the electric light will switch-on. The lower setpoint corresponds to the desired minimum maintained illumination level. The difference between upper and lower setpoints is known as the deadband. On some products the deadband has its own adjustment; the lower setpoint is the other adjustment. For open-loop systems a relatively small deadband from 10-25% of the lower setpoint is often sufficient, especially when a time delay is also employed to prevent frequent switching. In fact, a fixed-percentage deadband would work well for open-loop switching photosensors and would simplify the setup procedure.

Being able to customize the deadband is crucial for closed-loop switching systems to prevent on/off oscillations and maximize energy savings. Referring to a readout of the actual installed photocell signal is the easiest and most accurate method of determining the minimum amount of deadband required to prevent oscillations. Measure the photocell signal with the electric lights on and off; the difference in readings is the minimum deadband. To account for measurement variations and changes over time always increase this minimum deadband by at least 10%. Instead of a numerical readout, some products provide LED lights that indicate whether the photocell signal is above or below the switch points. The deadband is set by observing the LED lights while adjusting the upper set-point. If after switching-off the lights the LED indicates that the signal level is below the lower set point, then the upper setpoint must be raised. For systems without a numerical readout, expect to spend at least a few minutes performing a trial-and-error approach to set the deadband.

A time delay in turning the lights off should be built into the switching photosensor, or the installer should be able to set an adjustable time delay. This ensures that the photosensor switching is not associated with short-term reflectance changes or the sun emerging between clouds. A time delay of 10 minutes is usually sufficient and does not affect the energy savings significantly. Conversely, when the work plane illuminance level falls below the lower set point, the lights should instantaneously turn on to ensure design light levels are maintained. Before resorting to time delays longer than 30 minutes if frequent switching is a problem, ensure that the deadband is set correctly.

Lumen Maintenance Applications

Integral response photosensors can be useful for compensating for lamp lumen depreciation (LLD) and luminaire dirt depreciation (LDD) in applications without daylight. LLD is the phenomenon in which the light output of a fluorescent lamp decreases gradually (typically by approximately 10%) over the life of the lamp. LDD is caused by dirt that collects on the surfaces of lamps and luminaires and can decrease the total output of the lighting system by an additional 5–20%, depending on the luminaire type, the application, and the intervals between cleanings (IESNA 1993). Luminaires in dirtier areas or that are seldom cleaned will experience greater LDD. Because of these factors, lighting specifiers typically design lighting systems to provide higher initial task illuminances than the design level. An integral control response photosensor system in such an application could be set to maintain a constant illuminance corresponding to the design illuminance. Initially, the system would be designed to exceed the design illuminance but would be dimmed by the photosensor to provide the design level. Later, as LLD and LDD reduce the maximum light output of the electric lighting system, the photosensor would adjust its dimming signal to maintain the design illuminance. Integral control photosensors excel at maintaining a constant photocell signal, and for lumen maintenance applications they will provide better regulation of the lighting than proportional response photosensors.

A sliding set point system can partially compensate for lumen depreciation. The adjustment will not be complete because of differences in ceiling/task illuminance ratios between daylight and electric light.

Economics

Initial Cost

In addition to the purchasing cost, initial costs include any incremental cost for dimming ballasts if the photosensor control system will dim the lights rather than switch them on and off. Dimming ballast incremental costs range from $30 to $70 per ballast or, on average, $0.50 US per square foot of floor space being controlled. Today's photosensor control systems also include additional wiring to connect the photosensor to the luminaire (lighting fixture) ballasts, power supplies, and/or relays. These additional costs must be added to the cost of the photosensor to determine the total initial cost of a fully functional photosensor control system.

Energy and Electric Demand Savings

The energy savings realized by using a photosensor to control a lighting system are influenced by many variables, including:

- Available daylight, including the size, placement, orientation, and number of windows and skylights, as well as their exterior shading, treatments (such as blinds), and tinting
- Photosensor control algorithm (switching versus dimming)
- Optimization of photosensor setup and tuning
- Reflectances of surfaces within a space
- Geometry of the space
- User adjustments to the photosensor (such as manual override)
- Design illuminance

Wide ranges in claimed energy savings, from 7% to 80% of the controlled lighting energy (Rea and Maniccia 1994), have been reported. Generally, the lower end of the range represents the effect of photosensors used in lumen maintenance control schemes. The higher end of the range generally represents a photosensor combined with another control strategy such as manual dimming, automatic switching, or occupancy sensors used with energy-efficient luminaires.

Peak electric demand savings due to the use of photosensors in conjunction with daylighting may approach 100%, if the photosensor fully switches-off the lighting during peak daylighting times. A building's peak electric demand will normally occur during periods of high occupancy, bright skies, and high temperatures, the ideal conditions for maximum use of daylight. Under these conditions, a switching photosensor control system will turn off all lights within the controlled area. A dimming system may dim the lights to their minimum setting or turn off the lights, if so equipped.

When calculating the energy cost savings, it is important to utilize the utility rate structure rather than the average cost per kilowatt-hour (kWh) saved. The average cost-per-kWh-saved method will tend to underestimate the energy cost savings. This method assumes, for example, that if there is 30% energy savings (kWh), there is 30% peak electric demand savings (kilowatts). For photosensors used in daylighting systems, the energy savings that occur throughout the day and month may be 30%, but the peak demand reductions, which occur at a specific 15 or 30 minute time interval, may be 80% or even 100%. Using the utility rate that is applicable to the building and taking credit for the demand reduction and energy savings separately will result in a more accurate depiction of the energy cost savings.

Predicting Energy Savings

To predict the performance of a photosensor-controlled system, the specifier must have the response functions of the photosensor and the ballast and understand the range of possible ceiling and task illuminances from daylight for the particular space and sensor location (see the sidebar, "Predicting Daylight in Spaces"). With an understanding of the application (daylighting or lumen maintenance), the specifier can determine the sensor signal at which dimming will start and stop, as well as the amount of dimming.

Many issues complicate these estimates. For example, it may be difficult or even impossible for a specifier to estimate illuminances from daylight accurately because of occupant preferences for open or closed blinds, which may change by

Daylight in Spaces

Exterior horizontal illuminances from daylight (excluding direct sunlight) can be as high as 10,000 to 20,000 lux (lx) [10.76 lx = 1 footcandle (fc)] on clear or overcast days and as high as 40,000 lx on partly cloudy days (IESNA 1993). White (1986) suggested that office spaces with windows should be designed to produce task illuminances from daylight of at least 2% of the exterior horizontal illuminance produced by daylight, which would yield task illuminances of at least 200 to 400 lx on clear and overcast days and at least 800 lx on partly cloudy days.

In the same study, White also found task illuminances from daylight exceeding 10% of the exterior horizontal illuminances on work surfaces 0.5 meters (m) [1.6 feet (ft)] from the window. However, task illuminances from daylight decreased rapidly with increased distance from the window, to about 1.5% of the exterior horizontal illuminance on work surfaces 2.5 m (8.2 ft) from the window.

The contribution of direct sunlight to task illuminances usually is excluded when discussing daylighting because occupants generally find the brightness of direct sunlight on visual tasks objectionable. In such cases, occupants usually will use window shades or blinds to reduce or eliminate the contribution of direct sunlight, especially from south-facing windows (Rubin et al. 1978; Rea 1984). Even in rooms with east- or west-facing windows, window shades or blinds are often used by occupants to exclude sunlight.

season and according to weather, or because of changing office layouts or tasks.

Proportional response photosensors (both open- and closed-loop) are more likely than integral response photosensors to be successful for daylighting applications with vertical windows. Proportional response photosensors allow for gradual increases in total illuminance with increasing amounts of daylight through windows. This helps to overcome the perception of a darkening room relative to increasing brightness outside. However, occupant preferences and habits regarding the use of window blinds vary significantly, making energy savings estimates inaccurate for specific cases, and probably lower than expected for averages assuming 100% occupant compliance.

A method of predicting energy savings is to simulate the building using a software program, such as the DOE-2 software simulation package or similar software. DOE-2 considers thermal loads, including lighting. Developing the input for daylighting may require software programs like SPOT, which can predict electric lighting energy savings well; however, it will not predict heating and cooling load interactions. Other useful software includes Radiance and/or physical building modeling using an overcast sky simulator or heliodon.

Alternative Approaches

Manual Dimming

Manual dimming controls should also be considered, especially for single-person offices. Occupants can, and do, manually dim the lights when daylight is available, and the personal control may increase their satisfaction with the lighting system. In a study of lighting controls in private offices, manual controls, which are often easier to install and adjust than photosensors, saved at least as much energy as photosensor controls in single-person offices with daylight (DiLouie 1996). Energy codes, however, may not provide credit for, or allow manual control as an alternative for automatic controls, especially for large spaces.

Time Clocks

For simple dusk-to-dawn exterior lighting needs, consider using time clocks instead of photosensors. Astronomical time clocks are available that keep track of the time of the year and adjust on/off times according to the actual sunrise/sunset. Astronomical time clocks can also be useful for interior applications, such as atriums, where daylight provides sufficient light regardless of the season or weather conditions.

Performance Evaluations

NLPIP identified manufacturers of photosensors and either purchased or requested product samples for testing. The tests, conducted at the Lighting Research Center laboratory in Troy, New York, included 14 products from 10 different manufacturers. Of the 14 products tested, nine were dimming controls, four were switching controls, and one switched and dimmed.

Table 3. Photosensors Tested by NLPIP

Manufacturer	Model (Controller)	Sensor	Type	Sensor Type	Control Type	# of Zones	Ballast Compatibility	Indicators
Axis Technologies	AX232B-120	Included w/control	Dimming	CdS	Logarithmic proportional *	1	Axis	None
Douglas Lighting Controls	WPC-5621	Included w/control	Switching	Si, light to frequency	Switching	1	Any	Two LEDs show on/off states and blink when within deadband
Douglas Lighting Controls	WPC-5700	Included w/control	Dimming	Si	Integral	1	0-10 V	None
Easylite	2500072 Daylite Harvester	Included w/control	Dimming	Si, integrated amp	Closed-loop stepwise proportional	One; multiple with additional hardware	Easylite	Flashing fluorescent lamps
Leviton	CN100 and CN221	ODCOP-W	Dimming	Si	Integral	1	0-10 V	Eight LEDs indicate mode, status, and light level
Lithonia - Acuity Brands	ISD DPC (ESD-PLC)	Included w/control	Dimming	Si	Integral	1	0-10 V	None
Lithonia - Acuity Brands	Digital Equinox, SYRS EXT	LSA APS IN R2	Dimming	Si	Integral	1	0-10 V	LEDs blink status code
Lutron	ECO System	C-SR-M1-WH	Dimming	Si	Closed-loop proportional **	At least 64 (individual ballast groupings)	Lutron	Alpha-numeric and graphical display on PDA remote
Novitas	02-PCC	01-PCI (indoor)	Switching	CdS	Switching	1	Any	Two LEDs show whether photocell signal is above or below setpoints
PLC-Multipoint	LCM-12	CES	Switching	Si	Switching	4	Any	4-line alpha-numeric LCD
Sensor Switch	CM-PC-ADC ***	Included w/control	Dimming / Switching	CdS	Integral / Switching	1	0-10 V / Any	One LED blinks different patterns
Watt Stopper	LCD-203	LS-290C	Dimming	Si	Proportional	3	0-10 V	2-line alpha-numeric LCD
Watt Stopper	LCO-203	LS290-C	Switching	Si	Switching	3	Any	2-line alpha-numeric LCD
Watt Stopper	LS-301	Included w/control	Dimming	Si	Closed-loop proportional	1	0-10 V	Two LEDs inside photosensor indicate communication, errors

* proportional on a logarithmic scale
** offset set-point is not adjustable
*** switching and dimming combined in one device

Test Methods

Spatial Response

The spatial response was measured on a 2.5 m bar photometer equipped with black metal baffles and located in a black-painted room. The photosensor, or photocell component if supplied as separate devices, was mounted to a two-axis goniometer located at one end of the bar photometer, and a 50-watt MR16 flood lamp was mounted approximately 2 m away to illuminate the photosensor. Measurements of the photocell signal were recorded for every two-degree increment of each axis for all azimuthal angles and elevation angles up to 145 degrees or the photocell's physical cut-off angle, which was typically 100 degrees.

The type of photocell signal measured depended on the type of photocell used in the product. For silicon photodiodes, the photocurrent was measured with a picoammeter (Keithley 6485). For photoconductive devices, the resistance of the cell was measured with a digital multimeter (Agilent 34401A). For integrated detector modules and sealed (potted) devices, the output voltage was measured with the digital multimeter (Agilent 34401A). To gain direct access to the silicon photodiode or photoconductive cell element within some devices, the devices were carefully removed from their housing, electrical circuit board traces were cut, and thin (30 gauge) wires were soldered to the photocell element. The devices were reassembled in their housings for testing. For devices that had to be taken apart in this manner, NLPIP obtained two samples so that one sample could remain intact for other parts of the evaluation.

The silicon photodiode and voltage output modules were tested for linearity of response because a linear intensity response is important for measuring accurate spatial and spectral response functions. Photoconductive cells are highly non-linear, so in order to obtain accurate spatial and spectral responses, the functional relationship between light intensity and output signal must be established. This was accomplished by illuminating the photocell with an 8-inch integrating sphere lit by a mechanically filtered, adjustable incandescent light source to maintain a constant illuminating spectrum and spatial distribution while measuring the response of the photocell over a range of light intensities. Plotted on logarithmic axes, the data were fitted with quadratic polynomials with resulting r^2 values greater than 0.99. This curve fit was then used to linearize the resistance measurements taken on the bar photometer and used for the spectral response measurements described below.

Spectral Response

Monochromatic light with a FWHM (full width at half maximum) bandwidth of 10 nm was produced by passing light from a 100-watt halogen lamp through a 0.22-meter monochromator (Spex model 323B) and order-sorting absorptive glass filters. Two overlapping spectral scans were needed to cover the full range of reported wavelengths: 350 to 680 nm and 600 to 1000 nm. For each spectral scan the photocell was placed directly in the output beam of the monochromator (f/4 optics) and the output signal recorded in the manner as for the bar photometer spatial measurements. The photocell was removed, and a calibrated, reference silicon photodiode was placed in the beam. The scan was then repeated. The relative spectral response was calculated as the photocell response divided by the quotient of the reference response and its calibrated responsivity. The spectral scans from 600 to 1000 nm were scaled individually so the region of overlap with the 350 to 680 nm scans coincided. The two scans for each photocell were then combined and normalized. Resistance measurements for the photoconductive cell were linearized as described above before calculating the relative spectral response.

A visual inspection of the Watt Stopper LS-301 photosensor indicated that it employed a dielectric interference filter. The filtering characteristics of interference filters are known to be sensitive to the incident angle of the radiation. Therefore, NLPIP also tested this particular photosensor using an integrating sphere on the output of the monochromator to provide diffuse light (instead of a beam) incident on the photocell. The monitor cell was located at a second sphere port, and both the monitor and photocell readings were recorded at the same time. The results show the extent of the wavelength shift for diffuse illumination.

Response Function (Control Algorithm)

A four-inch integrating sphere with a monitor silicon photodiode and illuminated by three, one-watt green LEDs provided variable intensity illumination on the sensors while keeping the spectrum and distribution of light constant. The photocell being tested was placed either inside the sphere and attached to the sphere wall through a 1-inch opening, or taped to the outside of the sphere over the one-inch port opening. The light inside the sphere was precisely controlled by varying the current through the LEDs (1 to 500 mA) and measured on a relative scale by the monitor photodiode. The photosensor output control signal was also measured at the same time. For photosensors that have photocells with voltage output, the photocell voltage was also measured in order to link the relative illumination in the sphere to an absolute measure of photocell illuminance taken later. For the other photosensors, the measurements relating the photocell signal to the relative sphere measurement were performed at different times, with care taken to maintain the same position of the photocell relative to the sphere. In cases where access to the photocell element required cutting traces and adding wires, the duplicate sample specimen was used for this measurement.

To link the relative sphere measurements to absolute illuminance measurements, the photosensors were measured on the bar photometer using an incandescent lamp at a color temperature of 2856 K (approximating CIE illuminant A) with the sensor orientated at nadir. This provides a precisely defined spatial and spectral illumination from which the response to other spatial and spectral distributions of light can be calculated by using the data from the spatial and spectral response functions.

The open-loop response functions were determined by illuminating the sensors with the 4-inch integrating sphere and measuring the photosensor output for different adjustment settings. In all cases, NLPIP attempted to measure the response function for the extremes of the adjustment settings. For example, for products with dials, measurements were taken for the dials turned fully clockwise and fully counterclockwise, as well as for a few intermediate positions. The legends on the response function graphs indicate the adjustment settings.

For the products utilizing microprocessors with electronic capture of adjustment setpoints, NLPIP is not certain that the full range of adjustment setting was explored. Similarly, products with multiple adjustments present too many conditions to test or display, so only a few representative response functions are shown. Refer to the notes on each data sheet for further explanations.

Scale Model Bench Test

The open-loop response functions provide insight on how a photosensor will operate, but it is still difficult to determine what the actual maintained light levels will be when used in a complete system, which may be a closed-loop system. How a particular photosensor system will perform in a space depends on many variables involving the characteristics of the space, how it is installed, the amount of daylight, and other factors. Because the architecture of spaces and interior décors varies greatly from building to building, each photosensor is unique in its analysis.

Benchmark tests provide a means of assessing performance when it is impractical (or impossible) to capture all relevant aspects of performance in a metric or small set of metrics. Benchmark testing involves choosing a particular scenario that contains conditions similar to real-world conditions and an outcome measure that is likewise meaningful. An important feature of photosensors is that they must work in a variety of spaces. Therefore, choosing one particular space should not severely disadvantage a well-performing product. Benchmark tests, although imperfect, allow for product comparisons when assessing performance of complicated systems with numerous input variables and a seemingly infinite number of variations.

NLPIP conducted a benchmark performance test on the photosensors using a 1:8 scale model of a side-lit room. Benchmark tests require all products to be subjected to the same conditions. This is difficult to achieve in a full-scale room because daylight changes uncontrollably with time and weather conditions. Simulating daylight levels for full-scale rooms is also impractical due to the high luminous flux levels required. The scale model provides convenient, reproducible conditions. It is designed to have optical characteristics similar in scale to many interior spaces such as ceiling heights, window size, and surface reflectance. A photograph of the model is shown in Figure 6.

Figure 6. Daylighting controls simulator

The electric lighting was provided by two rectangular openings in the ceiling, covered with diffusers, and lit from above by a F32T8/SP41/U/6 lamp within an enclosure above the ceiling. The size of the openings and diffusers modeled two 2 ft x 4 ft troffer fixtures. An electronic dimming ballast (Universal Triad model B132R120V5) operated the lamp, except when the system being tested supplied its own ballast. "Daylight" was provided by a 400 W metal halide lamp (MH400/U/ED28) housed in a wall-pack fixture and coupled to a 1.5 ft x 2 ft x 1 ft white-painted box. The top third of the box was separated by a milky-white diffuser from the lower two-thirds of the box and had a black, metal shutter that was moved in and out to control the illumination on the diffuser and into lower section of the box. The lower section had an opening on the side that matched the window of the scale model. The box was placed against the window wall of the scale model to illuminate the window. A motorized mechanism moved the shutter to provide steadily increasing or decreasing "daylight" illumination over a period of approximately one hour.

Photosensors were installed one at a time in the model and on the ceiling, according to the manufacturer-supplied guidelines (if any). For products that included a special ballast that operated two lamps, a second lamp was connected and located outside the model, shielded to prevent it from affecting the light in the model. The products were set up according to manufacturer instructions with the intent to provide constant work plane illuminance. The exact illuminance set point varied from 400 to 600 lx for different products, due to the capabilities of the control and the ease of setup.

Setup and commissioning procedures were repeated until no further improvements in performance were achieved, or until eight hours of effort were expended on making the device work. Performance is defined here as a combination of maintaining the desired work plane illuminance and minimizing electrical demand. For dimming products, this corresponds to dimming to maintain a constant work plane illuminance; for switching products this corresponds to switching-off the electric lights when daylight provides the minimum required work plane illuminance and switching-on the electric lights when daylight levels fall below the desired work plane illuminance.

After a product was set up and commissioned, a day from morning to evening was simulated by slowly ramping-up the daylight from zero to a level greatly in excess of the desired work plane illuminance, followed by slowly ramping-down the daylight back to zero. The rate of increasing/decreasing daylight was approximately 100 lx per minute, which allowed the photosensor to stabilize and operate normally and to ensure time delays and response times did not influence the results. A more rapid ramp-up/ramp-down would not allow this.

Results

The results of NLPIP's photosensor evaluations are shown differently here than in previous *Specifier Reports*. Instead of listing different performance metrics and features in tabular form, each product's information and test results are displayed on a separate page, in the form of a data sheet for each product. Reasons for this change include: the photosensor products differ substantially in their design and features; few of the column headings apply to all products; and data sheets emphasize a systems approach to evaluating photosensors.

Considering the whole photosensor system is critical in order to determine how well a product will function in a given application. For example, the spatial and spectral responses influence how well a particular control algorithm will function. If adjustments to the control algorithm are possible, other qualities such as the spectral response may not be as important. The data sheet format is designed to bring the different elements of performance together, culminating with the bench test results, which reveal the overall performance for a given situation.

The data sheets for each product contain the following information:

- A short description of the product
- A photograph of the photosensor and necessary control components (excluding dimming ballast if 0-10 V compatible)
- A listing of characteristics, features, and notable observations from testing
- A graph of the open-loop response function for different setup adjustments, as given in the graph legend. For switching systems, the graph is a bar chart showing the switching light levels (and corresponding deadband) for different adjustment settings.
- A graph of the spectral response function compared to the CIE photopic standard [V(λ)]
- A 3-D plot of the spatial response with corresponding polar plots of the two indicated planes
- A graph of the bench test results

The bench test graphs show illumination levels (in lx) on the left-hand axis and control signals or power for dimming systems that include a special ballast, on the right-hand axis. For switching systems, the output state of the relay is shown on the right-hand axis. The daylight level (dark blue line) is shown as the daylight contribution to the work plane illuminance. It starts at a level of zero in the morning and ramps-up to a level in excess of 1000 lx. The electric + daylight work plane illuminance (light blue line) shows the total work plane illuminance. When daylight is zero early in the morning (and again late in the afternoon), the work plane illuminance equals the electric lighting contribution. Ideally, for dimming systems the work plane illuminance should remain constant as the daylight level increases by reductions in the electric lighting contribution. Once the lamps are fully dimmed (or switched-off) the work plane illuminance will increase by the amount that daylight increases, and indeed the lines eventually become parallel for all products. Similarly, as the daylight level decreases in the afternoon, increases in the electric lighting contribution will keep the work plane illuminance constant when the daylight contribution is less than the set point. All of the plots indicate a discontinuity near the middle of the x-axis where data was removed to expand on the relevant parts of the series where the daylight contribution was not excessive.

Conclusion

The products tested in this report vary widely in terms of features, complexity, system design, and likely cost. Available products range from simple 2-wire integral (reset) devices that connect directly with dimming ballasts to networked systems with wireless communication and interactive graphical displays. For large-scale installations the trend appears to be toward a complete control system approach in which the photosensor is part of a total lighting or even whole building control system, rather than an isolated, stand-alone product.

As made evident by this product sampling, however, being part of a feature–rich, networked system does not necessarily mean that the photosensor element will have a sophisticated or even adequate control algorithm underlying its operation. Products tested in this report that were part of a networked system had either integral or proportional control as the underlying control algorithm. Therefore, none had independent adjustment control of offsets and gains to make them fully adaptable to different installations. The bench test results demonstrate that these products perform no better than simpler products or products of 10 years ago at meeting the design criteria, constant work plane illuminance.

Nevertheless, the added features of new products can be an improvement when it comes to setting up the device and commissioning. Remote interfaces, whether from a wall-mounted switch plate, or a wireless remote, avoid the bother of climbing ladders, adjusting small potentiometers, and obstructing the sensor while making adjustments. The additional features and integration with other lighting controls makes it easier to customize a solution using several energy management strategies such as combining photosensing with occupancy sensing and load shedding. However, with these features and capabilities comes added complexity, which may lead to longer installation times and/or time invested in learning how to operate the system.

The datasheets included in this report provide a way to see the different characteristics of a particular product all together to help enforce the system concept that is so important when using photosensors. The information here is likely to be useful both when deciding what to purchase and when trying to figure out how the system works. NLPIP's research has not found a product that is an all-round winner: one that has a truly adaptable and accurate control algorithm, is scalable from a stand-alone system to a large interoperable and networked system, and is intuitive and simple to install and operate.

Data Sheets

The data sheets on the following pages provide important technical information about the photosensor products tested. These data sheets are helpful when comparing the various products and photosensor types. Each contains:

- A brief description and photograph of the photosensor
- A summary of characteristics, including control type, sensor type, minimum system components, commissioning adjustments, minimum dim level, power demand, and other information
- Various graphs, including bench test results, response function, spectral response, and spacial response
- Comments and notes, including observations by NLPIP testing staff

This information will be helpful when deciding which photosensor system to purchase and when preparing to use the system.

Data Sheet: Axis Technologies AX 232 with B-120 Sensor

This dimming ballast offers integrated photosensor dimming control. Each ballast has a sensor with a 4-foot cable. Ballasts are available in one-, two-, three-, and four-lamp versions. Three-pole DIP switches provide commissioning adjustments.

Characteristics

Control type: Integral ballast and photosensor

Sensor type: CdS cell

Works with: Axis only

Minimum system includes: Photocell and ballast

Commissioning adjustments: Three-pole DIP switch selects one of eight possible settings

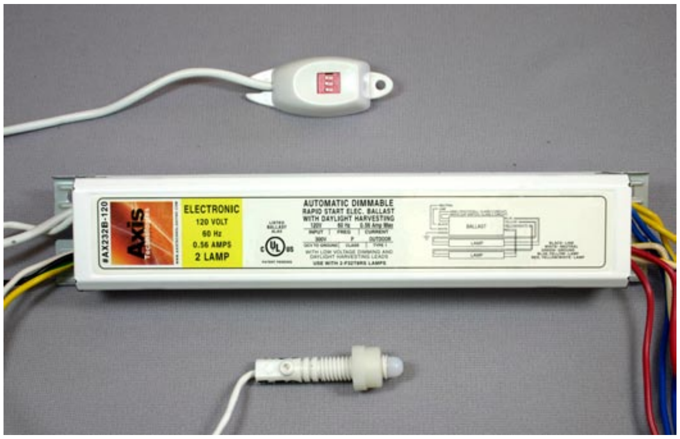
Minimum dim level: 18% of maximum light output

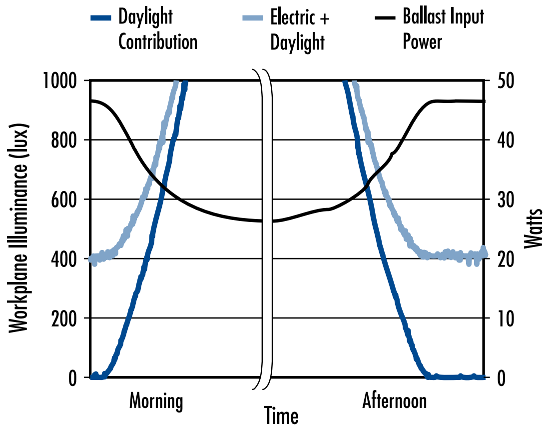
Power demand: Dimmed = 25 W (2-lamp); 100% = 68.5 W (2-lamp)

Display: None

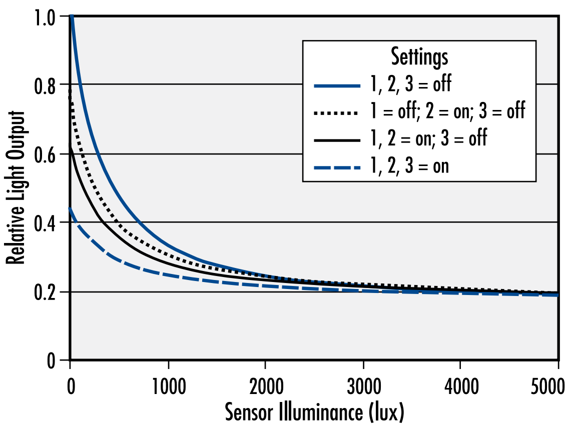
Comments/Notes

No offset in the response function results in the lamps always being dimmed when used in a closed-loop configuration. Open-loop operation is difficult due to proximity of sensor to ballast. In the bench test, the highest attainable illumination from the lamps was 400 lx; however, when not dimmed (photocell covered) the lamps produced an illuminance over 600 lx. The fixed-curve shape of the response function did not provide sufficient dimming to maintain a near constant work plane illuminance.

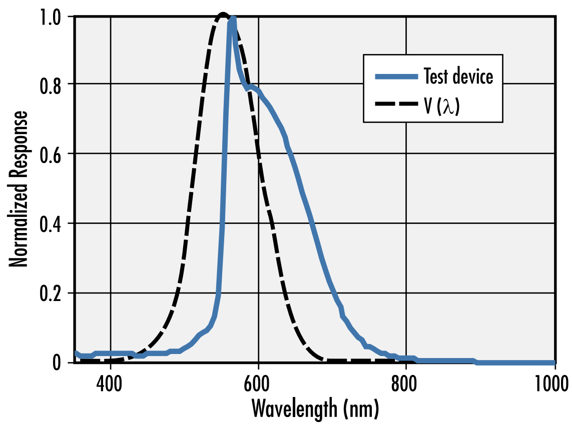




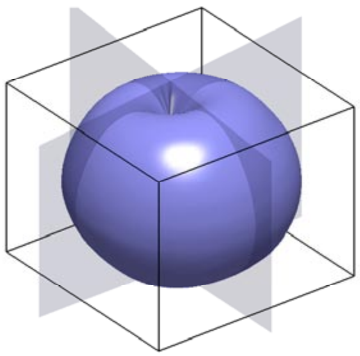
Bench Test

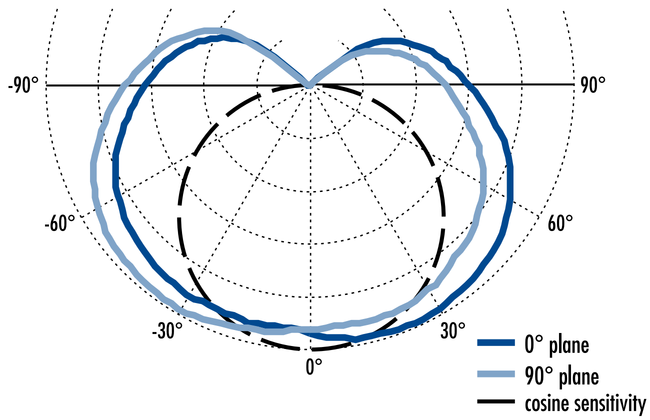


Response Function



Spectral Response





Spacial Response

Data Sheet:
Douglas Lighting Controls WPC 5621

Integrated controller and sensor for switching.

Characteristics

Control type: Switching. Requires 24 V ac power pack (power supply and relay).

Sensor type: Filtered silicon photodiode. Sensor head swivels 30 degrees within housing to allow spatial response to be centered on different directions.

Minimum system includes: 24 V dc power supply, relay module, WPC 5621

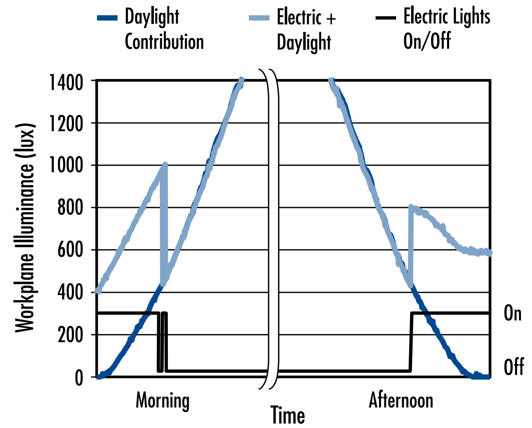
Commissioning adjustments: One analog slide control determines setpoint within the selected switching range. A second analog slide control determines the deadband by adjusting the difference between on and off switch points (see response function graph). A four-position overall range selector switch (1-30, 1-60, 1-200 and 1-500 footcandle ranges) selects the range covered by the slider controls. Two time delay settings (5-second test/setup, and 3-minute setting) are selected with a switch.

Display: Two LEDs (red and green) indicate without delay whether the photocell signal is higher, lower, or between the setpoints.

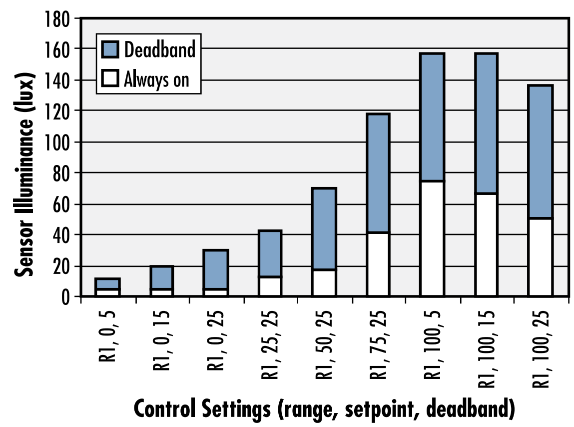
Comments/Notes

The bench test results graphs shows an extra off/on cycle in the morning, perhaps because the deadband was not set large enough. Note that the electric light level changed from morning to afternoon; perhaps the fluorescent lamps were cold when data collection was started.

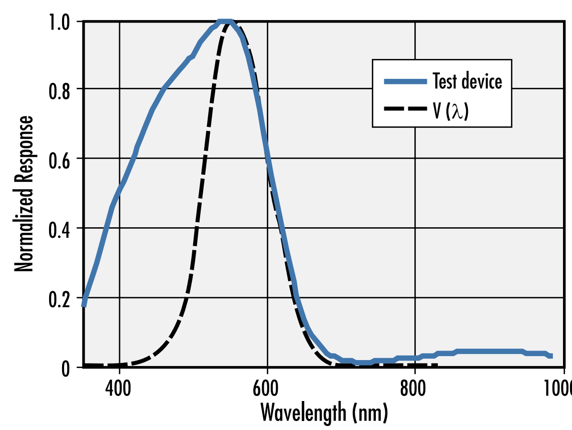
Bench Test



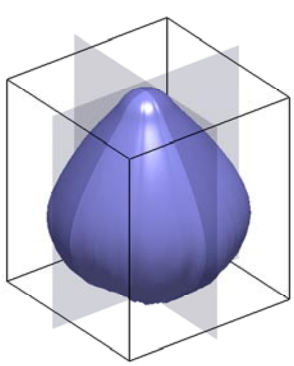
Response Function

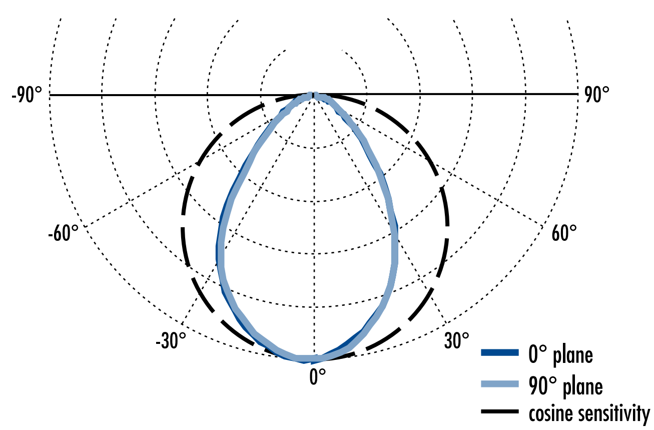


Spectral Response



Spacial Response





Data Sheet:
Douglas Lighting Controls WPC 5700

Integrated controller and sensor. This photosensor is compatible with 0-10 V dimming ballasts.

Characteristics

Control type: Dimming. Operates using 0-10 V ballast signal for power (no power pack required).

Sensor type: Filtered silicon photodiode. Sensor head swivels 30 degrees within housing to allow spatial response to be centered on different directions.

Works with: 0-10 V dimming ballasts

Minimum system includes: 0-10 V dimming ballast, WPC 5700

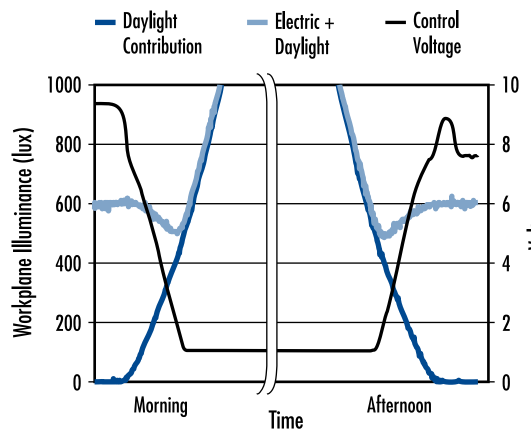
Commissioning adjustments: One analog slide control determines setpoint within the selected range for this integral (reset) type photosensor. Jumper connection selects one of two ranges. A second jumper defeats time delay for test and setup.

Minimum dim level: Ballast dependent

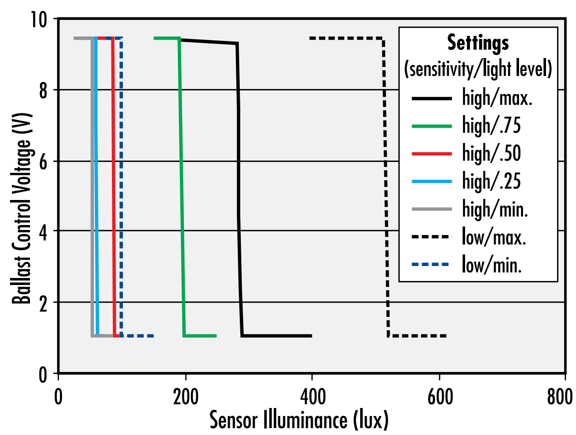
Display: None

Comments/Notes

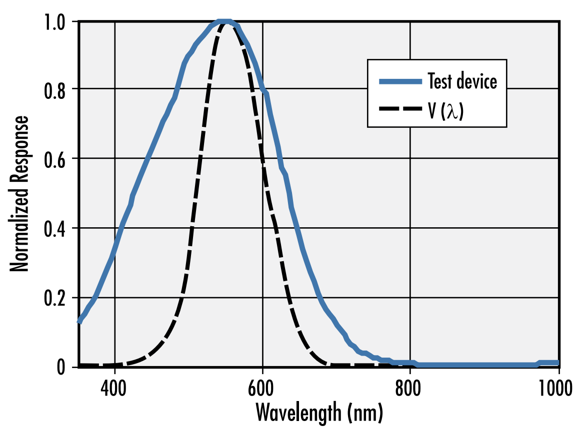
The bench test shows classic integral (reset) performance with more dimming than necessary to keep a constant work plane illuminance, but the deviation is small (20%), perhaps attributable to the fairly narrow spatial response.



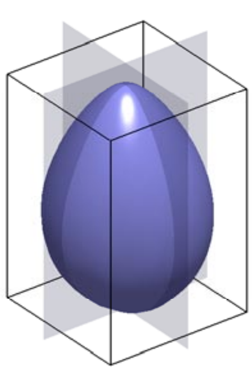
Bench Test

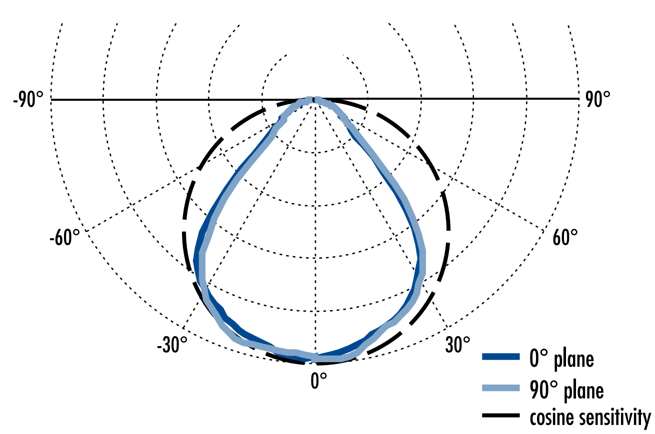


Response Function



Spectral Response





Spacial Response

Data Sheet:
Easylite 2500072 Daylite Harvester

Integrated controller and sensor. This lighting system includes dimming ballasts, photocells, controllers, and wall switch/dimmers that interface together using low voltage wiring with RJ11 connectors (telephone jacks).

Characteristics

Control type: Dimming

Sensor type: Silicon photodiode

Works with: Easylite ballasts only

Minimum system includes: Photocell, controller, and special dimming ballast

Commissioning adjustments: In lieu of conventional pushbuttons, a flashlight beam is used to communicate with the photosensor much like a wireless remote control. Flashing on-off sequences of light at the photosensor causes it to enter a calibration mode in which it ramps the electric lamps up and down. Additional on or off signals from the flashlight indicate where in the dimming ramp to capture the setpoint or setpoints.

Minimum dim level: 7% of maximum light output

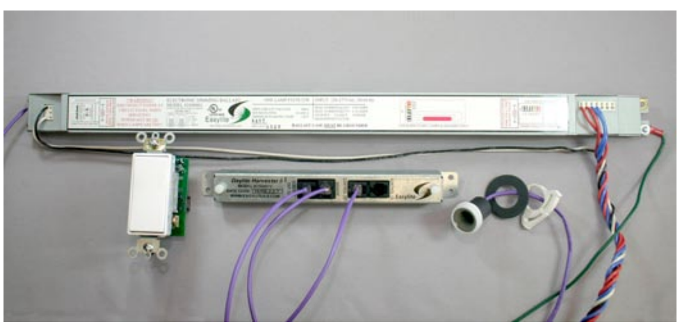
Power demand: Dimmed = 9.4 W (1-lamp, F32T8/U); 100% = 35 W (1-lamp, F32T8/U)

Display: The system flashes the electric lighting (rapid on-off cycles) to indicate entering setup mode and setup error.

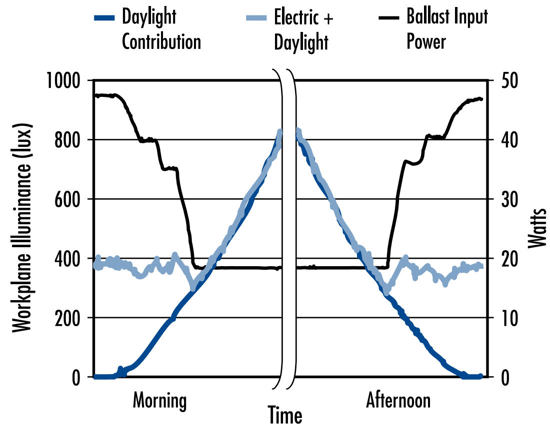
Comments/Notes

This controller apparently dims in steps as revealed in the response function graph. The bench test shows that within the dimming step size a constant work plane illuminance is achieved.

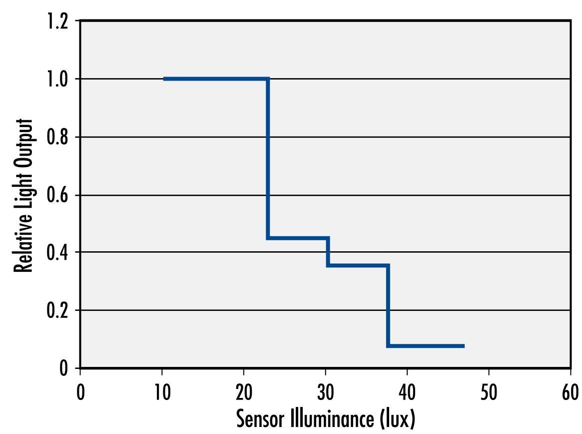
Due to the method of adjustment, the full range of response functions were not able to be determined.



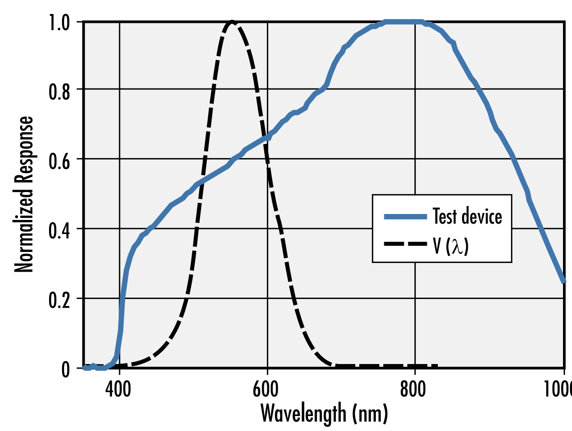
Bench Test



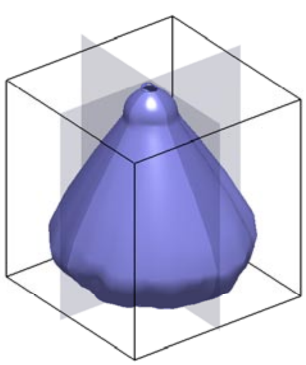
Response Function

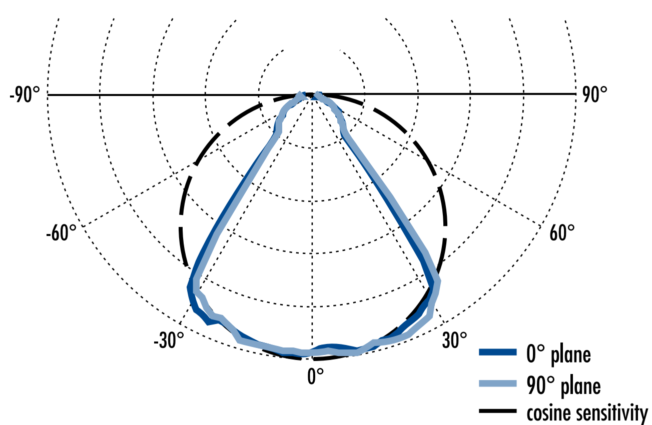


Spectral Response



Spacial Response





Data Sheet: Leviton CN100 and CN121 with ODCOP-W Sensor

This multi-function control device includes photosensor input for compatible 0-10 V dimming ballasts.

Characteristics

Control type: Dimming

Sensor type: Filtered silicon photodiode

Works with: 0-10 V dimming ballasts

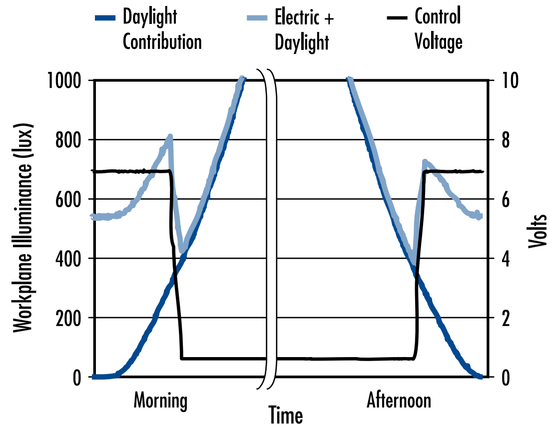
Minimum system includes: 0-10 V dimming ballast, dimming power pack (power supply and relay), dimming controller, and photocell

Commissioning adjustments: A manual dimmer and on/off switch, typically mounted in an electrical wallbox with decorator wall plate, has two nested rocker switches and a recessed button to enter the programming mode, select different menu choices and adjust the setpoint for this integral (reset) control system. A rotary switch selects device's communication address.

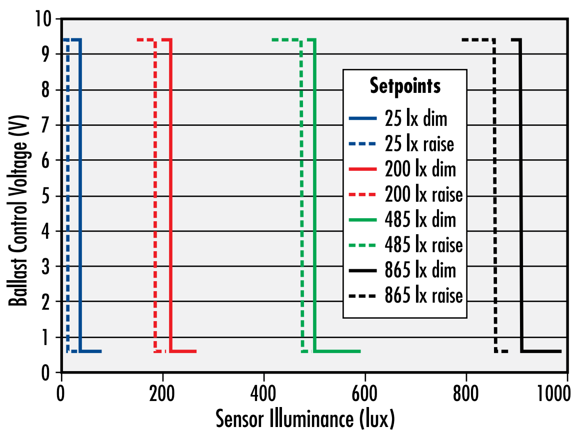
Display: Six LEDs are used to display the current programming menu/function, or work together as a level indicator. Another LED indicates communication between wall switch device and the controller and yet another shows on/off status.

Comments/Notes

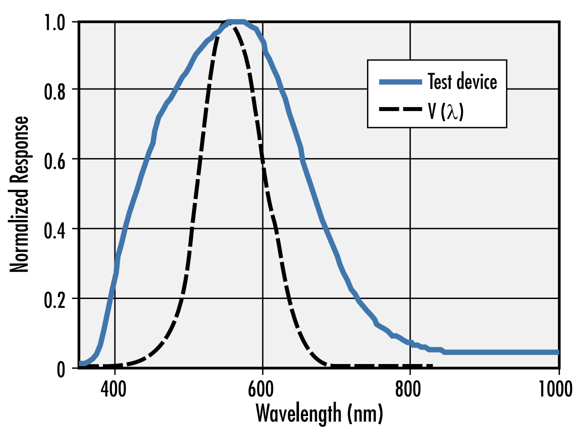
The response function reveals an integral (reset) control algorithm, but with hysteresis. The effect of the hysteresis in this case was to center the relatively large deviations in work plane illuminance about the setpoint.



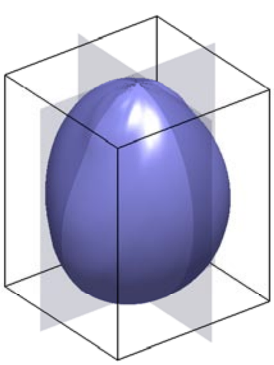
Bench Test

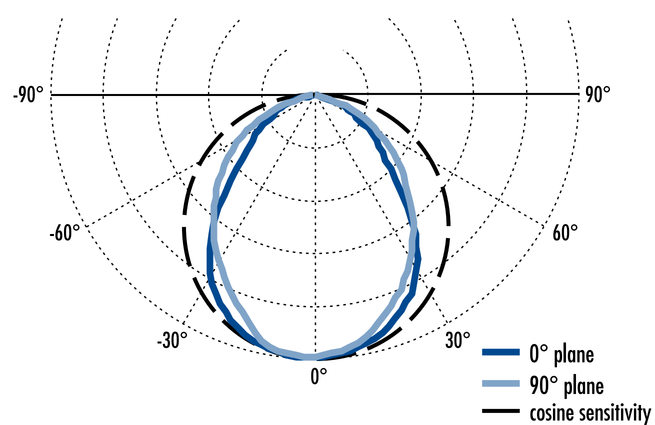


Response Function



Spectral Response





Spacial Response

Data Sheet:
Lithonia ISD DPC (ESD-PLC)

Integrated controller and sensor. This dimming photosensor is compatible with 0-10 V dimming ballasts.

Characteristics

Control type: Dimming. Operates using 0-10 V ballast signal for power (no power pack required).

Sensor type: Filtered silicon photodiode

Works with: 0-10 V dimming ballasts

Minimum system includes: 0-10 V dimming ballast, ISD DPC

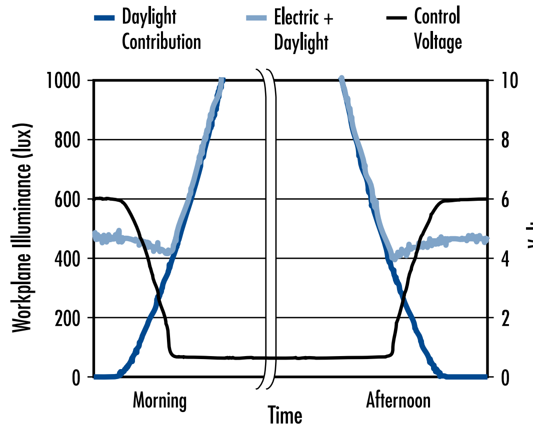
Commissioning adjustments: One multi-turn (29 revolutions) potentiometer adjusts the setpoint for this integral (reset) type photosensor.

Display: None

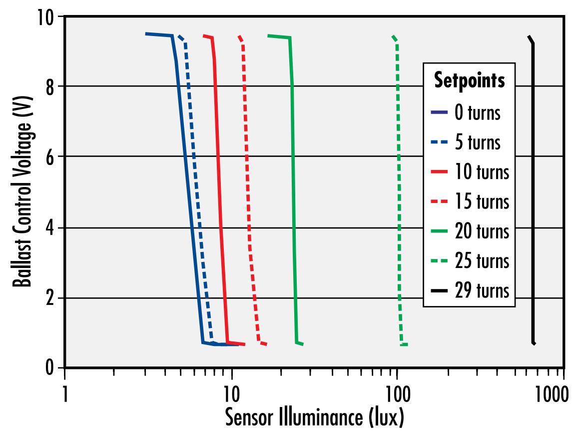
Comments/Notes

The bench test shows classic integral (reset) performance with slightly more dimming than necessary for a constant work plane illuminance. Integral (reset) control likely works well for this system due to the relatively narrow spatial response of the photocell.

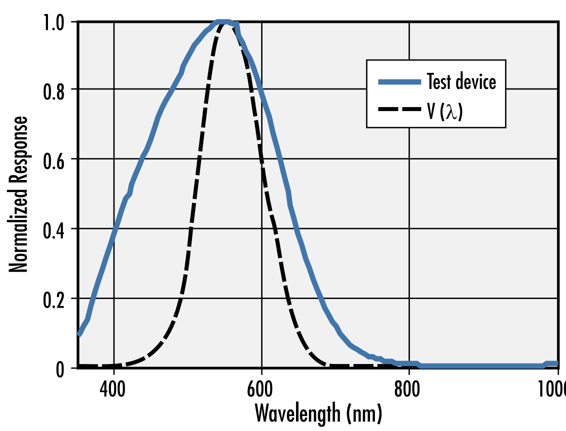
Bench Test



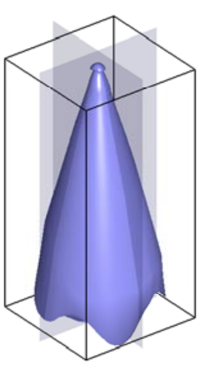
Response Function

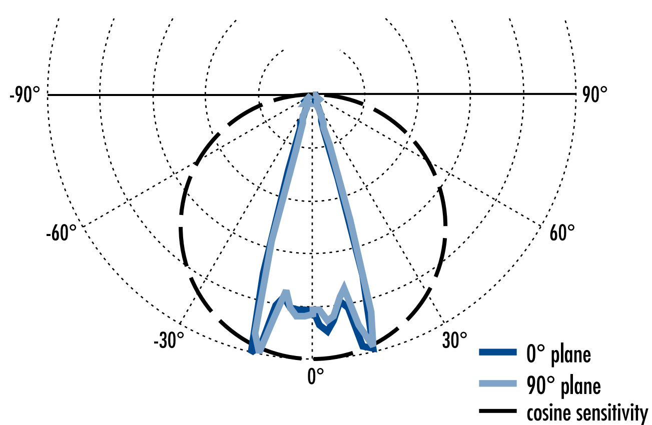


Spectral Response



Spacial Response





Data Sheet:
Lithonia Digital Equinox SYRS EXT with LSA APS IN R2 Sensor

This lighting control system includes photosensor inputs.

Characteristics

Control type: Dimming

Sensor type: Filtered silicon photodiode

Works with: 0-10 V dimming ballasts

Minimum system includes: 0-10 V dimming ballast, Synergy controller or Equinox Digital controller and power pack (power supply and relay), and photocell

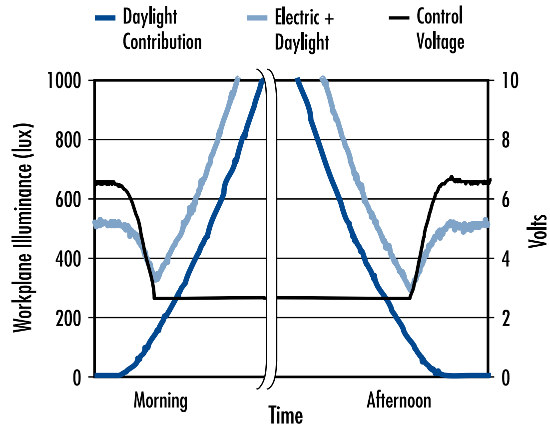
Commissioning adjustments: A manual dimmer and on/off switch, typically mounted in an electrical wall box with decorator wall plate, has three buttons to raise, dim and switch the electric lights. Behind the wall plate is a 4-pole DIP switch used to enable setup mode and store the setpoint for this integral (reset) type controller.

Display: LEDs on the raise/lower buttons flash in different sequences to indicate different errors, or illuminate without flashing to indicate successful saving of setpoint.

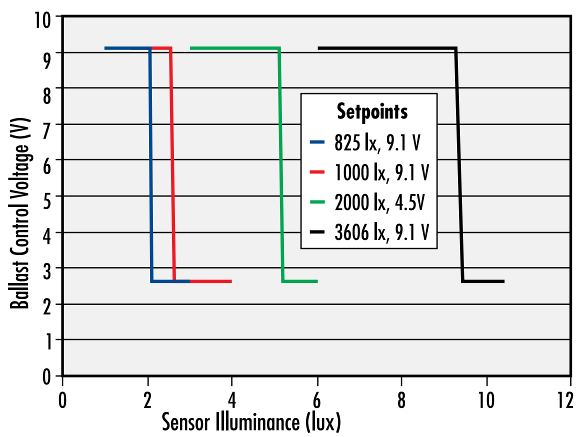
Comments/Notes

The bench test shows classic integral control performance with more dimming than necessary to maintain a constant work plane illuminance. Despite the very narrow spatial sensitivity, the sensor signal did not track the workplane illuminance well. The controller also limited the control voltage to 2.6 V, preventing full dimming.

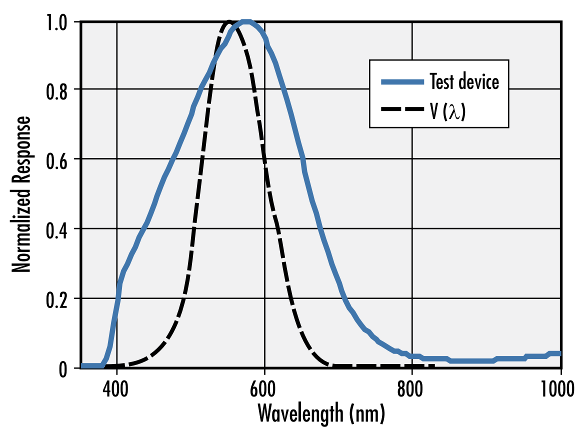
Bench Test



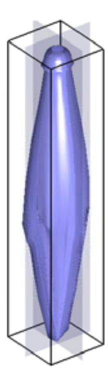
Response Function

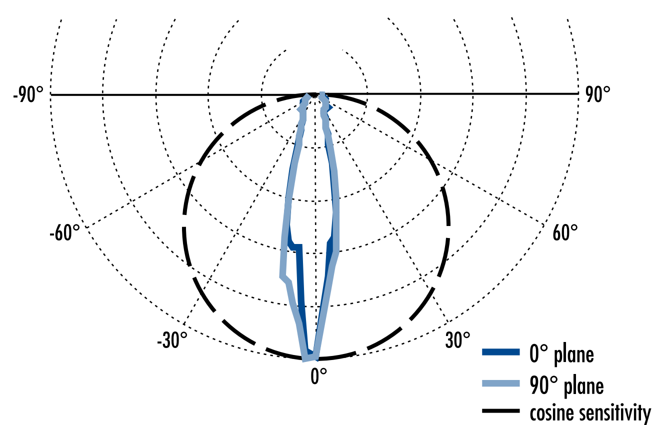


Spectral Response



Spacial Response





Data Sheet: Lutron ECO System with C-SRM1-WH Sensor

This lighting control system includes photosensor inputs and integrated dimming ballasts.

Characteristics

Control type: Dimming

Sensor type: Filtered silicon photodiode

Works with: Lutron ECO ballast, or other ballasts (when used with additional ballast interface control module)

Minimum system includes: ECO system programmer (PalmOne Tungsten PDA running Lutron's proprietary control application), ECO system bus supply (provides power to system), ECO system digital ballast, Eco daylight sensor (photocell)

Commissioning adjustments: Menu-driven graphical user interface displayed on PDA guides user through setup and commissioning procedures and provides manual dimming and on/off switching. The gain for this proportional controller is set by using the PDA to dim the electric lights and indicate the desired level, at which point the system calculates and stores the gain setting.

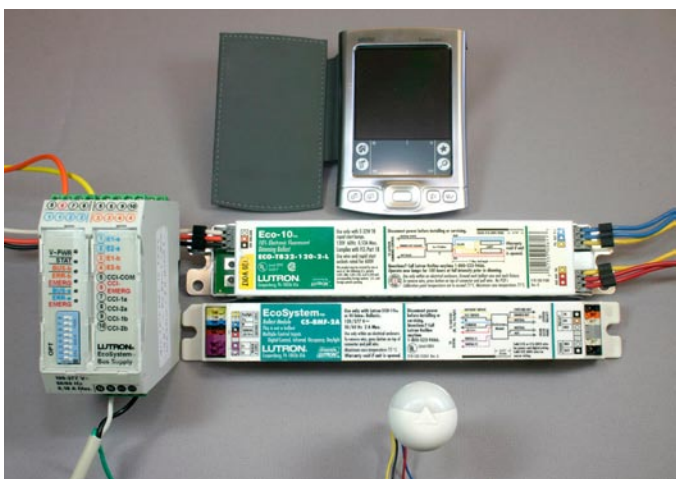
Minimum dim level: 13%

Power demand: Dimmed = 23.7 watts; 100% = 70.9 watts (for two 32 W T8 lamps)

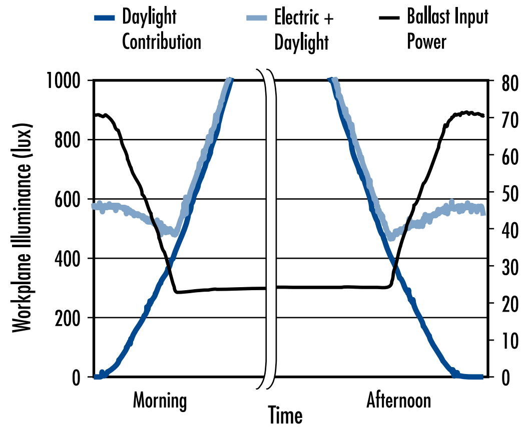
Display: PDA LCD screen

Comments/Notes

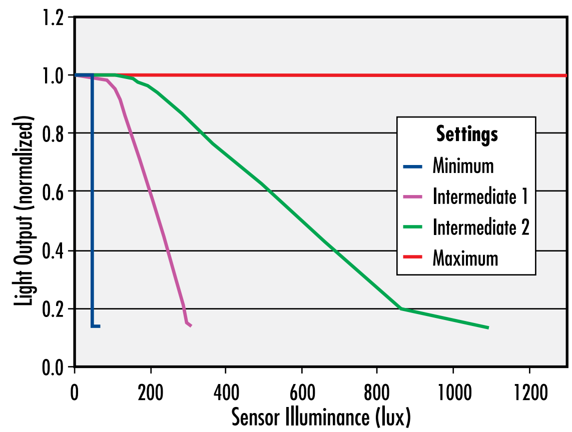
The proportional control algorithm provides some offset, giving it characteristics of a closed-loop proportional control, but the offset is not adjustable.



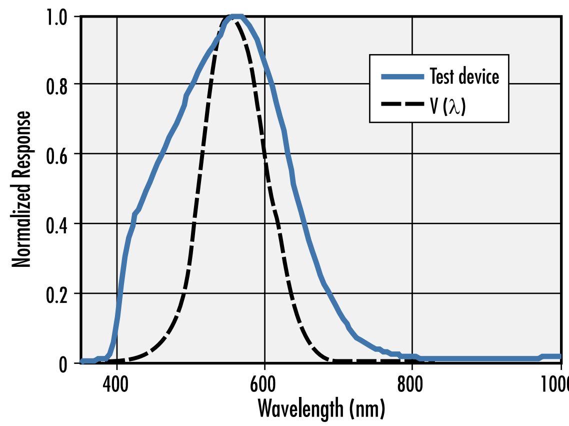
Bench Test



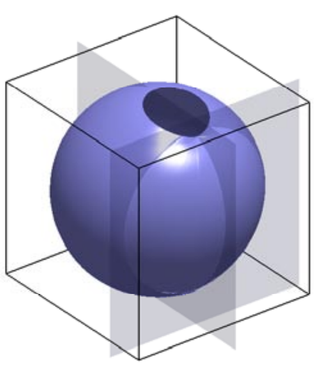
Response Function

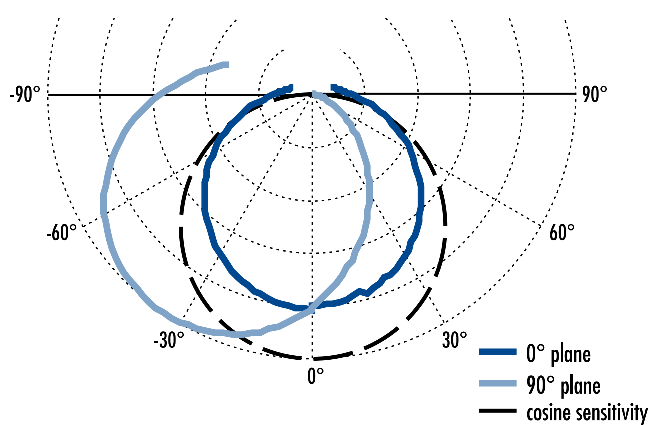


Spectral Response



Spacial Response





Data Sheet: Novitas 02-PCC with 01-PCI (indoor) Sensor

This controller and sensor is for on/off lighting control.

Characteristics

Control type: Switching.

Sensor type: CdS cell

Minimum system includes: 24 V dc power supply, relay module, 02-PCC and 01-PCI sensor

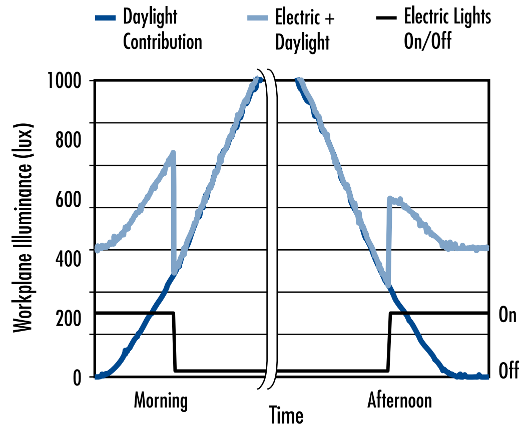
Commissioning adjustments: Two 3/4–turn potentiometer knobs adjust high and low setpoints. Slide switch overrides sensor control and switches lights on. The adjustments are not independent of one another, i.e. adjusting the high setpoint affects the low setpoint. This is demonstrated in the response function graph that shows the top and bottom deadband limits varying widely when only one knob is adjusted.

Display: Two LED indicators, one associated with each potentiometer adjustment, indicate switching thresholds. The LEDs do not indicate Boolean logic states (on or off), but rather the user is instructed to interpret their intensity and flicker rate.

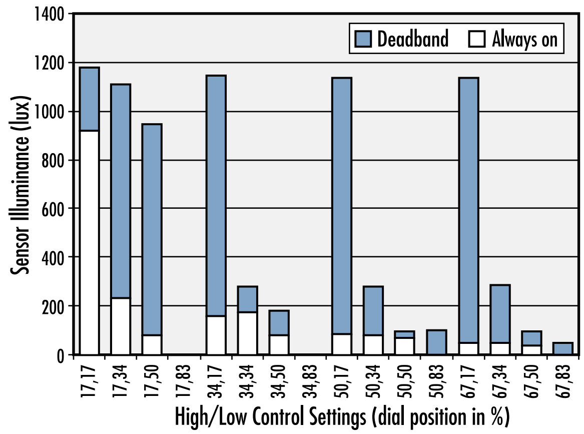
Comments/Notes

A significant portion of the adjustment knob settings produce conditions where the electric lights either never turn off or never turn on.

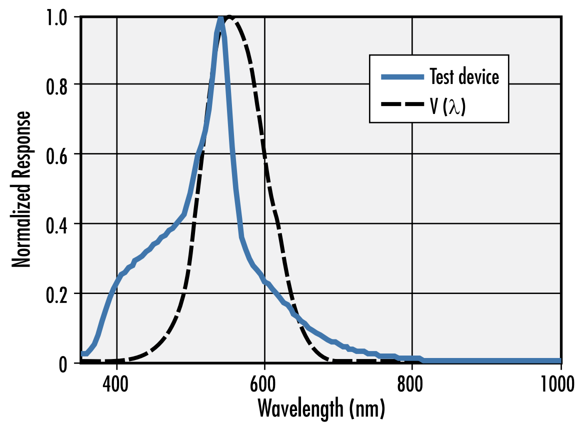
Bench Test



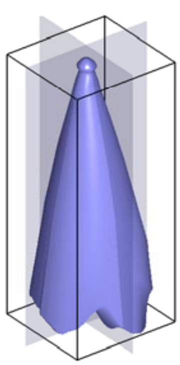
Response Function

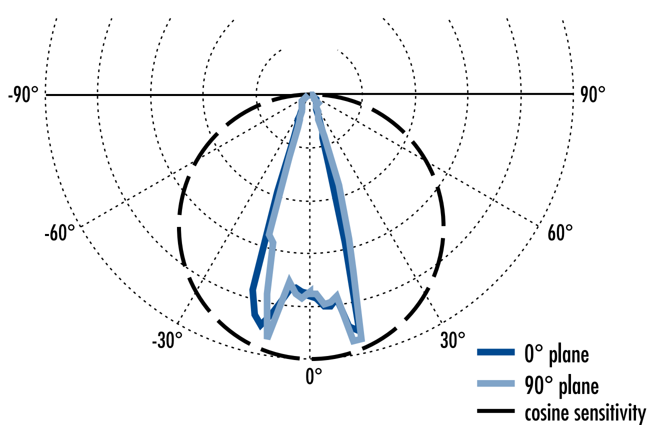


Spectral Response



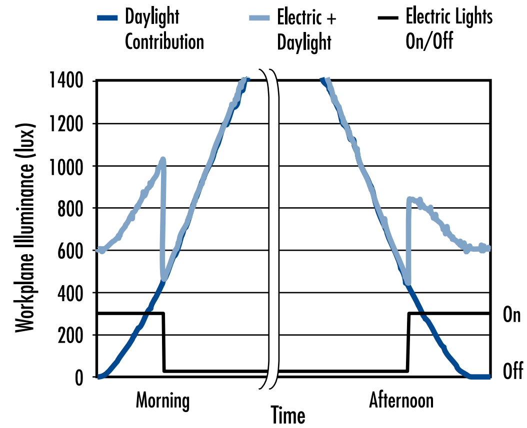
Spacial Response





Data Sheet:
PLC-Multipoint LCM-12 with CES Sensor

Controller and sensor for on/off lighting control of multiple control zones.



Bench Test

Characteristics

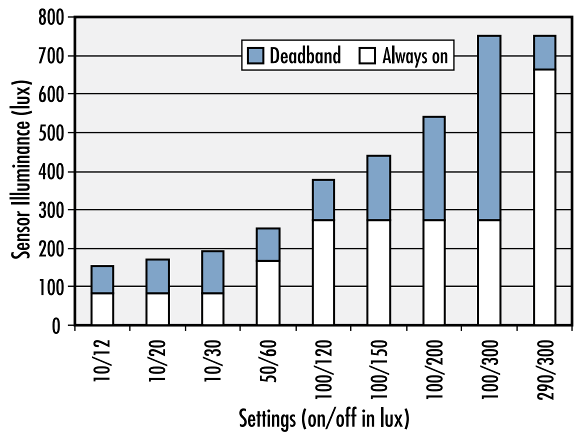
Control type: Switching

Sensor type: Filtered silicon photodiode

Minimum system includes: LCM-12 controller, 24 V dc power pack (power supply and relay), CES photocell

Commissioning adjustments: Fully independent high and low setpoints are numerically entered using six buttons and LCD display. Photocell is factory calibrated so values are displayed and entered in units of lux.

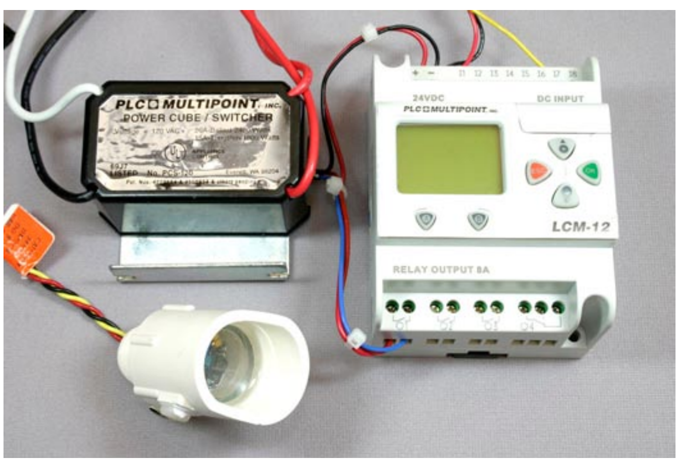
Display: Four-line alpha-numeric LCD displays current photocell reading, entered values, status and setpoint values.

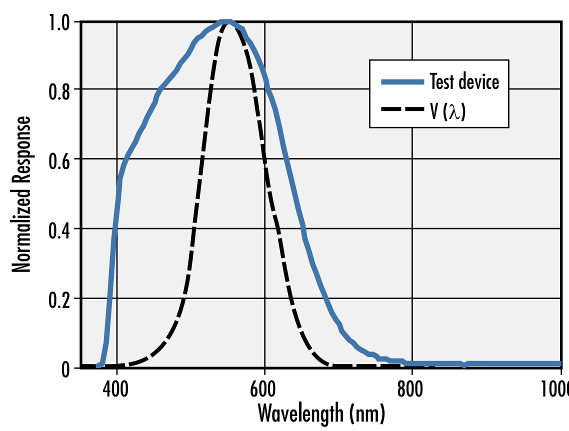


Response Function

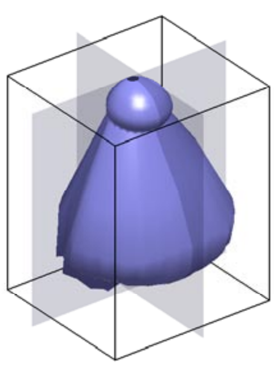
Comments/Notes

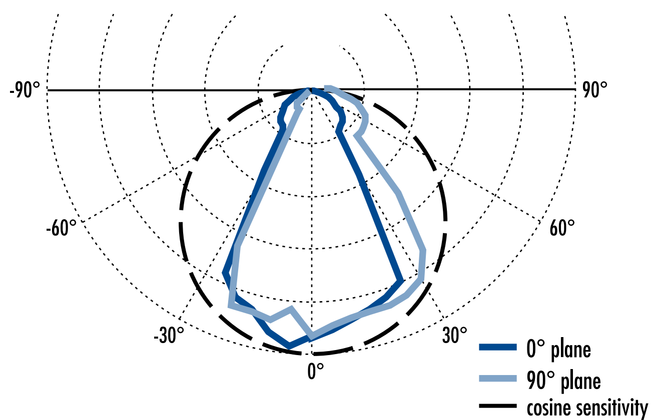
Note that switching and deadband values shown on response function graph do not coincide with values displayed on controller. This is most likely due to differences in the spectral power distribution of the source used to obtain the response function graph (metal halide lamp) and that used to calibrate the photocell (unknown). Nevertheless, the values are roughly in the correct proportions.





Spectral Response





Spacial Response

Data Sheet: SensorSwitch CM-PC-ADC

Integrated controller and sensor. This photo-sensing controller is for either 0-10 V compatible dimming, on/off switching, or combined dimming and switching.

Characteristics

Control type: Switching or dimming

Sensor type: CdS cell

Works with: 0-10 V ballasts for dimming; any load for switching

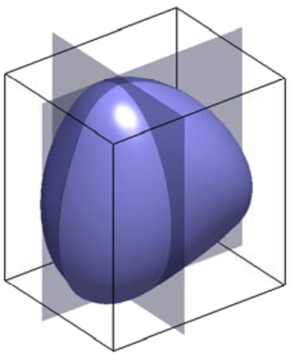
Minimum system includes: Switching = photosensor, 15 to 24 V dc power pack (power supply and relay); Dimming = photosensor, 15 to 24 V dc power supply.

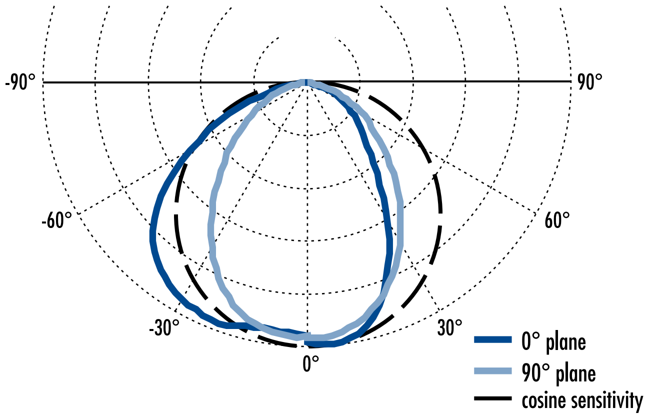
Commissioning adjustments: A single button is pressed repeatedly according to particular codes to enter different programming modes. Numeric values for the setpoint of this integral (reset) control are entered by repeatedly pressing the button a specific number of times for each digit of the number. Values are indicated in units of footcandles. When used as a switching photosensor a single setpoint is entered as described above and an automatically determined deadband is applied (see response function graph.) For the bench test, the automatically determined deadband was not sufficient to eliminate on/off oscillations during certain times during the simulated morning and evening.

Display: A single LED flashes different sequences to indicate programming modes and echo the number of button presses for confirmation.

Comments/Notes

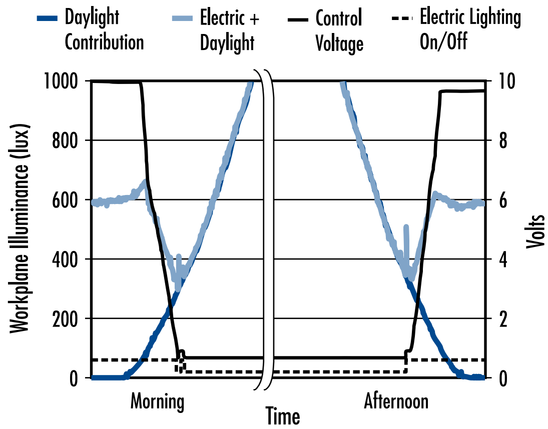
The unique feature of this product is that it dims the electric lights and then switches them completely off as daylight levels increase. The integral control algorithm, however, contributes to make the work plane illuminance fall well below the setpoint. On/off oscillations occurred both in the morning and afternoon indicating an insufficient deadband even with the electric lights being fully dimmed when the switching takes place. Note that switching and deadband values shown on response function graphs do not coincide precisely with entered setpoint values (in units of footcandles). This is most likely due to differences in the spectral power distribution of the source used to obtain the response function graphs (metal halide and T8 fluorescent) and that used to determine the factory footcandle calibration (unknown). Nevertheless, the values are roughly in the correct proportions.



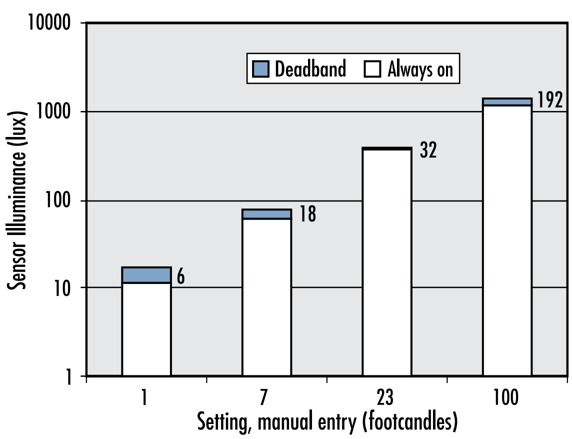


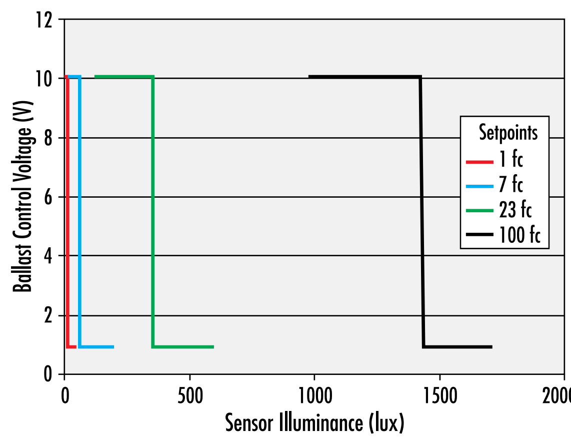
Spacial Response

Bench Test

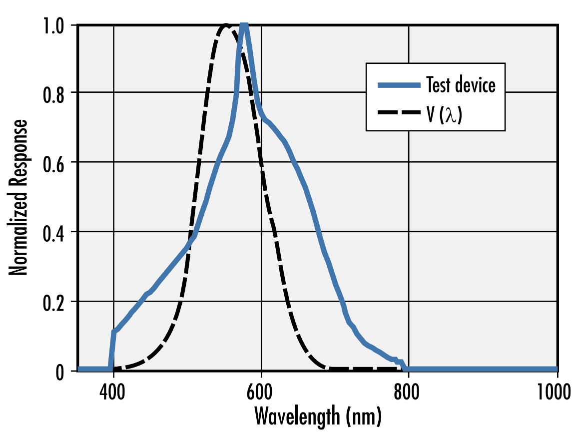


Response Function





Spectral Response



Data Sheet:
Watt Stopper LCD-203 with LS-290C Sensor

This controller and sensor system controls up to three zones of dimming.

Characteristics

Control type: Dimming

Sensor type: Filtered silicon photodiode

Works with: 0-10 V compatible ballasts

Minimum system includes: 24 V dc power pack (power supply and relay), LCD-203, LS-290C sensor

Commissioning adjustments: One to three zones each with independent gain adjustment set via four pushbuttons that interact with LCD display. Photocell has three ranges of sensitivity (jumper selected). Gain adjustment process allows user to raise or dim electric light output of zone to desired level and then automatically captures corresponding photocell reading and ballast control signal level to arrive at appropriate gain setting.

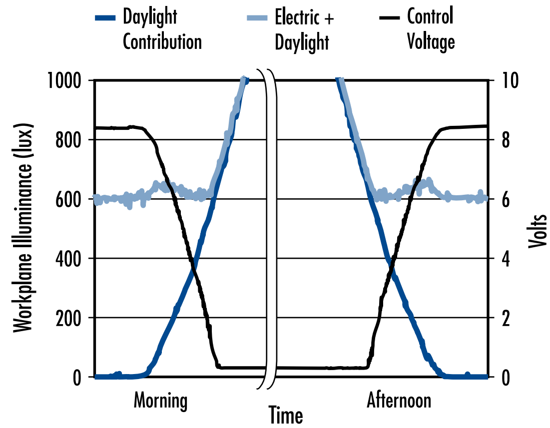
Minimum dim level: Ballast dependent

Display: Two-line alpha-numeric LCD display that shows status, adjustment settings, and diagnostic information.

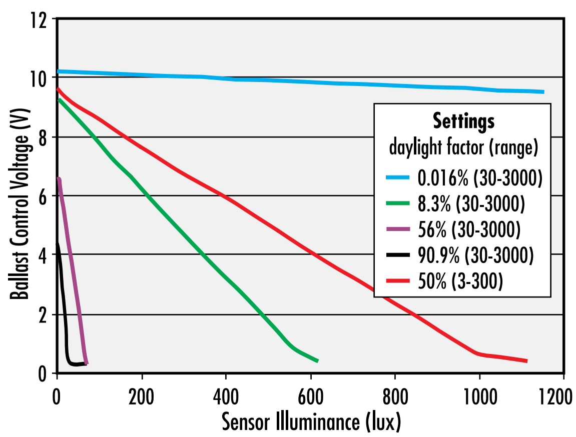
Comments/Notes

The response function is classic open-loop proportional control; however the y-intercept is slightly negative, meaning that for very high gain settings (large daylight factors) the full light output will never be attained, even with a completely dark photocell.

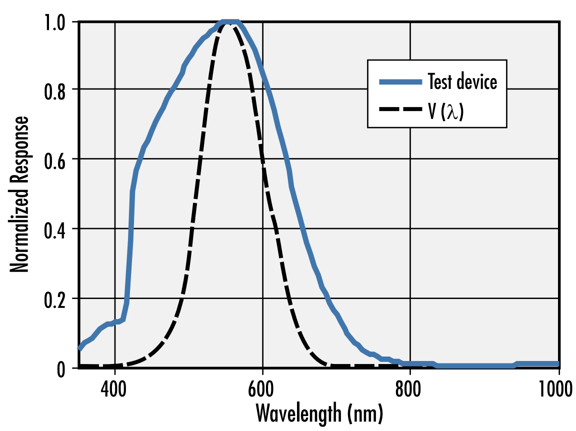
Bench Test

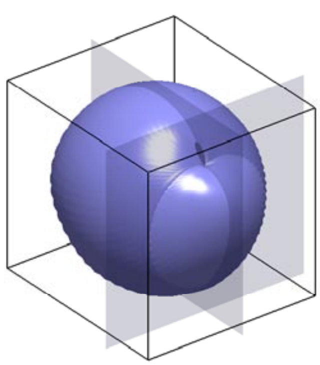


Response Function

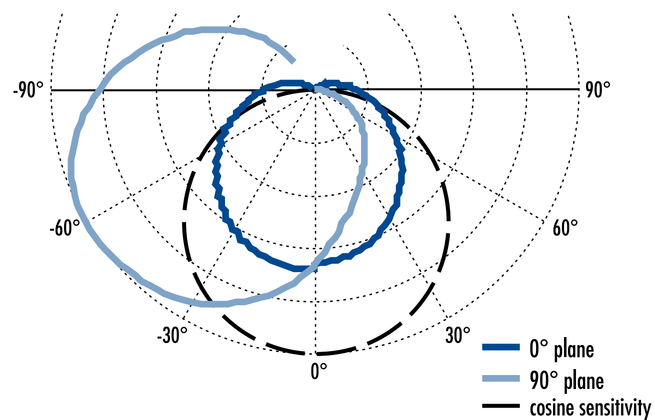


Spectral Response





Spacial Response



Data Sheet: Watt Stopper LCO-203 with LS-290C Sensor

This controller and sensor controls up to three zones of on/off lighting.

Characteristics

Control type: Switching

Sensor type: Filtered silicon photodiode

Works with: 0-10 V dimming ballasts

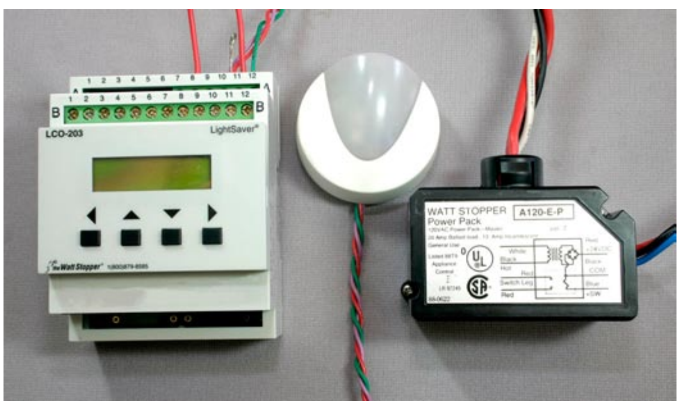
Minimum system includes: 24 V dc power supply, relay module, LCO-203, LS-290C sensor

Commissioning adjustments: One to three zones each with independent adjustments set via four pushbuttons that interact with LCD display. Photocell has three ranges of sensitivity (jumper selected). The user must first establish the gain setting relating the photocell signal to the work plane illuminance (see gain setting for LCD203, p. 46). Next, the lower setpoint is entered numerically in terms of work plane illuminance using the buttons and LCD display. The deadband is then entered as a percentage of the lower setpoint. On and off time delays can be entered numerically, ranging from 0 to 60 seconds and 3 to 60 minutes respectively.

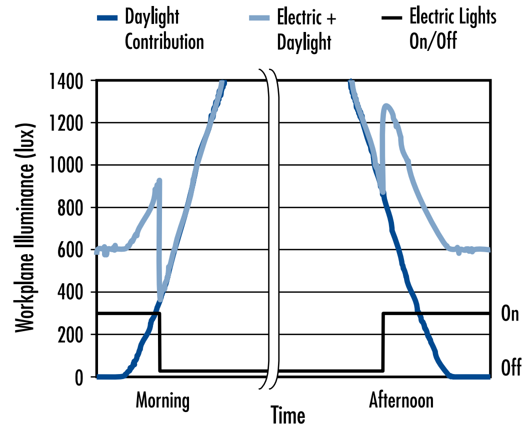
Display: Two-line text and numeric LCD display. Shows status, adjustment settings, and diagnostic information.

Comments/Notes

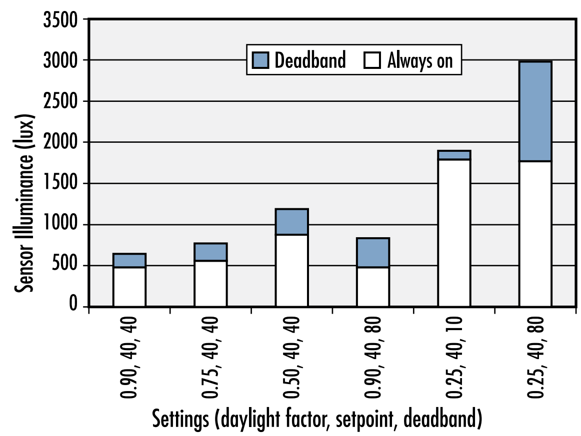
The bench test results show an asymmetry in the morning and afternoon switch points for which NLPIP has no explanation.



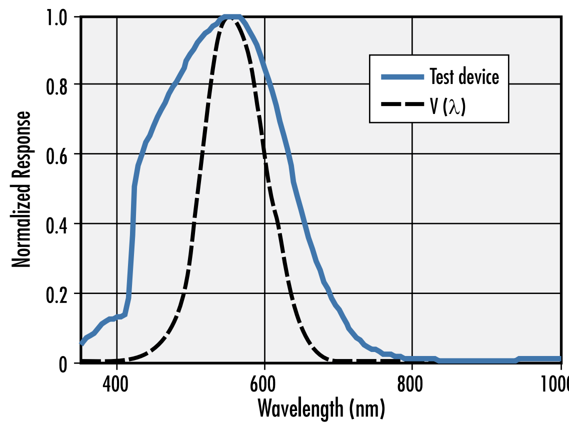
Bench Test



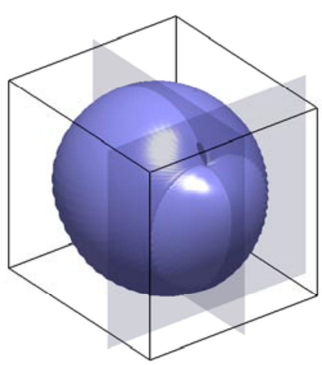
Response Function

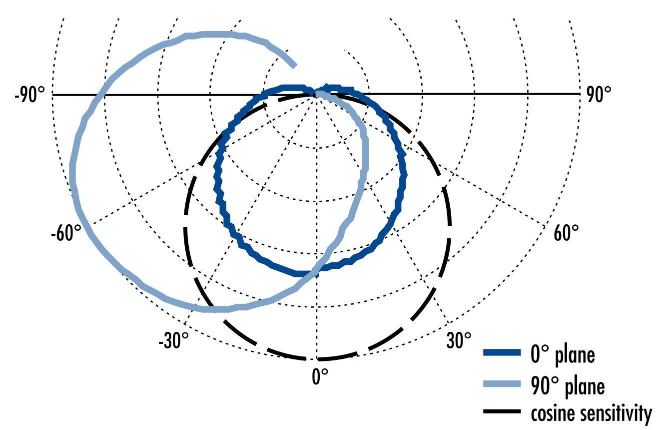


Spectral Response



Spacial Response





Data Sheet: Watt Stopper LS-301

Integrated controller and sensor. This photosensor is compatible with 0-10 V dimming photosensors.

Characteristics

Control type: Dimming

Sensor type: Filtered silicon photodiode

Works with: 0-10 V compatible dimming ballasts

Minimum system includes: LS-301 photosensor, handheld remote control, 24 V dc power pack (power supply and relay)

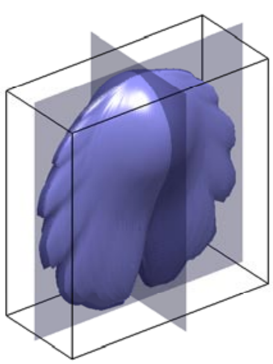
Commissioning adjustments: All adjustments are made using handheld infrared remote control. Remote has five buttons: two raise and lower electric light level and allows manual override, one stores night setting, one stores day setting, and one starts automatic control. This sliding setpoint control algorithm requires setup to be done under two conditions: at night or with no daylight present, and with daylight present. For each condition, the settings are made by raising or dimming the electric lights to the desired level and pressing the day or night button on the remote.

Display: A red LED in the photosensor flashes different sequences indicating communication and setpoint capture. An amber LED in the photosensor indicates incomplete or improper setup.

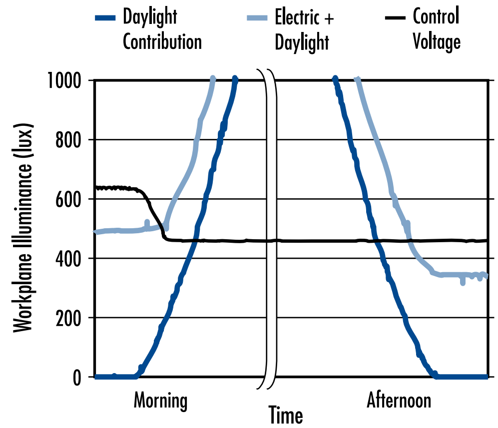
Comments/Notes

Despite being the only product that offers a true closed-loop proportional control algorithm, the bench test results show unsymmetrical morning/afternoon results. The controller did not raise the electric light level in the afternoon to maintain the setpoint. Also, the response function graph indicates that when the photocell illuminance exceeds approximately 2000 lux (an unlikely high light level) the controller returns the electric lights to full output.

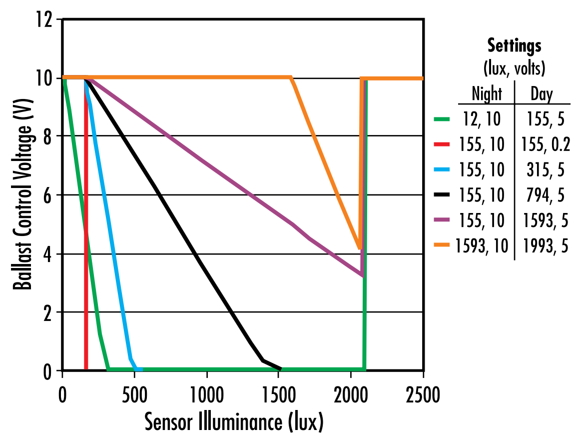
The photocell employs a dichroic filter for precise photopic match for on-axis illumination. However, under realistic conditions with light incident from all angles, the photopic match is not as ideal due to the angular dependence of the filter, but it is still the most accurate of those tested.



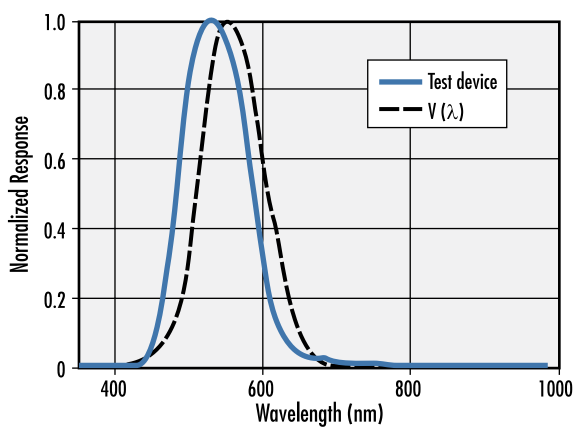
Bench Test



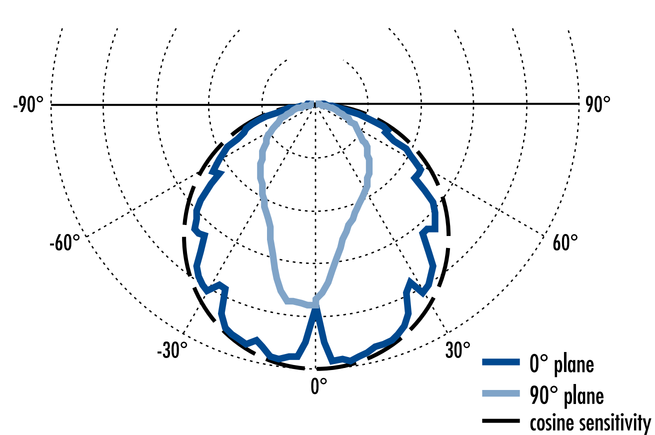
Response Function



Spectral Response



Spacial Response



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Manufacturers' Information

Company	Web site	Telephone
Axis Technologies, Inc.	www.axistechnologyinc.com	(866) 458-9880
Douglas Lighting Controls, Inc.	www.douglaslightingcontrols.com	(877) 873-2797
Easylite Lighting Systems	www.easyliteils.com	(303) 786-7470
Leviton Manufacturing Co.	www.leviton.com	(800) 736-6682
Lithonia Lighting - Acuity Brands	www.lithonia.com	(770) 922-9000
Lutron Electronics Co., Inc.	www.lutron.com	(888) 588-7661
Novitas	www.novitas.com	(800) 553-3879
PLC-Multipoint, Inc.	www.plcmultipoint.com	(866) 998-5483
Sensor Switch, Inc.	www.sensorswitch.com	(800) 727-7483
Watt Stopper/LeGrand	www.wattstopper.com	(488) 988-5331

Photosensors

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Specifier Reports

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National Lighting Product Information Program Publications

Guide to Fluorescent Lamp-Ballast Compatibility, 1996
Guide to Specifying High-Frequency Electronic Ballasts, 1996
Guide to Selecting Frequently Switched T8 Fluorescent Lamp-Ballast Systems, 1998

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Power Reducers, 1992; *Specular Reflectors*, 1992; *Cathode-Disconnect Ballasts*, 1993; *Exit Signs*, 1994; *Reflector Lamps*, 1994; *CFL Downlights*, 1995; *HID Accent Lighting Systems*, 1996; *Occupancy Sensors*, 1998; *Photosensors*, 1998; *Lighting Circuit Power Reducers*, 1998; *Screwbase Compact Fluorescent Lamp Products*, 1999; *Energy-Efficient Ceiling-Mounted Residential Luminaires*, 1999; *Dimming Electronic Ballasts*, 1999; *Electronic Ballasts*, 2000; *Parking Lot and Area Luminaires*, 2004; *Low-wattage Metal Halide Lighting Systems*, 2006

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