

**Development and Demonstration  
of an Improved, Energy-Efficient,  
Photosensor Lighting Control**

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**Final Project Report**

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## **Executive Summary**

The Lighting Research Center (LRC) conducted a two-year project to develop, demonstrate and evaluate an improved daylight photosensor for private office lighting applications. The goal of the project is to demonstrate a device that overcomes the installation, commissioning and performance barriers associated with current photosensors on the market, and save an average of 30% of the energy used for lighting windowed offices. The first year of the project was devoted to technology development of a self-commissioning photosensor and the manufacture of prototypes for evaluation. The prototypes developed during the first year were evaluated in a small-scale demonstration of the technology consisting of 10 private offices, two at the LRC and eight in Connecticut. The final phase of the work involved raising market awareness of the device through technology transfer activities and working with lighting controls manufacturers to foster commercialization of the technology.

Fifteen prototype devices were made with assistance from Sensor Switch, Inc., a Connecticut controls manufacturer, with whom the LRC had negotiated an agreement offering free licensing of the technology in exchange for manufacturing assistance. The prototype devices feature a two-component system architecture consisting of a control unit that replaces a standard wall switch, and a remote, wireless sensor. The photosensor utilizes a digital microprocessor that automates the commissioning procedure, resulting in minimal user involvement and a commissioning time of less than 2 minutes in most cases. The innovative control algorithm separates user preference adjustability from the commissioning process, thereby enabling commissioning to be done once, while user adjustments customizing the aggressiveness of the dimming can easily be changed at any time. The aim is to increase occupant satisfaction with automatic photoelectric dimming control by not over-dimming, and giving the occupant some control over the illumination level. This report details the design of this LRC photosensor prototype.

The results of the six-month demonstration/evaluation showed an average office energy savings of 29% with the photosensor compared to a manual on/off switch. The offices in the evaluation were purposely chosen to exhibit a range of different conditions including window size, daylight exposure and office layout. Consequently, the energy savings varied widely from office to office, ranging from near zero energy savings to energy savings over 60% in some offices. Occupant satisfaction with the photosensor was very high with no occupants complaining of inadequate light levels. Most occupants reacted favorably to the photosensor, while the rest were indifferent, indicating that the energy savings did not come at the expense of occupant satisfaction.

Commercialization efforts are underway with interest from Sensor Switch and two other manufacturers. The LRC pursued a U.S. patent covering the developed technology with the aim of keeping the technology available for commercialization and further development; this patent is expected to be issued by August 2003. Market awareness activities include a featured section on the LRC website, a trade magazine article, presentation at international trade show (Lightfair International 2003), numerous presentations to LRC visitors and LRC partners, and a technical paper is planned for submittal to a peer-reviewed journal later this year.

## **1. Project Background**

Photosensors for interior lighting control have had very little market penetration over the 20 years or more of their commercial availability. Presently, sales of photosensors account for less than 1% of the total revenue generated from lighting controls in the U.S.<sup>1</sup> This is despite numerous case studies showing energy savings up to 50% or more depending on daylight availability and the use of other lighting controls such as occupancy sensors and manual dimmers. What remains to be determined is not whether photosensors can save significant amounts of energy, but rather, if the technology can be implemented cost effectively. The main barrier for photosensor use, gleaned from previous LRC studies<sup>2</sup>, is an economic quandary between market demand and investment in technology development. Distrust in the technology from previous bad experiences and the risk involved with using an unproven technology create little market demand for products. Small market demand, in turn, prevents technological development because manufacturers will not invest in technology development that is perceived to have little market demand.

As the case for daylighting is becoming stronger, the desire to have controls that can take advantage of the energy saving and peak demand-limiting benefits of daylighting is also increasing. Changes in the way electric power is sold as a result of utility restructuring and increasing environmental concerns are refocusing efforts on ways to limit energy use and peak demand. This is likely to increase interest in photosensors and provide a new economic model for their use. Enabling technologies such as lower-cost dimming ballasts with improved control interfaces and the likely emergence of load-shedding dimming ballasts are also contributing to more interest in photosensors.

This project is concerned with developing photosensor technology that is cost effective to implement, and which can be consistently implemented from case to case with reliable operation. Technology development at this stage, along with demonstrations, is intended to increase market awareness and interest in photosensor controls by demonstrating concepts and applying technology that might otherwise be overlooked. This should spur further technology investment by commercial manufacturers, resulting in better products and more widespread use of photosensors.

## **2. Project Objectives and Design Goals**

The goal of this project is to develop a prototype photosensor for small, private office type spaces using fluorescent lighting, and evaluate its performance in a field demonstration. Previous investigations of photosensor performance at the LRC provided knowledge of the technological barriers preventing their wider use. The areas of photosensor technology receiving the most attention in this project are the photosensor control algorithm, the commissioning procedure, and the ease and cost of installation. The guiding design principles are:

- A control algorithm favoring universal applicability over precision
- Acknowledge that occupants' lighting needs are the top priority, and that dimming and switching off the electric lighting is of secondary importance

- Provide the occupant a means for light level adjustment independent of commissioning
- Automate the commissioning process as much as possible to ensure that it is done properly and inexpensively
- Minimize installation cost and difficulty

Note that even though energy savings is not explicitly stated above, it is assumed that the only reason for installing photosensors is to reduce energy use and/or electrical demand. It is difficult to make specific energy saving goals for photosensors because such savings are heavily dependent on the conditions at the particular installation site or sites, such as the available daylight, the occupants' lighting needs, the type of lighting equipment, and the presence of other controls. Nevertheless, a goal of the project is to show a 30% average energy savings at the evaluation sites compared to manual on/off control. While electrical demand savings may be equally important, it is difficult to quantify in economic terms and so demand savings is not explicitly stated as a project goal.

### **3. Design Characteristics**

#### **3.1 Overview**

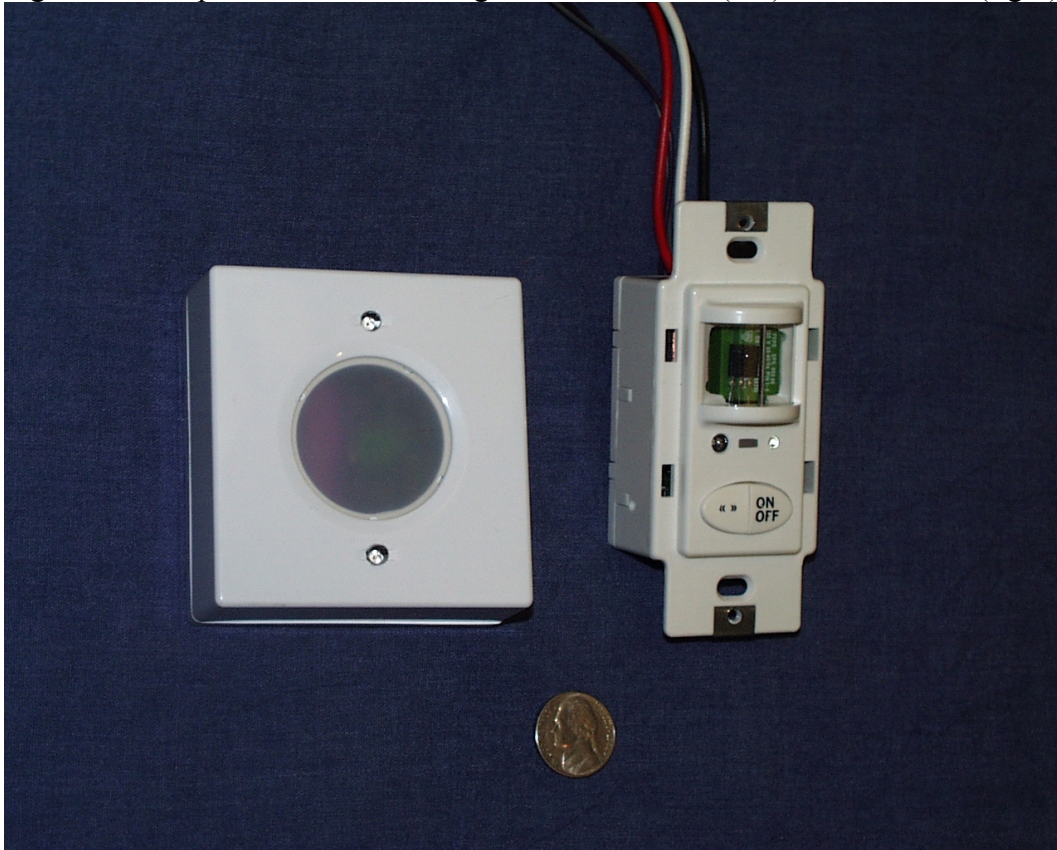
The LRC photosensor consists of two separate devices: a wall-switch controller and a remote, wireless sensor. Figure 1 shows a photograph of the two devices. The wall-switch controller, installed in an electrical gang-box, replaces the traditional light switch located near the entrance of a room. The wall-switch controller receives power and is connected to the dimming ballasts in the room via the power line wires and dimming control wires brought to the electrical gang-box. The wall-switch controller can then control the dimming of the fluorescent lighting as well as switch the power supplied to the dimming ballasts for on/off control. The wall-switch controller also incorporates a manual on/off switch, a user preference/override input button, and three LED status indicators.

The remote sensor is a wireless, self-powered device that senses and transmits light level information to the wall-switch controller via an infrared optical transmitter. The wall-switch controller receives the transmitted signals, processes the information according to the programmed control algorithm, and dims and/or switches the fluorescent lighting. The remote sensor also transmits a simple commissioning instruction when a button on the device is pressed, initiating the commissioning process.

#### **3.2 Remote Sensor**

A remote, wireless sensor was chosen for two reasons. When commissioning, the sensor provides a means for measuring light levels at the workplane without requiring an illuminance meter or additional light sensors. This also eases installation hardships by avoiding the need to run wires to a ceiling location, allowing the sensor to be placed at an optimal or more easily accessed position.

Figure 1. LRC photosensor consisting of remote sensor (left) and controller (right).



From a system architecture approach, separating the sensor from the controller allows easier integration of different control/energy saving strategies. For example, a manual dimmer or occupancy sensor could be added to the room without changing the operation of the light sensor, or requiring a separate controller. In this case, the controller would be programmed to accept multiple inputs (i.e., wireless IR transmissions) from different sensors and user-input devices located in the room. Perhaps a better way to view the system is to start with a controller that accepts many different sensor and user inputs. To reduce installation expense, the controller is located at a position that is convenient for access to power and ballast control wiring, independent of the sensor and user interface controls for less constrained, optimal placement of these devices. Sensors and user interface devices are added to the system depending on what type of control is needed. For example, a lighting specification may call for an occupancy sensor in every room as a first measure of capturing the greatest energy savings. Once this special controller is in place, at only a marginal increase in cost over installing traditional occupancy sensors, adding photosensors to, say, the perimeter offices would involve only placing the wireless sensors in the rooms and commissioning. Wireless dimmers could similarly be added to any room as needed. In this example, the controller and all the associated building wiring would be identical; the controller is able to accept and process wireless signals from each of the different sensors present in the room. Multiple energy saving strategies could easily be implemented without additional wiring expenses and system integration concerns.

### 3.2.1 Sensor Characteristics

The important characteristics of the remote sensor for operational performance include spectral response, spatial response and range of response. These characteristics, identified in previous photosensor studies<sup>2,3,4</sup> determine the information that the sensor gathers from its environment and relays to the controller. The better this information, the more accurately the controller can maintain the desired illumination levels in the room.

Other characteristics important from a product point of view include physical size, software/logic control, signals for communication, power management and battery life. These characteristics are discussed below.

#### 3.2.1.1 Spectral Response

The remote sensor uses a silicon photodiode as the light sensitive element. Because a bare silicon photodiode is sensitive to ultraviolet, visible and near-infrared radiation, with maximum sensitivity in the near-infrared region, a filter is needed to give the sensor a wavelength sensitivity that closely matches the human photopic sensitivity. This imparts the sensor a response proportional to visible light. Manufacturing a filter that closely matches the photopic response is not a trivial task and the cost of such filters increases tremendously as the matching improves. Making a closely matching filter requires three or more types of filter glass, all ground to precise thicknesses and then cemented together to form a composite filter. In commercial quality illuminance meters where such a filter is required, filter cost can easily exceed \$200. Such a large component cost would not make for a commercially viable product, so a less expensive, compromised solution was sought for the photosensor.

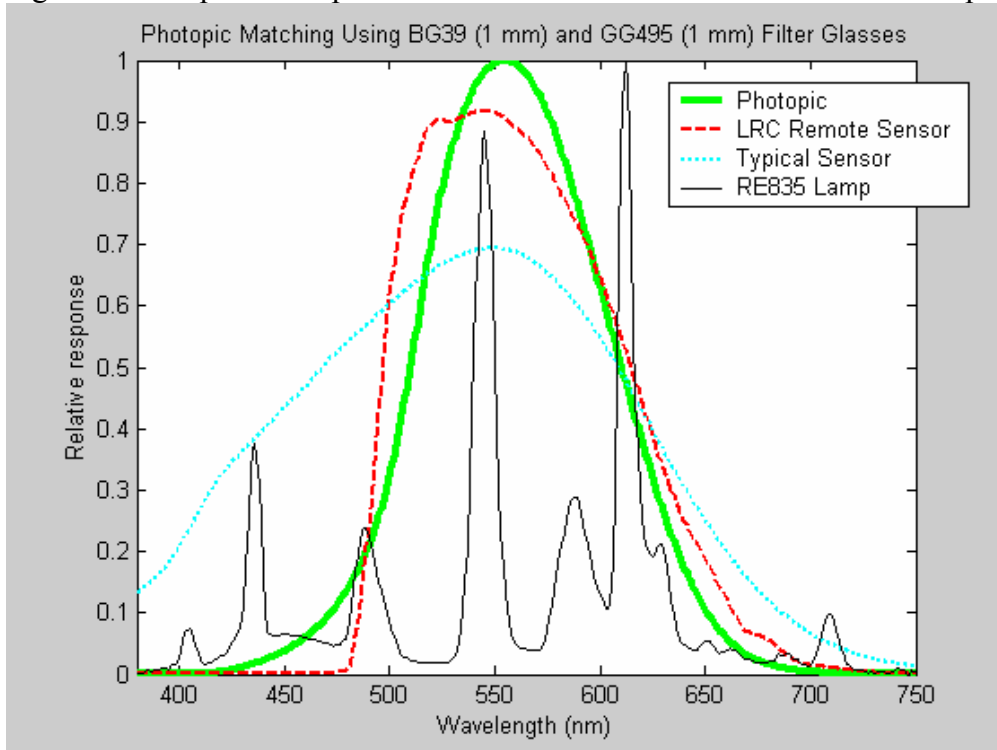
Current photosensor products on the market use only an infrared blocking filter with a silicon photodiode to achieve a very crude, photopic response<sup>2</sup>. With this arrangement, the error in response between daylight and fluorescent illumination often exceeds 40%. (The signal from daylight illumination is 40% greater than the signal from fluorescent illumination at the same luminous intensity.) A closer photopic match can be obtained when an infrared blocking filter is used together with an ultraviolet blocking filter. In addition, careful selection of the filters can dramatically improve the photopic match without the need for custom grinding to adjust filter thickness.

The filter for the remote sensor was made by cementing two absorptive glass filters from Schott Glass (types BG39 and GG495). The filters were purchased from stock supplies at a nominal thickness of 1 mm. The 50 mm square filters cost \$40 each and were cut into 8 mm square pieces to cover the silicon photodiode. The potential to make 36 composite filters from the two \$40 pieces of filter glass reduces the price of each filter to \$2.22.

Figure 2 shows the response of the LRC remote sensor, a typical commercial photosensor, the standard photopic response and a spectral power distribution for a RE835 fluorescent lamp for comparison. The  $f_1$ ' error of the filter<sup>5</sup> is 21% compared to an  $f_1$ ' of 65% for a typical commercial photosensor employing only an infrared blocking filter. In terms of response

differences when calibrated under fluorescent illumination, the filter combination on the remote sensor has a 5% signal error when measuring daylight, while the typical commercial photosensor shown, using only an infrared blocking filter, has a 31% signal error.

Figure 2. The spectral response of remote sensor with other curves for comparison and reference.



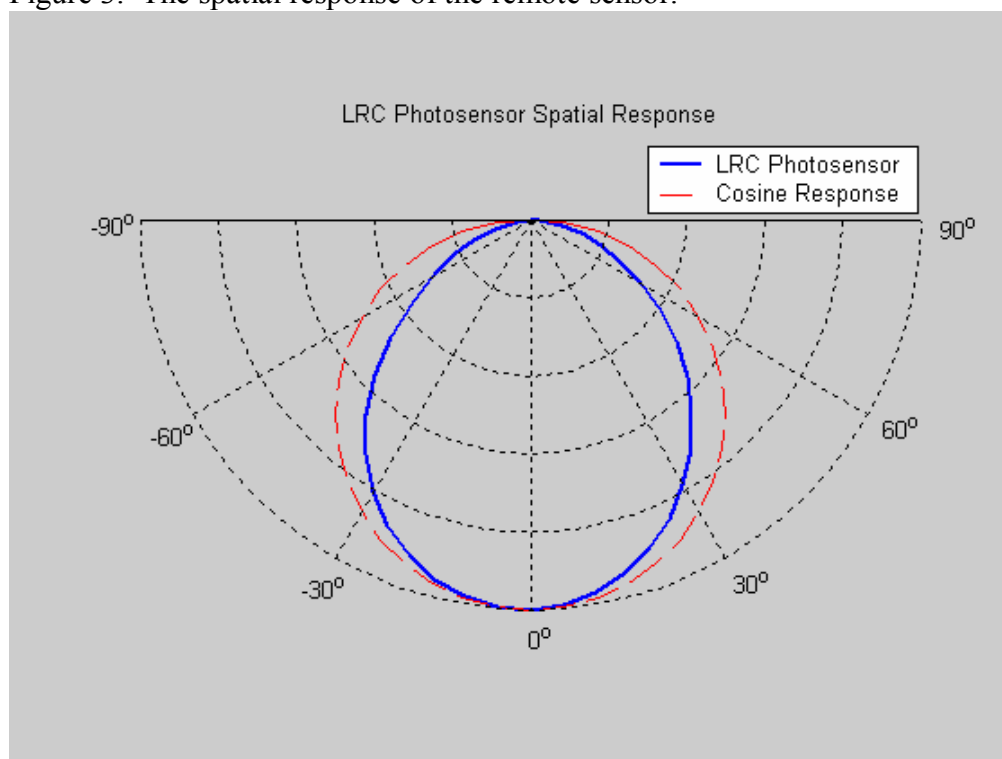
### 3.2.1.2 Spatial Response

Previous simulation and analysis of photosensors<sup>6</sup> showed that performance is not very sensitive to spatial response, provided the photosensor has adequate dynamic range and is commissioned properly. Other work<sup>4,7</sup> suggests that a wider spatial response provides better overall control under varying conditions because wide-angle sensitivity measures a more representative light level in the room than narrow-angle sensitivity. The latter is only true if the photosensor is shielded from direct views of the window and specular reflections of the sun and sky.

Figure 3 shows a polar plot of the sensitivity of the LRC photosensor for illumination incident at different angles. The response is symmetric about the zero degree direction (nadir). Following the guidelines discussed above, the LRC photosensor has a fairly wide angular sensitivity — slightly narrower than a cosine response. The LRC photosensor achieves this response by having a partially diffuse optical window, slightly recessed into the sensor housing. Because of its symmetric and rather wide response, the sensor may receive direct daylight if placed near a window. Therefore, some care must be exercised when positioning the photosensor to avoid direct window views. However, until more data is available showing the advantages of more complicated, perhaps nonsymmetrical response sensitivities, symmetric design is the simplest

and minimizes the difficulties with installation and commissioning. A symmetrical response simplifies the commission process by making the sensor placement insensitive to orientation.

Figure 3. The spatial response of the remote sensor.



### 3.2.1.3 Range of Response

Room sizes, configuration and surface finishes vary widely, so it is not surprising that the amount of light detected by a photocell mounted on the ceiling will also vary widely for different rooms. A simple calculation of the required dynamic range of a ceiling mounted photocell follows.

For the appearance of smooth, continuous dimming in a closed-loop feedback situation, assume that all measurements need a resolution of at least 1%. A resolution of 1% corresponds to a dynamic range of 100:1 for a particular range setting. NLRIP measurements<sup>8</sup> indicate that some rooms can have a workplane/ceiling illuminance ratio as high as 20:1, contributing a factor of 20 to the required range. Workplane illuminance levels can vary by a factor of ten or more which proportionally affects the ceiling illuminance. These three factors make the total required range of response of the photosensor 20,000:1. Uncertainty in predicting the sensitivity of the finished product and uncertainty in each of the above assumptions for determining the dynamic range makes a safety factor of approximately 5 a prudent measure, bringing the total range to 100,000:1.

The LRC photosensor accomplishes this huge dynamic range by automatically selecting one of four sensitivity ranges for the analog circuitry before converting the signal to digital format. The

analog circuitry uses a transimpedance amplifier to convert the photodiode current to voltage. Combinations of four gain-setting resistors are switched in and out of the circuit to give nearly four decades of range. A 12-bit, analog-to-digital converter provides a digital representation of the signal, which is reduced to ten significant bits for data transmission to the controller. Together, the ADC output and the range setting comprise a light reading. The total dynamic range of the light reading is over 500,000:1. (Theoretically, the total range would be 100,000:1 resulting from 10-bits times three decades of range adjustment, but offset adjustments and saturation of the low-current amplifier circuit reduce this range.) The resolution of the photosensor in absolute units is approximately 0.15 lux for the most sensitive range, with a maximum reading on the least sensitive range of approximately 80,000 lux.

### **3.2.2 Data Transmission**

The remote sensor transmits light level readings and commissioning button actuation to the wall-box controller. Wireless transmission is accomplished by an infrared light emitting diode (IRLED) having a peak wavelength of 940 nm. Data is encoded using a pulse-distance modulation scheme with a carrier frequency of 33 kHz. This communication scheme was not necessarily optimized for this application, but instead resulted from decisions based on what was commercially available, inexpensive, and what could quickly be made to work within the confines of this development project. Even without attempting to design an optimum communication scheme, many important aspects needed to be considered for successful communication.

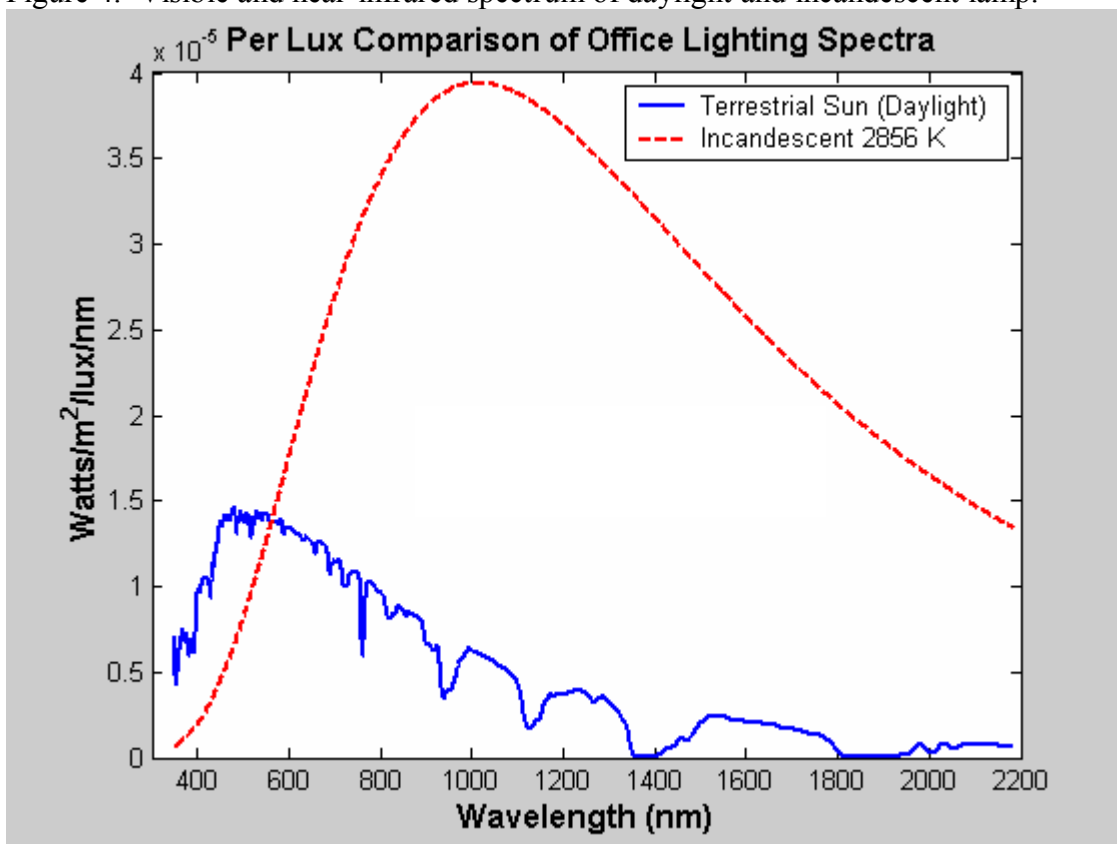
The first decision to be made was to choose between infrared optical and radio wave communication. Radio wave communication has the potential for much lower power consumption, which is important for battery life, size and cost. Rough calculations indicate at least a 100:1 improvement over optical techniques in this regard. This is due to the need for much lower signal strengths because, unlike the optical spectral region, there is very little background energy in the radio region of the electromagnetic spectrum — mainly only other man-made, communication signals. The infrared spectrum, on the other hand, is filled with radiation from the sun and electric light sources that emit broadband radiation over the entire optical spectrum. To communicate in the optical part of the spectrum, signals must be of sufficient strength to be detected on top of the noise level accompanying such high levels of background radiation.

Radio communication also differs from free-space optical communication in how easily the signals propagate through building materials, i.e., walls ceiling and floors. Optical signals are easily blocked and can be largely contained within a room. The ability of radio waves to travel freely through walls, floors and ceilings is a great benefit for many devices such as cell phones and computer networks, but for local lighting control it is problematic and would require individual device addressing or other techniques to overcome. Due to the potential for signals to interfere with one another, radio devices are subject to much stricter FCC regulations making it difficult to bring such devices to market quickly. For these reasons, an optical communication method was chosen for the prototype. As short-range wireless technology continues to advance

and new protocols such as Bluetooth emerge, it seems likely that many more low-cost, low-power, market-ready, wireless technologies will be available in the near future.

The choice of operating at 940 nm as opposed to other infrared wavelengths was the result of choosing a part of the spectrum where there would be the least background radiation from either daylight or fluorescent sources. Figure 4 shows the spectra of terrestrial sunlight. Generally, in the near IR region, less power is present at longer wavelengths. Strong atmospheric absorption of sunlight near 940 nm causes a further reduction in this area. Combining this with an absence of mercury line emission near 940 nm makes this the best wavelength choice for communication.

Figure 4. Visible and near-infrared spectrum of daylight and incandescent lamp.



A pulse-distance modulation scheme was used because it was easy to implement with the microprocessor. Originally, it was thought that any carrier frequency between 30 and 40 kHz would avoid interference from electronically-ballasted fluorescent lamps. However, it was later discovered that many electronic ballasts operate at a fundamental frequency close to 40 kHz, so of the two frequencies tested, much better communication performance was had using a carrier frequency of 33 kHz rather than 38 kHz. Perhaps more disconcerting than not knowing at exactly what frequency the ballast operates, was the observation that as fluorescent lamps are dimmed, significant amounts of modulated IR emissions are generated that cover the entire frequency range used for this type of optical communication. While not severe enough to jam all optical communications completely, in cases where the signal was initially marginal, dimming the lamps

consistently led to communication loss. This phenomenon needs further investigation to ensure robust, low-power, optical communication in future designs.

The data from the remote sensor is transmitted in 16-bit blocks. Each block consists of a two-bit address (addressing was not used in the preliminary field test), a two-bit mode (normal, calibration), a two-bit range setting (for the four possible range settings), and a 10-bit analog to digital converter (ADC) reading. In the pulse-distance modulation scheme, 1s and 0s are encoded as two different time periods between pulses of the carrier frequency. A pulse consists of 20 on/off cycles at the carrier frequency. A “1” is encoded with a delay of 2.4 ms, and a “0” is encoded with a delay of 1.2 ms. This type of encoding is suitable for decoding by a microprocessor which simply has to measure the time between received pulses. While the time to transmit is variable depending on the number of 1s and 0s in the data, the amount of time that the IRLED is operated is constant.

For each transmission, the IRLED is on for 5.1 ms ( $30 \mu\text{s}$  per cycle @ 33 kHz \* 50% duty cycle \* 20 cycles \* 17 pulses). Two IRLEDs operated in series are pulsed with a drive current of 200 mA. From this, it is calculated that each transmission requires 0.00102 amp-seconds of battery charge. As a reference point, a single cell AA size alkaline battery rated at 1.5 amp-hours provides 5,300,000 transmissions. At one transmission per minute, the battery would last for 3,600 days, or 10 years assuming no battery leakage or other loads.

### **3.2.3 Power Supply**

The power loads for the remote sensor include the analog photocell amplifier, the ADC, the microprocessor and the IRLED for communication. The photocell amplifier presents a continuous load of about  $8 \mu\text{A}$ . The ADC consumes power only when it is performing a conversion and the amount is negligible ( $< 30$  nanoamp-seconds per conversion). The microprocessor requires approximately 8 milliamps when running and the IR communication power requirements are stated above. Clearly, the microprocessor dominates the power requirements by orders of magnitude. However, the microprocessor can enter into a “sleep mode” where the current draw is reduced to about 30 microamps. The average current draw is then the weighted average of the time spent in active and sleep modes. Waking up the processor and taking a light measurement every 2.3 s (the shortest sleep cycle available) produces an average current draw of approximately  $110 \mu\text{A}$ . Incidentally, most of the active time is spent waking up the processor and waiting for the oscillator to stabilize as opposed to performing user program instructions. This implies that a custom-programmed processor with a slower clock speed and faster wake-up period could substantially reduce current draw and dramatically increase battery life.

Given the power requirements for microprocessor and optical communication, the only inexpensive wireless power source for the remote sensor is a battery. Solar cells were briefly investigated, but for indoor illumination levels of, for example, 100 lux on the ceiling, the area of the solar cell would need to be in excess of  $100 \text{ cm}^2$  to power the average load and provisions would be needed to provide the high bursts of current for optical data transmission and intermittent processor operation.

The choice of battery for the prototype was determined by the battery life (internal leakage) voltage requirements, and capacity. The processor module, being a stock item, was designed for 5-volt operation. Therefore, the voltage supply must be maintained slightly above 5 volts. Although more expensive than standard alkaline batteries, lithium batteries have a shelf-life of over 10 years, a cell voltage in excess of 3.0 V with a flat discharge voltage curve, and an energy density over twice that of alkaline cells. Two AA lithium batteries in series, with a capacity of 2.1 A-hr were used to power the remote sensor.

The average current of the remote sensor, measured over a period of an hour, was 120  $\mu$ A. At this current level the battery life is calculated to be 729 days, or nearly two years. Custom programmed processors operating at voltages of 3.0 V or less could offer over twice the life for the same current draw because the two batteries could be used in parallel for twice the amp-hour capacity. With additional steps of slowing down the processor clock and optimizing the sleep/wake cycle, a battery life exceeding 10 years is certainly realistic.

In pursuit of achieving battery life greater than 10 years, an inquiry was made to a Forth, Inc., a company specializing in embedded control design, to quote a price for developing custom software implementing the operation of the remote sensor using the Texas Instruments MSP430 processor. The MSP430 is a low-cost, 16-bit microprocessor purposely developed for low-power battery operation. Using the MSP430 processor, Forth engineers were highly confident that the average current consumption of the completed device would be less than 10  $\mu$ A, providing a battery life of over 15 years. The cost to develop the program code was quoted at \$6,480.

### **3.2.4 Logic Control**

The remote sensor utilizes an 8-bit microprocessor module to control the operation of the sensor and process light measurements for transmission. The module used in the prototype is a Basic Stamp II, made by Parallax, Inc. The module contains an 8-bit microprocessor, a 2K EEPROM, a clock resonator, a serial communications interface, and a low power voltage regulator — all on a 24-pin circuit board about the size of a postage stamp. The microprocessor is programmed with a rudimentary operating system that interprets commands stored in an EEPROM. The commands in the EEPROM constitute the application specific program written in a Basic-like programming language on a PC, and then put into the EEPROM via the serial interface.

Because the remote sensor has a limited energy supply, every opportunity was taken to reduce energy consumption in this device. The strategies were (1) minimize the active on-time by shifting as much data processing as possible to the wall-switch controller; (2) minimize the frequency of data transmissions; and (3) shutdown as much as possible by entering into a power-saving sleep-mode and staying there as long as possible.

To minimize processing time, the remote sensor has a very simple program. Upon application of power, or after a reset, the sensor transmits a calibration command to the wall-switch controller. The sensor then takes readings every 2.3 seconds and transmits every reading for a period of five minutes. This provides rapid updates of light level to enable efficient commissioning. After the

allotted time for the commissioning period ends, the remote sensor continues to wake-up and take light level measurements every 2.3 seconds, but not every measurement is transmitted.

To conserve the amount of energy used for optical data transmission, updated light readings are not transmitted unless there is a change of more than 1% from the previous reading. One percent may seem like too small a change to consider, but since the sensor is providing data to a closed-loop feedback system, small changes must be updated to maintain loop stability, otherwise light level oscillations can occur. Still, only transmitting when there is a change in light level reduces the number of data transmissions considerably and ensures that the photosensor quickly responds to changes in daylight. For example, if window blinds were suddenly pulled shut on a bright day, the remote sensor would transmit the change in illumination in less than 2.3 seconds. The wall-switch controller can then immediately react to the new light level information and adjust the electric light level. If the light level read by the remote sensor does not change by more than 1% over a 10-minute period, then a transmission is sent to refresh the previous value and resets the criterion used for the next 1% change.

### **3.3 Wall-switch Controller**

The wall-switch controller receives light level data from the remote sensor, processes that information according to the photosensor control algorithm and interfaces with the dimming ballasts. The wall-switch controller also provides a user-interface for manual on/off control, user override, user preference setting, and status indications. Since many of these functions are necessary for other types of lighting control (e.g., dimming, occupancy sensing), future versions of the wall-switch controller could be made to accept inputs from dimmers and occupancy sensors without adding to size, power consumption or cost of the device; only the software needs to be changed. Further description of the hardware and software of the wall-switch controller is given below and separated into the following functional circuit elements: power supply, microprocessor, sensor communication, and ballast interface.

#### **3.3.1 Power Supply**

Efficiently supplying power to building controls is more difficult than one might first imagine. Even though the wall-switch controller is replacing a switch within an electrical box having line voltage wiring, safely accessing that power is difficult.

The first issue is to efficiently convert the line voltage to a low voltage, dc supply (120 or 277 Vac to 5 Vdc). The wall-box controller requires approximately 25 milliamps at 5 Vdc, a power requirement of 125 milliwatts. Traditional split-bobbin transformers work well, but tend to be very inefficient for this load size. The split-bobbin transformer used in the device has an input power of 1.2 watts for 120 Vac input and over 2 watts for 277 Vac input. Accounting for dc regulation losses, this type of transformer is only 30% efficient. Toroidal transformers offer higher efficiencies, but the smallest commercially available size, at nearly four times the volume of the split bobbin transformer, was too big to fit inside a package intended to fit inside an electrical gang-box. Since toroidal transformers produce higher efficiencies at smaller volumes

than other transformer types, it seems likely that a custom torroidal transformer could be made that would satisfy the size requirements and have over twice the efficiency of the split bobbin type. In question is the cost due to the difficulty of winding such a small torroidal transformer.

Non-isolated voltage converters were also investigated in hopes of increasing efficiency and eliminating a bulky transformer. While the efficiencies of the non-isolated converters were better than that of a split-bobbin transformer, the gain in efficiency was not enough to outweigh the disadvantage of the circuit not being isolated from the power line, which, for a prototype circuit, was considered important.

The second issue for supplying power to the controller is the necessity to have a neutral wire connection available in the electrical gang-box. While there are products on the market that derive power from only being connected to the line wire, the operation of these devices is dependent on continuously passing current through the load, even when the load is switched off. This works fine for incandescent lamp and magnetic ballast loads, but many electronic loads will not pass current readily, or, as the case with many electronic ballasts, the current causes charges to accumulate resulting in undesirable actions such as periodic lamp flashing when switched off.

It is common wiring practice not to include neutral wires at wall switch locations because a neutral connection is not needed for traditional on/off switches, and it is expensive to run extra wires. Therefore, nearly all existing buildings have only line wires at the switch location. For this reason, installing a device at the switch location that requires a neutral wire in a retrofit application is difficult and expensive. This problem is not unique to photosensor devices, but it is a problem for occupancy sensor devices as well. For occupancy sensors, a partial solution to this problem is to install a ceiling mounted device, which makes the electrical wiring easier, especially for suspended ceilings. However, this photosensor device requires easy access by the occupant to set preference levels. So, as with a dimmer, the device, or part of the device, must be located within easy reach on the wall. Improvements to the way power is accessed by the device warrant further investigation and development. Using a low-power, custom-programmed microprocessor, such as from the Texas Instruments MSP430 family, the power requirement of the wall-switch controller could be significantly reduced, perhaps to as little as 3 mA at 3 volts, or 9 mW. Such low power requirements could be met using the practices used for occupancy sensors and other retrofit lighting controls that “leak” a little current through the ground wire.

### **3.3.2 Microprocessor**

The wall-box controller utilizes an 8-bit microprocessor module similar to that used in the remote sensor, but with more memory and processor functions than the Basic Stamp 2. The module is a BX-24 module, manufactured by Net Media, Inc. This device was chosen for its ease of programming (in Visual Basic), floating-point math support, interrupt and multitasking capability, and fairly low power requirements (20 mA at 5 V operation). The processor is clocked at 7.56 MHz, has 400 bytes of static RAM, and a 32 kB EEPROM for program storage and/or non-volatile memory.

### **3.3.3 Communication with Remote Sensor**

An infrared receiver module is used to receive and demodulate the optical signal from the remote sensor. It is a commonly used device found in many consumer electronic devices such as remote-controlled televisions and VCRs. The output from the receiver module is a 5-volt, pulse distance encoded signal suitable for direct reading by the microprocessor.

The infrared receiver module comes complete with input optics that provide the device with nearly a full hemisphere of spatial response, thus, when placed on the wall, nearly the whole room is visible for accepting communication signals.

### **3.3.4 Ballast Interface (Power and Dimming)**

The wall-box controller uses a latching electromechanical relay to switch the load (fluorescent lamp ballasts) on and off. A latching relay was chosen to reduce power consumption. Solid-state relays were also considered, but a suitable model having sufficiently low leakage current for driving small electronic loads combined with low drive current could not be found from manufacturers' stock. The electromechanical relay is suitable for any size load up to 10 amperes. The microprocessor controls a driving circuit for delivering the appropriate pulses of current needed to switch the relay.

The dimming interface for connection to the dimming leads of 0-10V dimming ballasts was designed to be purely passive using a digitally programmed variable resistor, or digital potentiometer. The decision to use a variable resistor instead of an active voltage controller resulted from difficulty obtaining stable dimming control when using active voltage controllers employing operational amplifiers. A much simpler voltage controller using a transistor with a digital potentiometer was designed, but not implemented in the final circuit due to poor temperature regulation. The disadvantage of using a resistor instead of an active voltage controller is that it severely restricts the number of ballasts that can be connected and controlled by the circuit. While an active circuit can conceivably control 50 or more ballasts connected in parallel, a resistor can only handle about four ballasts. A commercial device for 0-10V control would have to use an active circuit to handle a variable number of ballasts properly. The problems encountered with this interface demonstrate the shortcomings of the 0-10V control interface in general. Both ballast manufacturers and control manufacturers need to address these potential interface problems. The variable resistor interface was used for the prototype because it was considered the most predictable and straightforward approach to dimming 0-10V ballasts. In hindsight, however, the small sacrifice in precision using the transistor design is probably of negligible consequence in practice.

The digital potentiometer interfaces to the microprocessor via a three-wire serial interface. The digital code selects one of 256 wiper positions on the fixed, 20 k $\Omega$  resistor. A dual device is used giving 512 levels over a range from 200  $\Omega$  to 40 k $\Omega$ . This range and resolution provides the appearance of continuous dimming for a range of ballast types and for up to about four ballasts connected in parallel.

### **3.3.5 Software**

The software for the wall-box controller is written in a form of Visual Basic specially modified for programming the BX-24 device. The Visual Basic software for the BX-24 contains a library of high-level functions that deal with basic input and output as well as supporting the different features of the microprocessor such as the ADC, real-time clock, multi-tasking, watchdog timer and other timer/counters on the chip.

The software program for the wall-switch controller handles the user interface buttons, receives optical communications from the remote sensor, executes the control algorithm that determines the dim levels, and controls the switching and dimming of the ballasts.

The program makes use of the multitasking feature of the BX-24. Three separate programs, or tasks, continually run at the same time using a time-sharing multitasking technique that switches from task to task every 2 ms or less. The tasks are, (1) Main; (2) ReadLightTask; and (3) SaveEnergyTask. A large subroutine in Main deals with the commissioning procedure.

#### **3.3.5.1 Main Program Loop**

Table 1 provides a summary of the assumptions and equations that constitute the control algorithm. The algorithm is an extension of the closed-loop, proportional control algorithm described by Rubenstein and Verderber<sup>4,9</sup>. The innovation to the control algorithm involves adapting it to a digital microprocessor implementation, and adding a user preference input separate from the commissioning set point calculations that controls the aggressiveness of dimming. The main program loop continually recalculates the value of what the electric light received by the remote sensor (e.g., electric light ceiling illuminance) should be in order to maintain the desired task illuminance. Input for this calculation comes from variables shared by the other running tasks, namely ReadLightTask, which is updating the most recently received remote sensor readings, and SaveEnergyTask, which provides the current user preference setting. The Main program loop also checks for special conditions such as commissioning button presses and then branches to the appropriate subroutine.

Execution of one iteration of the Main program loop requires approximately 15 ms to complete. Since the response time for controlling the dim level of the electric lighting need not be this rapid the opportunity for dramatically slower execution speed to reduce processor cost and/or energy consumption is available. In fact, a delay period of 0.5 s was added to the loop to aid in debugging the software and as a means of controlling the dimming rate. Adding the 0.5 s delay demonstrates that the photosensor algorithm uses only about 3% of the processing capability available, leaving sufficient capacity to implement other lighting control features and/or communication protocols using the existing processor hardware.

An important aspect of the control program is that dimming is done slowly and smoothly over time. The program accomplishes this by allowing only a fraction of the required change in light level to occur during each loop iteration of 0.5 s. Increases in illumination occur in increments of 2% of the requested change, while decreases in illumination occur in increments of one percent. By changing the light level based on a fraction of what is requested, large changes in needed

illumination can still occur quickly, while calls for small changes have very little immediate effect. For example, shutting the window blinds during the day when the electric lights are very dim or switched off results in a call for a large change in the electric light level. A fraction of the large change is still significant enough change to quickly switch the lights on and increase the output from the very low dim levels. While it may take 10s of seconds for the light level to approach its final value, there are no long delay times during which the occupant is left in the dark.

Also of great importance is the avoidance of frequent electric light on/off switching. Two techniques are used in concert to avoid excessive switching, a hysteresis loop and a time delay. A hysteresis loop is cycle that takes two different paths between states depending on the previous history of states. For the case of switching lights, lights are switched off (from the previous state of being on) at one level, 100 lux for example, but are switched on (from being off) at a lower level of for example, 50 lux. For light levels between 50 and 100 lux as given in the example above, no action occurs. This is often referred to as a “dead-band.” For the photosensor, the lights are switched off when daylight provides more than 150% of the required workplane illuminance. The electric lights are switched on when the workplane illuminance is less than 100% of what is required. Depending on the user preference setting, the required illumination level may be up to three times the light level provided by the electric lights.

A hysteresis loop avoids switching due to the small changes in the daylight level that continually occur, but daylight levels can also change rapidly by large amounts as clouds pass in front of the sun. To avoid frequent switching due to large oscillations in the daylight level, a 10-minute time delay is implemented for the action of switching off the lights. No time delay is implemented for switching on the lights. The time delay is also capable of being re-triggered in midst of a timing the delay. The result is that light level must be maintained in excess of the switch-off threshold for a 10-minute period before the electric lights will be switched off. The lights will be immediately switched on whenever the switch-on threshold is reached.

### **3.3.5.2 ReadLightTask**

The ReadLightTask continuously monitors the input pin of the processor that receives output from the infrared receiver module. All high-low transitions at the input are tested to see whether they conform to the parameters defining the timing of an IR communication. If so, the data is decoded and passed to the variables holding the latest updated values for the sensor signal level (e.g., ceiling illuminance), mode (normal or calibration), and device address (if used). A white LED status light briefly flashes to indicate a received communication from the remote sensor. The flash is very faint so not to be an annoyance to the occupants of the room, and it proves to be very useful in providing communication confirmation.

### **3.2.5.3 SaveEnergyTask**

The SaveEnergyTask continually monitors the user preference input button for actuation. Each momentary press of the preference button advances the value of alpha in the control algorithm to the next higher value, or back to the lowest value in a cyclic fashion (alpha = 0, 0.33, or 0.67).

The alpha value corresponds to different amounts of aggressiveness for dimming the electric lights in response to daylight. With an alpha value of zero the control algorithm is designed to maintain a near constant workplane illuminance. An alpha value of one removes any dependency on the remote sensor and maintains the electric light level at full output. Values of alpha between zero and one result in a workplane illuminance level that increases as daylight enters the space at a rate proportional to the value of alpha. In other words, before the electric lights are completely dimmed, the workplane illuminance must be  $1/\alpha$  times that produced by only the electric lights. For example, if the design workplane illuminance is 300 lux, and alpha is set to 0.5, then the electric light would be completely dimmed when the workplane illuminance reached 600 lux from entering daylight.

Having alpha as an adjustable parameter lets occupants enjoy the option of having daylight provide them with increased illumination levels while still providing some energy savings. The amount of energy saved will be less than if a constant design illumination level were kept, but since in many daylit rooms the daylight levels are far in excess of the design electric light levels, the reduction in energy saving may actually be small. Importantly, however, with alpha greater than zero the electric lights will not dim much during periods of marginal daylight when reductions in workplane illuminance are more critical for the occupants needs. This serves also to ease the need for much precision in the amount of dimming compared to when a constant illumination level is maintained.

A manual override is provided on the wall-switch controller that brings the electric lights up to full power regardless of the light level. The override is activated by pressing and holding the user preference button two seconds. A momentary press of the user preference button exits the override condition, returning the controller to its previous state. The wall-switch controller will automatically exit user override after approximately 4.5 hours and return to its previous state.

#### **3.3.5.4 Commissioning**

The commissioning process is shown in Table 2. Pressing a button on the remote sensor initiates commissioning. This is convenient because the remote sensor must be located on the desktop (or workplane location where illumination levels need to be maintained) when the commissioning process starts. Table 2 shows that the total commissioning process takes less than two minutes (104 seconds) if successful on the first try, plus the time required to move the remote sensor from the desktop to its final ceiling location, typically an additional 20 seconds.

The commissioning process is not always successful on the first try because proper commissioning relies on the assumption that the daylight level remains constant, or nearly so, for the duration of the commissioning process.

The longest period during the commissioning process (~36 s) is spent calibrating the dimming response function of the dimming ballast. This is necessary because different dimming ballasts have different dimming response curves. The wall-switch controller must know what control corresponds to a certain amount of light output from the lamps. If dimming ballasts were all manufactured to a standard that defined the relationship between input signal and light output,

this calibration step could be omitted and the process shortened. The shortened process time would increase the likelihood that daylight levels of illumination would remain nearly constant over the commissioning period.

The next longest length of time during the commissioning process is spent waiting for the fluorescent lamps to stabilize after being turned on and off (20 s initially, 5 s thereafter). It is conceivable that these waiting times could also be reduced to half the values used in the prototype by sacrificing 10 to 15% in electric light output reading precision. Optimization of the tradeoff in performance between the benefits of a short commissioning period and more accurate electric light output readings is best determined in the course of field trials to see which works best for over the range of conditions that are encountered. The values given in Table 2 worked well, but are most likely not optimum.

### **3.3.5.5 Data Logging/Downloading**

Program space and non-volatile storage of the commissioning set points and the ballast calibration lookup table occupy only about 6k bytes of the 32k byte EEPROM on the BX-24 module. The extra non-volatile memory, and excess processor capacity, provided the means to have the wall-switch controller log energy-use data, avoiding the need for external monitoring equipment.

Energy-use data is calculated for each program loop cycle iteration (approximately a 515 ms period) and continuously accumulated. Every hour the accumulated total is stored to non-volatile EEPROM storage. Three pieces of data are stored every hour; the actual energy consumption (with control), the energy consumption had there not been a photosensor (without control), and the user preference setting.

Energy consumption is calculated by multiplying the power (in watts) by the elapsed time of each loop iteration. The input power of the electric lighting is calculated from a functional curve fit relating the dimming control signal to the measured input power. The functional fitting equation was determined from power measurements done in the laboratory for each lamp/ballast system configuration used in the field trials. Energy calculations for the without control condition use either the full light output power measurement, or zero if the occupant has the lights manually shut off.

Data is retrieved from the wall-switch controller via a specially constructed device that optically couples to one of the LED indicator lights on the wall-switch controller and relays the data being transmitted by the LED to a computer via a serial cable connection. The EEPROM holds approximately 2500 hours of data, and takes approximately 10 seconds to download at 19.2k baud. When the EEPROM is full, data is overwritten starting with the earliest data.

**Table 1. Control Algorithm Assumptions and Equations**

	<b>ASSUMPTIONS</b>	<b>EQUATIONS</b>
1	Light due to Daylight & Electric components is additive.	$\text{LightATask}_{DE} = \text{LightATask}_D + \text{LightATask}_E$ $\text{LightATCeiling}_{DE} = \text{LightATCeiling}_D + \text{LightATCeiling}_E$
2	Since the light sensor unit cannot be conveniently located in the task area, it is placed on the ceiling, with the assumption that the ratio of light at the task area to light at the ceiling is a constant. Two ratios ("D" for Daylight, "E" for Electric) are calculated as part of a calibration done when the system is installed; this requires that the remote sensor be positioned first at the task, then on the ceiling.  The D ratio requires two daylight-only measurements.  The E ratio could be made with electric-only measurements, but this would require nighttime measurements. Therefore ...  ... the relationships above are used to convert to an equation that requires daylight-only & daylight-electric measurements.	$\text{LightATask} / \text{LightATCeiling} = \text{Constant}$ $D = \text{LightATask}_D / \text{LightATCeiling}_D$ $E = \text{LightATask}_E / \text{LightATCeiling}_E$ $E = (\text{LightATask}_D - \text{LightATask}_D) / (\text{LightATCeiling}_D - \text{LightATCeiling}_D)$
3	The goal is to keep LightATask <sub>DE</sub> constant ( $\geq$ that produced with electric lights at full brightness).	$\text{LightATask}_{DE} = \text{LightATask}_{E_{cal}}$
4	Use the above equations to solve for LightATCeiling <sub>E</sub> as a function of LightATCeiling <sub>D</sub> .  In operation, LightATCeiling <sub>DE</sub> is measured by the photoelectric sensor/electronics in the remote sensor and transmitted to the wall-box unit. The wall-box unit then adjusts LightATCeiling <sub>E</sub> to keep LightATask <sub>DE</sub> constant (for instance, an increase in LightATCeiling <sub>DE</sub> will result in a decrease in LightATCeiling <sub>E</sub> ). This is a feedback process.	$\text{LightATask}_{DE} = \text{LightATask}_{E_{cal}} = (\text{LightATask}_D + \text{LightATask}_E)$ $= (D * \text{LightATCeiling}_D) + (E * \text{LightATCeiling}_E)$ $= (D * (\text{LightATCeiling}_{DE} - \text{LightATCeiling}_E)) + (E * \text{LightATCeiling}_E)$ $= (D * \text{LightATCeiling}_{DE}) + (E - D) * \text{LightATCeiling}_E$ $\text{LightATCeiling}_E = \frac{\text{LightATask}_{E_{cal}} - (D * \text{LightATCeiling}_{DE})}{(E - D)}$
5	It is desirable to give the user some control over the degree of "aggressiveness" of the system. Introducing an "alpha" term into the equation accomplishes this (increasing alpha decreases aggressiveness). The user controls alpha, in three steps (low, medium, high) via a button on the wall-box unit, and can even override the entire system by holding down the button for at least 2 seconds.	$\text{LightATCeiling}_E = \frac{\text{LightATask}_{E_{cal}} - D * (1 - \alpha) * \text{LightATCeiling}_{DE}}{(E - D)}$ $0 \leq \alpha \leq 1$

Table 2. The LRC photosensor commissioning sequence.

	Remote Sensor	Wall-switch Controller	Elapsed Time (s)
<b>Step 1</b>		Normal operation	
	Commissioning button pressed		
	Transmit commissioning mode	Receive transmission with commissioning mode	0.0
	Continually read photocell and transmit data	Turn on Commissioning LED indicator	
	Continue this sequence for 5 minutes, or until commissioning button is pressed again	Turn electric lights on full power	
		Wait 20 s (warm-up and stabilize light output)	20.0
		Wait for updated light level reading	22.3
		Light level reading = LightAtTaskDEcal	
		Turn off electric lights	
		Wait 5 s (to ensure lights are off)	27.5
		Wait for updated light level reading	29.8
		Light level reading = LightAtTaskDcal	
		Turn electric light on full power	
	Commissioner sees commissioning LED turn off	Turn off commissioning LED indicator	
	Commissioner moves remote sensor to ceiling position	Wait for next transmission of commissioning mode data from remote sensor, t(move)	
		...	
<b>Step 2</b>	Commissioning button pressed	Still waiting for commissioning mode data	
	Transmit commissioning mode	Receive transmission with commissioning mode	t(move) + 29.8
	Continue this sequence for 5 minutes, or until commissioning button is pressed again	Continually blink commissioning LED indicator	
		Wait 20 s (time for commissioner to move away from remote sensor)	t(move) + 49.8
		Turn off electric lights	
		Wait 5 s (to insure lights are off)	t(move) + 54.8
		Wait for updated light level reading	t(move) + 57.1
		Light level reading = LightAtCeilingDcal	
		Turn electric light on full power	
		Wait 5 s (stabilize light output)	t(move) + 62.1
		Loop for i = 1 to 15	
		Start on highest 0-10V control resistance setting, step down 6% each loop iteration	
	After 5 minutes without a	Wait for updated light level reading	
	commissioning button press,	Light level reading = lookup table value	
	transmit data every 10 minutes,	Next	t(move) + 98.9
	or whenever reading changes by	Turn off electric lights	
	more than 1%	Wait 5 s (to insure lights are off)	t(move) + 103.9
		Wait for updated light level reading	
		Check that daylight did not change by more than 15% from LightAtCeilingDcal measurement	
		Resume normal operation	~t(move) + 104

## **4. Performance**

This two-year project began in January 2001. The first year was devoted to designing and developing the improved photosensor and making 15 prototypes for evaluation. The second year involved installing the prototypes in two LRC offices and eight offices in Connecticut for evaluation. The photosensors were evaluated for energy savings, ease of installation and commissioning, and occupant satisfaction with the automatically controlled lighting.

The evaluation period was scheduled to occur from December 21, 2001 to June 20, 2002. This six-month period, from winter solstice to summer solstice, was chosen to so that the evaluation would encompass the complete range of sun angles. Unfortunately, technical problems with a capacitor component within the device, and the time spent troubleshooting the problem, delayed the evaluation for the Connecticut offices. To obtain a year's worth of sun angles, the evaluation period for the Connecticut offices was rescheduled for the period from June 21 to December 21, 2002. For the two prototypes installed in the LRC offices, data was recorded from December 21, 2001 to November 2002 for one, and from January 21, 2002 to December 2002 for the other.

### **4.1 Energy Savings**

#### **4.1.1 Energy data**

Tables 4a through 4d list the energy use and savings for each office. Table 5 summarizes this information and shows the total savings. For most offices, the data is reported monthly. For two of the offices at the NU-East facility, an energy management system was in use that switched off power to the photosensor each evening. The loss of power at the wall-box controller reset its internal clock thereby not allowing accurate tracking of calendar time to be maintained. For these offices, the energy saving could not be separated into monthly time periods. The values shown correspond to the time between the two occasions when data were downloaded from the photosensors.

For every table, the “With” column lists the actual energy use for the controlled lighting in each office with the photosensor installed and operating. This amount was calculated by the wall-box controller as described in section 3.3.5.5. The “Without” column lists the energy use that would have occurred had there been no photosensor dimming or switching of the lights. The Without numbers do include the effects of manual switching, i.e., energy use accumulates only when the lights are switched on. The “Saved” column shows the difference of the Without and With columns, expressed in kilowatt-hours and as a percentage of the Without amount.

**Table 4a. LRC offices**

		Andy's Office, LRC				Sandra's Office, LRC			
Start	End	With	Without	Saved	Saved	With	Without	Saved	Saved
Date	Date	kWh	kWh	kWh	%	kWh	kWh	kWh	%
21-Dec-01	21-Jan-02	3.0	6.1	3.1	51.4				
21-Jan-02	21-Feb-02	4.4	11.3	6.9	61.1	2.8	9.5	6.7	70.2
21-Feb-02	21-Mar-02	2.8	8.9	6.2	69.1	4.9	13.5	8.6	63.8
21-Mar-02	21-Apr-02	2.6	7.7	5.1	66.2	3.4	13.8	10.4	75.6
21-Apr-02	21-May-02	2.9	8.9	6.0	67.4	5.6	14.5	8.9	61.4
21-May-02	21-Jun-02	1.7	8.5	6.8	79.6	2.8	14.0	11.2	80.1
21-Jun-02	21-Jul-02	1.1	3.9	2.8	71.5	6.3	14.6	8.3	56.5
21-Jul-02	21-Aug-02	1.6	5.8	4.3	73.0	4.0	11.2	7.1	64.0
21-Aug-02	21-Sep-02	2.1	9.1	7.0	77.4	3.7	17.7	14.1	79.4
21-Sep-02	21-Oct-02	3.3	10.2	7.0	68.0	2.5	8.4	5.9	70.3
21-Oct-02	21-Nov-02	5.1	10.3	5.2	50.2	6.2	11.1	4.9	43.9
21-Nov-02	21-Dec-02					9.3	12.8	3.5	27.7

**Table 4b. NU offices (panel-level time clock in use)**

		Rm 1-22B, NU-East				Rm 1-19H, NU-East			
Start	End	With	Without	Saved	Saved	With	Without	Saved	Saved
Date	Date	kWh	kWh	kWh	%	kWh	kWh	kWh	%
21-Jun-02	4-Sep-02	117.4	197.8	80.5	40.7	54.3	70.8	16.5	23.3
4-Sep-02	20-Dec-02	35.9	48.2	12.3	25.5				

**Table 4c. NU offices (no apparent time clock use)**

		Rm 2-21H, NU-East				Mutchler's office, New Britain			
Start	End	With	Without	Saved	Saved	With	Without	Saved	Saved
Date	Date	kWh	kWh	kWh	%	kWh	kWh	kWh	%
21-Jun-02	21-Jul-02	47.0	55.1	8.2	14.8	57.6	61.1	3.4	5.6
21-Jul-02	21-Aug-02	30.6	50.6	20.0	39.5	83.9	86.9	3.0	3.5
21-Aug-02	21-Sep-02	37.1	65.4	28.3	43.3	42.7	44.5	1.8	3.9
21-Sep-02	21-Oct-02	38.6	67.9	29.3	43.2	20.9	21.3	0.3	1.6
21-Oct-02	21-Nov-02	26.9	32.2	5.2	16.3	17.8	17.8	0.0	0.1
21-Nov-02	21-Dec-02	21.2	30.7	9.5	30.9	19.6	19.6	0.0	0.1

**Table 4d. RPI-Hartford campus**

		Tracy's office, RPI Hartford				Rebecca's office, RPI Hartford			
Start	End	With	Without	Saved	Saved	With	Without	Saved	Saved
Date	Date	kWh	kWh	kWh	%	kWh	kWh	kWh	%
21-Jun-02	21-Jul-02	19.5	25.3	5.8	23.1	13.6	23.2	9.6	41.4
21-Jul-02	21-Aug-02	15.8	23.0	7.2	31.4	9.3	14.7	5.4	36.8
21-Aug-02	21-Sep-02	23.4	30.7	7.3	23.7	25.0	31.7	6.8	21.3
21-Sep-02	21-Oct-02	21.8	34.9	13.1	37.5	20.4	29.0	8.5	29.5
21-Oct-02	21-Nov-02	24.7	39.2	14.6	37.1	34.9	44.4	9.5	21.4
21-Nov-02	21-Dec-02	0.9	0.9	0.0	0.5	25.7	32.6	6.9	21.3
		Kristin's office, RPI Hartford				Dottie's office, RPI Hartford			
Start	End	With	Without	Saved	Saved	With	Without	Saved	Saved
Date	Date	kWh	kWh	kWh	%	kWh	kWh	kWh	%
21-Jun-02	21-Jul-02	22.3	22.4	0.1	0.2	28.3	28.5	0.2	0.8
21-Jul-02	21-Aug-02	22.1	22.1	0.0	0.0	27.1	27.1	0.0	0.0
21-Aug-02	21-Sep-02	22.2	22.2	0.0	0.2	42.5	43.1	0.7	1.6
21-Sep-02	21-Oct-02	34.2	34.5	0.3	0.8	31.5	31.5	0.0	0.1
21-Oct-02	21-Nov-02	36.4	38.1	1.7	4.6	34.7	34.7	0.0	0.0
21-Nov-02	21-Dec-02	26.9	29.7	2.7	9.3	32.8	32.8	0.0	0.0

**Table 5. Summary of energy savings**

Location	Start	End	With	Without	Saved	Saved
	Date	Date	kWh	kWh	kWh	%
LRC, Andy	21-Dec-01	21-Nov-02	30.5	90.8	60.3	66.4
LRC, Sandra	21-Jan-02	21-Dec-02	51.5	141.2	89.6	63.5
NU-East, 1-22B	21-Jun-02	21-Dec-02	153.3	246.1	92.8	37.7
NU-East, 1-19H	21-Jun-02	4-Sep-02	54.3	70.8	16.5	23.3
NU-East, 2-21H	21-Jun-02	21-Dec-02	201.3	301.8	100.5	33.3
NU, Mutchler	21-Jun-02	21-Dec-02	242.5	251.1	8.6	3.4
Hartford, Tracy	21-Jun-02	21-Dec-02	106.1	154.1	48.0	31.1
Hartford, Rebecca	21-Jun-02	21-Dec-02	128.9	175.7	46.8	26.6
Hartford, Kristin	21-Jun-02	21-Dec-02	164.1	168.9	4.9	2.9
Hartford, Dottie	21-Jun-02	21-Dec-02	196.8	197.7	0.9	0.5
						<b>Average</b>
						<b>28.9</b>
All combined	21-Jun-02	4-Sep-02	1329.3	1798.3	468.9	26.1

**4.1.2 Analysis of Energy Data**

The energy data collected from all sites shows great variation in energy use as well as energy savings. Even though all sites are single occupancy offices with windows, the energy use varied from 30.5 kWh to 242.5 kWh. Reasons for the large differences in energy use are attributed to differences in connected load, patterns of use, and available daylight. Some examples of these effects are as follows:

- LRC, Andy’s office has only one 2-lamp fixture for 60 watts of connected load. With ample daylight from a large, clear window fitted with horizontal slatted blinds, often the lights are not even switched on in the morning to start the day. This results in very little energy use either with or without a photosensor.
- NU-East, Rm 1-22B has three 3-lamp fixtures for 280 watts of connected load. The room appears to be in use for 12 to 16 hours per day resulting in potentially large energy consumption. With north-, as well as east-, facing windows the photosensor saves a large amount of energy (37.7%).
- At RPI-Hartford, Tracy’s and Rebecca’s offices have northern exposure and more lightly tinted windows than Kristin’s and Dotti’s which have heavily tinted windows (window transmittance estimated at 20 to 35%). Kristin’s window is further obstructed by being exposed to a center courtyard with a large, leafy tree providing shade. As winter arrived, energy savings began. In addition, in all four of these offices the designed electric illuminance level is approximately 700 lux — two times recommended lighting levels. Combined with tinted windows, daylight has less impact when such high illuminance levels are maintained.

Window blinds also greatly affect energy savings from the photosensors. In one case it was reported that the window blinds are kept shut most of the time to avoid viewing the trash dumpster immediately outside the window. In many other cases, vertical blinds are used which are not as effective as horizontal blinds for redirecting sunlight/daylight to the ceiling.

The placement of the on/off and user preference buttons on the wall-box controller unfortunately caused many accidental actuations of the user adjustment setting upon attempting to manually turn the lights on and off. This problem results from using a plastic housing that was not designed for this particular product, but one that was already available. The two buttons are too small and located adjacent to one another making it difficult to press just one, unless conscious care is exercised. Consequently, the user preference would frequently be pressed as the lights were switched on or off. This is evident in the analysis of the user preference settings, which for six of the offices show nearly an equal amount of time spent at each setting. Table 6 shows the percentage of time spent on each setting for every office. Since none of the occupants reported frequently changing the setting (only one occupant reported changing the setting once) the changes are deemed unintentional. Presumably, the energy saving would have been greater had the setting always remained on the green setting which corresponds to the most aggressive setting where a nearly constant workplane illuminance is maintained.

Energy savings for the individual offices over their respective logging periods ranged from 0.5% to 66%, with an average office savings of 29%. In terms of total energy use, however, the savings is reduced to 26% because offices that had larger connected loads and longer periods of lighting use (perhaps the lights were frequently left on all night) had proportionally less energy savings. The fact that some offices had little or no energy savings should not be interpreted as a failure on the part of the photosensor, but rather the opposite. The photosensor appropriately commissioned itself and maintained the required level of illumination. Again, a contributing factor of low energy savings is attributable to unintentional use of the less aggressive preference settings described above. Results from the occupant survey, detailed below in section 4.2, support this; there were no complaints about having too little light. A look at the commissioning set points for the different offices reveals large differences in daylight levels and ceiling/task illuminance ratios. The large dynamic range of the photosensor and the automatic

commissioning procedure proved very successful in dealing with the wide variety of office spaces used as demonstration sites.

**Table 6. User preference settings**

	Percent of time operated at each setting			
	Dimming Aggressiveness Settings			
Office	Green (most)	Orange	Red (least)	Override
Hartford, Kristin	38	39	19	4
Hartford, Tracy	52	28	20	0
Hartford, Rebecca	30	37	32	2
Hartford, Dotti	37	39	23	1
NU-East, Rm 122B	0	99	0	1
NU-East, Rm 119H	35	26	39	0
NU-East, Rm 221H	28	32	40	0
NU, Mutchler	65	35	0	0
LRC, Andy	96	4	1	0
LRC, Sandra	79	13	8	0

The offices chosen for this demonstration/evaluation were from four distinctly different sites, and at each site, different offices were chosen for different window exposures, e.g., northern, southern, eastern and western. Added to this is the variability of the office occupants regarding use of window blinds. Therefore, it is not too surprising to see such large variation in the energy savings from space to space. Consistent with other studies on daylighting is the observation that the northern window exposures offer the most consistent energy savings from daylighting. Southern exposure can offer significant savings, but the savings depends heavily on blind use and whether the windows are heavily tinted. Vertical window blinds, while useful for blocking direct sun glare, do not redirect daylight towards the ceiling as horizontal blinds so it is not surprising that the offices with vertical blinds on southern, eastern and western exposures do not offer as much savings as offices with these exposures having horizontal blinds. While this study is too limited to conclusively demonstrate these effects, it is interesting to note that, in hindsight, the results are consistent with what is known about daylighting.

#### 4.2 Occupant Satisfaction

Occupant satisfaction with use of the photosensor was determined through interviews with the office occupants occurring about midway through the evaluation period and informally at the end of the evaluation period (if the occupants happened to be present during energy data retrieval). During the more formal occupant interviews a list of specific questions were asked. A copy of these survey questions is shown in **Appendix A**. This list of questions provided some structure to the interviews and made certain that all the topics of interest were covered. However, the main point of the interviews was to get unsolicited comments from the occupants regarding their experience with the photosensor.

The survey questions were grouped into three categories: (1) general questions about the lighting in their office before the photosensor installation; (2) general questions about the lighting after the photosensor

installation; and (3) specific questions about the operation of the photosensor. Eight occupants were surveyed. The author excluded himself from the survey, and one occupant was too busy to respond.

Regarding the specific questions concerning the lighting before the photosensor installation, six occupants would switch on the lights once in the morning as they arrived, and then switch off the lights as they left for the night. One occupant never switched lights on or off because the lighting was controlled by a time clock, and one reported switching the lights on and off as necessary throughout the day. After the photosensor installation, all would switch the lights once per day, except for the occupant with the time clock whose behavior didn't change.

Concerning window blind use, five reported rarely, if ever, adjusting the blinds after initial adjustment. Two reported frequently adjusting the blinds as needed and one occupant who moved into the office after the photosensor was already installed didn't have a window in her previous office. Installing the photosensor did not apparently change window blind use, except for one occupant who reported having the blinds closed a bit more, and another reporting that maybe they closed the blinds less frequently after having the photosensor. No reason for these actions was given. For the most part, installing the photosensor did not affect peoples' use of the window blinds.

When asked whether it was easy or difficult to achieve comfortable lighting, seven reported that it was easy during the day and after dark, and one reported that it was difficult during the day, but easier at night. This difficulty was attributed to there being too much overhead light during the day. On a similar question, five reported that the lighting was often too bright and one reported glare from the window. Installing the photosensor apparently helped the situation because five reported that since having the photosensor it was easy to achieve comfortable lighting and three said that it was very easy. Similarly, the five who reported that it previously was often times too bright, reported no problems with brightness with the photosensor. One did report that at one time the lighting was too dim, but that after changing the user preference setting to yellow from green (to less aggressive dimming) the light level was fine. This action demonstrates the importance of a user adjustment.

For the overall rating of the quality of the lighting in the offices, five rated it adequate, two good and one excellent before the photosensor installation. After the photosensor installation, seven rated it good and one excellent. For each occupant the rating improved or remained the same. The conclusion is that the photosensor did not degrade the quality of the lighting in the offices, and in a few cases, it actually improved peoples' satisfaction with the lighting.

Responses to the specific questions about the photosensor operation were as follow. Five occupants did not notice the lamps dimming and, of the three that did, none reported it distracting. Three noticed the light being automatically switched on and off, with one of the three finding it occasionally distracting. That particular office had fairly substantial energy savings of 33%. Note that not all of the occupants experienced full dimming and switching. In the offices with near zero energy savings, the lights remained near full on all of the time.

Two occupants reported that having the photosensor changed the way they use their lighting. For one the change was now having the ability to change the dim setting (user preference on the aggressiveness of the dimming), and the other not longer switches the light on and off during the day as they leave the room because the photosensor usually already has the lights off during the day. The latter change in

behavior has a negative consequence being that people are more likely to forget to turn off the room lights when leaving during the day if the photosensor already has the light switched off. If this happens, the light might be left on all night long unless an occupancy sensor or time clock system is in use.

Three of the occupants felt that they had more control over the lighting in their office, while five thought there was no change. When asked if there was anything they would change about the photosensor to make it better, six said nothing, one said the on/off and preference buttons need to be spaced farther apart and easier to operate, and one said the appearance of the device needs to be improved. Both these issues would be addressed with a specifically designed enclosure for the device.

Finally, the occupants were asked (if they were to change offices) whether they would like a photosensor in their new offices. Six responded yes, and two said that it did not matter to them. Because the main reason for installing a photosensor is for energy savings, a “doesn’t matter” response is taken as a positive response in that having the photosensor did not bother the occupant.

Other relevant comments made during the interviews were:

- The “click” needs to be eliminated when the light switches on and off.
- I don’t have to think about switching the light off during the day because with the photosensor I know I’m not being wasteful.
- I like having the lights dim, and the fact that energy is being saved.
- The overhead lighting is too dim if the blinds are open all the way.
- I like the ability to change dim settings (user preference adjustment).
- The photosensor helped reduce glare from overhead electric lighting. Too much overhead light before the photosensor was installed.
- I notice that the lights are dim when I enter the office, but I don’t notice them actually dimming while I am in the office.
- The switch is a little less convenient than before, but otherwise there is no difference.

The above comment that says “...lighting is too dim if the blinds are open all the way,” is very important. It is probably indicating that the photosensor was commissioned with the blinds partially closed. (The photosensors were commissioned with window blinds in the position in which they were found, or partially opened if they were found closed.) Opening the blinds would change the light distribution in the room and could conceivably reduce the task illuminance. It was the same occupant who reported having to adjust the user preference to the next higher setting to solve the problem. This case underscores the difficulty of precise commissioning of the photosensor and the importance of easily accessed user adjustability after commissioning has been done. Having the user-adjustment button enabled the occupant to achieve satisfactory lighting conditions without calling in personnel to re-commission the photosensor while energy savings remained high at 31%.

### 4.3 Commissioning and Installation

Previous work and literature reviews<sup>2</sup> identified commissioning problems as the major barrier to the widespread use of indoor photosensors, especially when used in dimming systems. This project concentrated on lowering this barrier as much as possible though a complete understanding of what information is required for commissioning and using technology to automate the information gathering process. Simplifying the installation of photosensors is also an important barrier to their use, but such

problems involve the whole lighting system, and are not effectively addressed by the design of the photosensor alone. Nevertheless, the prototype photosensor improved some aspects of the installation procedure.

#### **4.3.1 Installation Issues**

The author performed installation of the photosensors at the LRC. The building had been renovated the previous year with a completely new electrical distribution system and lighting design. The two offices, occupied by Andy and Sandra, were already equipped with 0-10V dimming ballasts (Motorola Helios), controlled by a wall-mounted, integral dimmer and on/off switch. Installation of the photosensor involved simply replacing the on/off switch/dimmer with the wall-box controller photosensor device. Because the existing lighting controller required the same wiring connections as the new photosensor, no new wiring was needed. Installation involved the same amount of effort as installing the manual dimmer/switch.

Installation at the other sites in Connecticut was much more difficult because the offices either were not already equipped with dimming ballasts, or in those offices that did have dimming ballasts, the control wires did not extend to the light switch location. Consequently, new wires had to be installed in all these locations.

In addition to the need for low voltage dimming wires, all of the offices in Connecticut did not have a neutral wire present in the junction box containing the wall switch for the lights. This is standard wiring practice for switches since a neutral connection is not needed for a manual on/off switch. In new construction, however neutral wires are often made available inside switch junction boxes so that lighting controls can have access to power. Such is the case at the LRC offices. The design of the LRC prototype requires a neutral connection making it necessary to pull new wires into the wall-box. This is a very time-consuming process requiring an electrician. At the RPI-Hartford locations, the electrician found it easier to install an entirely new wall-box for the photosensor in each office. The electrician reported spending approximately one half hour per office installing the new wiring and the new dimming ballasts.

The need for a neutral connection is not unique to the photosensor prototype. Many lighting controls, such as occupancy sensors, must remain powered all the time, therefore requiring a neutral connection. There are some devices that are specifically designed for retrofit applications that do not need a neutral connection for power. For these devices, the electrical power use is small enough that adequate power is available by “leaking” a few milliamperes of current to the safety-grounding network. Even though this seems to be a commonly employed method of powering lighting control devices for retrofit applications, it is not known whether the electrical safety codes specifically allow it, or if they do allow it, what the allowed limits are for leaking current to the grounding system. In a commercial version of the photosensor wall-box controller, the current could presumably be reduced to levels enabling it to be powered by way of a ground connection, avoiding the need for a neutral connection.

The need to run low voltage dimming control wiring to the wall-box controller could also be eliminated by using commercially available power line carrier dimming ballasts. With such ballasts (e.g., Advance Mark X and certain ballasts made by Lutron) the dimming signal is transmitted over the power lines using a “phase-chopping” method. In fact, phase-chop dimming was considered for inclusion in the

photosensor prototype, but was omitted due to its added complexity and uncertainty over how the method is actually implemented since there is no known standard for implementing this method of dimming. With a power line carrier dimming signal and no need for a neutral wire connection, installation of the photosensor would be as easy as installing a new light switch. Installation of the photosensor by the electrician at the RPI-Hartford offices took between 7 and 10 minutes once all the wiring was in place.

### 4.3.2 Ease of Commissioning

The photosensors were commissioned by the author in most cases and in a few instances by the electrician who had done the installation, but still in the presence of the author. Because of the technical problems encountered when the photosensors were first installed in December and January, some of the photosensors were reinstalled and commissioned a few times until the problem was finally resolved in June. This allowed the author more experience with the commissioning process.

Table 7. Commissioning attempts and approximate times

Office	Number of tries	Weather Conditions	Approximate time (minutes)
Hartford, Dotti	3	partly cloudy	5
Hartford, Dotti	1	hazy sunshine	1.5
Hartford, Dotti	1	mostly cloudy	2
Hartford, Kristin	1	hazy sunshine	1.5
Hartford, Kristin	2	mostly cloudy	3
Hartford, Rebecca	1	hazy sunshine	1.5
Hartford, Rebecca	1	mostly cloudy	1.5
Hartford, Tracy	1	hazy sunshine	1.5
Hartford, Tracy	1	mostly cloudy	1.5
Hartford, Tracy	1	mostly cloudy	2
LRC, Sandra	2	partly cloudy	3
LRC, Sandra	1	?	1.5
LRC, Sandra	1	?	1.5
LRC, Andy	1	cloudy	2
LRC, Andy	1	?	1.5
LRC, Andy	1	?	1.5
NU, Mutchler	1	sunny	2
NU, Mutchler	3	partly cloudy	5
NU-East, Rm 119H	1	overcast	2
NU-East, Rm 122B	1	overcast	2
NU-East, Rm 221H	1	overcast	2
Average	1.3		2.1

Table 7 lists the different occasions when the photosensors were commissioned. Shown is the number of attempts until commissioning was successful, weather conditions at that time, and the approximate time spent commissioning. An unsuccessful commissioning was indicated by a lit status light on the wall-box controller. The main cause for an unsuccessful commissioning was changing daylight levels during the

commissioning procedure. A change in the measured daylight light levels of 15% or more during the commissioning procedure caused the controller to indicate the commissioning attempt as unsuccessful. Only four attempts out of the 21 trials resulted in an unsuccessful commissioning trial. The weather conditions during these unsuccessful trials was either partly or mostly cloudy. In all cases, a second or third trial was successful. The maximum time spent commissioning was approximately five minutes.

#### 4.3.3 Variability of Daylight During Commissioning

The commissioning process relies on the assumption that daylight illuminance levels inside the office are relatively constant during parts of the one- to two-minute commissioning period. The critical periods are from the time when the remote sensor measures the workplane illuminance to when it measures the ceiling illuminance, and then during the ballast dimming curve calibration. The first period is critical for obtaining the correct ceiling/task illuminance ratios for daylight and electric light, which the control algorithm uses for determining the proper electric light levels. It is highly unlikely that the electric light ratios will be affected by changes in daylight because the electric light levels are determined subtracting a measurements with both electric light and daylight from a measurement of daylight alone, and these measurements are taken within about six seconds of one another. Measurements of the daylight ratio, taken when the electric lights are switched off, will not be accurate if the amount of incoming daylight changes from the time when the workplane measurement is taken to the time when the ceiling measurement is taken. This period is variable, depending on how long it takes the person doing the commissioning to move the sensor from the workplane measurement location to its final ceiling location, plus the 15 seconds allowed by the procedure for the person to move out of the way. Typically, this time is less than one minute provided the person doing the commissioning is well prepared for placing the sensor at its final location. Unfortunately, inaccuracies in the daylight ratio due to changing daylight levels cannot be detected by the photosensor and can go unnoticed. However, the effect of such errors will affect the maintained light levels by an proportionally equal amount, i.e., if the daylight ratio is inaccurate by 15% then the maintained light level will be off by at most 15% when the electric lights are fully dimmed.

The second critical period when daylight should remain constant is during the last part of commissioning when the photosensor is calibrating the ballast dimming control curve by systematically reducing the control voltage and measuring the electric light level on the ceiling. In order to measure only the electric light level, the photosensor measures the combined daylight and electric light level and subtracts the daylight measurement with the electric light switched off. If daylight levels change from one measurement to the next, the electric light level will be miscalculated leading to an incorrect calibration of the control voltage. The photosensor, however, can minimize the chance of an incorrect calculation by comparing daylight measurements taken at the beginning and the end of the procedure. If the values are not within acceptable tolerances, then the photosensor can indicate that daylight levels changed and suggest that the commissioning procedure be redone.

An important question is, how practical is the assumption that daylight remains fairly constant during the commissioning process? To answer this question, daylight illuminance measurements were recorded over a period of several months in an LRC office to determine the variability of interior daylight levels for this particular climate. Obviously, daylight variability changes for different climates. In a desert

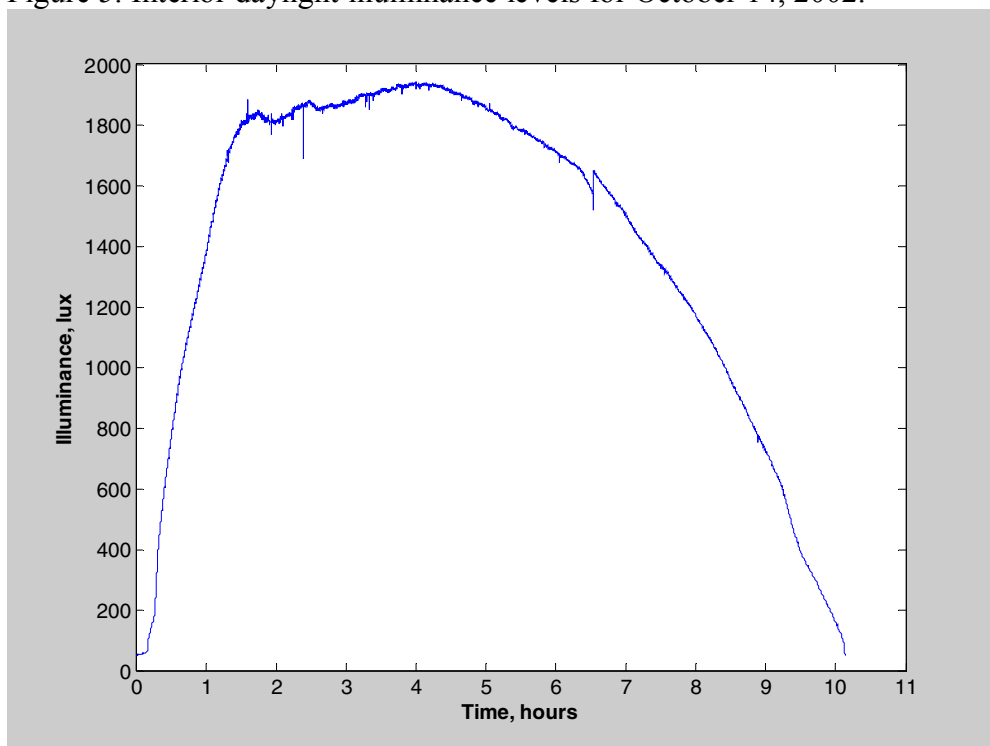
climate, daylight is expected to be much less variable than in the northeast United States where cloudy and partly cloudy skies are common.

Daylight measurements were recorded every second for 120 days over a period of five months. Measurements were sporadically interrupted due to logistical reasons so the recording times were not always consecutive days, but the skipped days were not correlated to particular weather conditions so the data represent a fair sampling of the daylight for the range of weather conditions encountered during the five-month period. Figure 5 shows a plot of the daylight level recorded for one particularly sunny day on October 14, 2002. Figure 6 shows a similar plot for October 20, 2002, a day characterized by partly cloudy conditions where the sun was intermittently blocked by passing dark clouds all day.

From these types of measurements the probability of daylight levels remaining within a certain range of constancy can be calculated. For example, on October 14, 2002, the probability that the interior daylight level changed by more than 10% for any two-minute period is 96.25%, while on October 20, 2002, the probability of obtaining those same conditions is only 42.42%. As it turns out, October 20 had the lowest probability for periods of near-constant daylight levels over the five-month measurement period.

The probabilities change slightly depending on the constancy requirements. For example, for a constancy of 15% tolerance over a two-minute period the probabilities for the above two days are 97.67% and 46.77%, respectively. And for a 15% tolerance over a one-minute period the probabilities are 98.85% and 58.25%.

Figure 5. Interior daylight illuminance levels for October 14, 2002.



These probabilities are calculated for each day of measurement and the results are shown in Figures 7 and 8 for a 15% constancy tolerance and periods of two minutes and one minute respectively. For the two-minute period, the average probability is 83% with a minimum daily probability of 47% and a maximum daily probability of 100%. For the one-minute period the average probability is 91%, with a minimum probability of 58% and a maximum of 100%.

To interpret these results, there is a 91% chance of a successful commission on the first try no matter when during the day the commissioning is performed. If the person doing the commissioning chooses not to commission on an obviously variable day like October 20, 2002, then the probability of successful commissioning is greatly improved. Likewise, the probability of a successful commissioning increases greatly if one provides the opportunity to repeat the commissioning two or three times. The equation for calculating a successful commissioning given multiple opportunities to achieve it is given by:

$$P = 1 - (1 - P_{n=1})^n$$

where  $P$  is the probability of success,  $P_{n=1}$  is the probability of success for one attempt and  $n$  is the number of trials allowed. To understand this equation, note that the quantity  $(1-P)$  is the probability of failure, and the probability of failing multiple times in a row is the product of the probabilities, hence the exponent. Subtracting the result from one converts the answer from the probability of failure to the probability of success. Given two trials for achieving success, where the probability of success for each individual trial is 91% results in a 99.2% probability of success. A 58% probability of success for individual trials results in an 82% probability for two trials, and a 93% chance of success for three trials. So even on the most variable day recorded over a five-month period, there is over a 90% chance of successful commissioning if one allows three trials of a procedure that takes less than two minutes to perform.

Figure 6. Interior daylight illuminance levels for October 20, 2002.

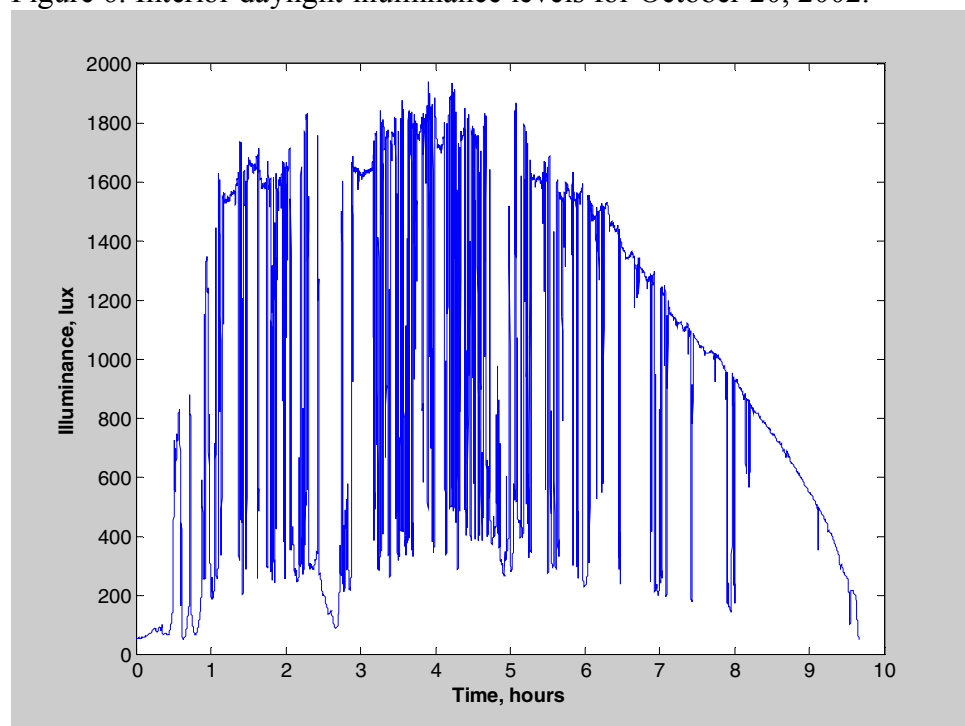


Figure 7. Probability of daylight change > 15% over 2-minute periods.

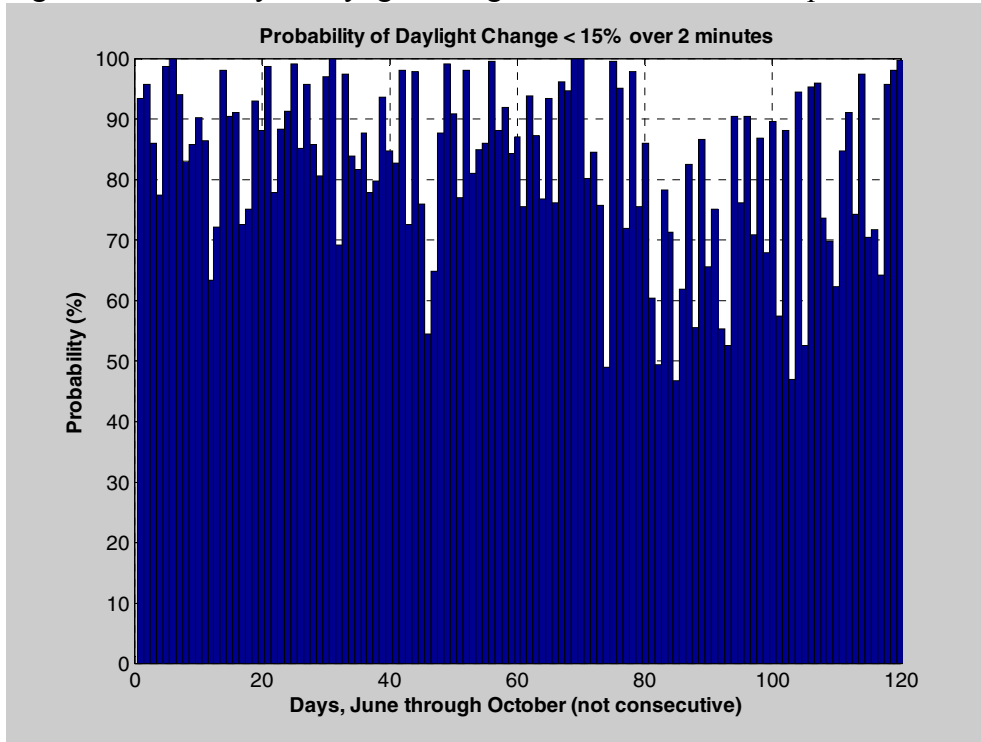
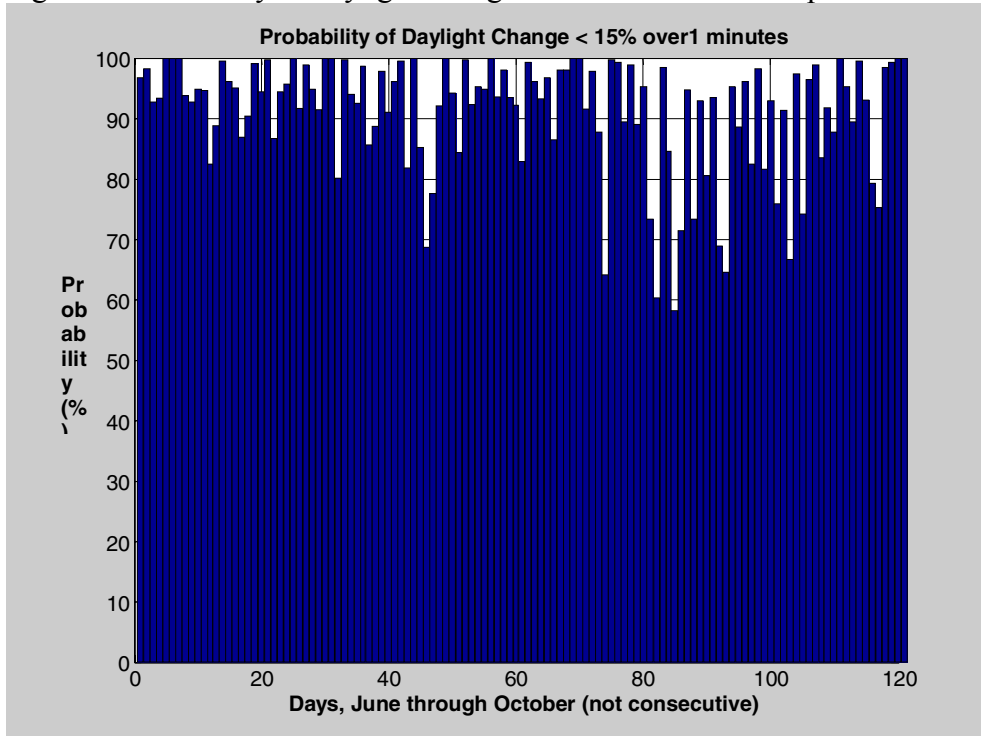


Figure 8. Probability of daylight change > 15% over 1-minute periods.



#### 4.3.4 Analysis of Commissioning Parameters

An analysis of the commissioning set points determined for each photosensor location, and stored in the non-volatile memory of the wall-box controllers, demonstrates the uniqueness of each space and the need for commissioning. Table 8 lists the summary statistics for the three set points needed for the photosensor control algorithm, the workplane/ceiling illuminance ratios for daylight and electric lighting, and the workplane illuminance provided by the electric lighting. The electric light level on the ceiling at the position of the remote sensor is also shown to point out the variability from office to office.

The workplane/ceiling illuminance ratios vary by a factor of four and five for daylight and electric lighting respectively. A ratio near one indicates that the workplane and the ceiling are about equally illuminated by either daylight or electric light. As seen in Table 8, some offices have a daylight ratio near one, but the lowest electric light ratio is over three, meaning that the electric lighting illuminates the workplane more than the ceiling by a factor of three. In one case the electric light ratio is over 15, indicating that the ceiling is only 1/15 as brightly illuminated as the workplane when daylight is not present. This same office has a daylight ratio of only 3.5. If daylight and electric light were given equal weighting, as is the case with many photosensor products on the market, the workplane illuminance could fall to less than one fourth the value provided by the electric lights when daylight is present. Such a condition would likely cause occupant complaints.

Table 8 also shows the statistics for the electric light level measured on the ceiling by the remote sensor. The range of values is from 290 to 1241 for the 10 offices. While not as dramatic as the possible ranges discussed in section 3.2.1.3, the range of light levels encountered still benefit from the auto-ranging feature of the remote sensor. If some of the offices had darker wall finishes with higher ceilings, the range of illuminance values could have been much larger.

Table 8. Commissioning set points for the 10 offices.

	Maximum	Minimum	Average	Std. Dev.
Workplane/Ceiling Daylight Ratio	4.3	1.1	2.4	0.9
Workplane/Ceiling Electric Light Ratio	15.1	3.1	7.8	4.0
Electric Light at Workplane (sensor units)	6550	1102	4307	2017
Electric Light at Ceiling (sensor units)	1241	290	559	273

Taking advantage of the need to commission some offices two or three times after fixing technical problems with the wall-box controller electronics, the commissioning set points recorded at different times could be compared. Table 9 shows the comparisons. For some comparisons, the commissioning was repeated within a month of the previous trial, but for others the commissioning was done many months later during a different season. Other variables affecting the commissioning set points could have also changed from time to time. These include the weather conditions at the time of commissioning, time of day, position of the window blinds, outside ground reflection, and tree foliage. These variable conditions emphasize the fact that commissioning a photosensor is not a process that relies on great precision, but rather one that chooses accurate representative values from a large range of possible values.

Table 9. Commissioning set points for multiple commissioning trials.

Office	Date		Daylight workplane/ceiling ratio	Electric light workplane/ceiling ratio	Workplane illuminance (lux)
LRC, Andy	12/18/01		1.47	3.06	1154
LRC, Andy	4/18/02		1.18	3.69	1232
LRC, Andy	12/2/02		1.27	3.34	1102
		<b>Average</b>	<b>1.31</b>	<b>3.36</b>	<b>1163</b>
		<b>% Range</b>	<b>23</b>	<b>19</b>	<b>11</b>
LRC, Sandra	12/18/01		3.10	3.73	1365
LRC, Sandra	1/4/02		3.08	3.70	1509
LRC, Sandra	1/18/02		3.07	3.69	1610
		<b>Average</b>	<b>3.09</b>	<b>3.70</b>	<b>1495</b>
		<b>% Range</b>	<b>1</b>	<b>1</b>	<b>16</b>
Hartford, Kristin	1/18/02		3.71	13.64	5517
Hartford, Kristin	6/21/02		3.04	10.49	4840
		<b>Average</b>	<b>3.37</b>	<b>12.07</b>	<b>5179</b>
		<b>% Range</b>	<b>20</b>	<b>26</b>	<b>13</b>
Hartford, Dotti	5/31/02		2.20	11.29	5397
Hartford, Dotti	6/21/02		1.25	10.25	5817
		<b>Average</b>	<b>1.72</b>	<b>10.77</b>	<b>5607</b>
		<b>% Range</b>	<b>55</b>	<b>10</b>	<b>7</b>
Hartford, Rebecca	1/18/02		3.13	14.62	4707
Hartford, Rebecca	5/31/02		3.54	15.11	6039
Hartford, Rebecca	6/21/02		2.82	12.33	4652
		<b>Average</b>	<b>3.17</b>	<b>14.02</b>	<b>5133</b>
		<b>% Range</b>	<b>23</b>	<b>20</b>	<b>27</b>
Hartford, Tracy	1/18/02		1.90	8.00	6128
Hartford, Tracy	5/31/02		2.05	8.44	6461
Hartford, Tracy	6/21/02		1.99	6.79	4218
		<b>Average</b>	<b>1.98</b>	<b>7.74</b>	<b>5602</b>
		<b>% Range</b>	<b>7</b>	<b>21</b>	<b>40</b>
NU, Mutchler	6/7/02		1.96	3.94	5329
NU, Mutchler	9/21/02		1.08	3.77	5107
		<b>Average</b>	<b>1.52</b>	<b>3.85</b>	<b>5218</b>
		<b>% Range</b>	<b>58</b>	<b>4</b>	<b>4</b>

Table 9 shows for the most part that the differences in the commissioning set points are less than 25%. However, two occasions show differences between 50 and 60%. These large differences are probably attributable to changes in the window blind position, and/or the effect of the sun's position in the sky. One of the offices had southern exposure and the other had eastern exposure, so blind placement might be critical at certain times of the day. Nevertheless, while a 60% variation might seem large, it is relatively small compared to the differences in the commissioning set points among different offices. Incidentally, both offices showed nearly zero energy savings, indicating that the daylight levels were small in these offices which could have contributed to the large variability in daylight ratios compared to the other offices.

## **5. Market transformation and technology commercialization**

The LRC conducted the following market transformations activities in an attempt to reduce market barriers to the use of the improved photosensor and increase the market for this newly developed product.

### **5.1 Website Activities**

The LRC has already developed a Photosensor Tutorial based on the Daylight Photosensor Project completed a few years ago. The goal of this project was to identify the barriers to the widespread use of photosensors. As a result the LRC proposed to develop an improved photosensor that would address the identified technical barriers.

The LRC developed a simplified version of the Photosensor Tutorial posted on its website. This simplified version includes the description of the improved photosensor and educates specifiers on its advantages and energy savings.

### **5.2 Technical Papers**

The LRC will be submitting a technical paper detailing the improved technology and reporting the results of the evaluation of the improved photosensors to the Journal of the Illuminating Society of North America.

### **5.3 Articles**

The LRC published an article on the improved photosensor in Lighting Design and Application magazine in January 2003.

### **5.4 Educational Materials**

The LRC prepared a 1-page graphic (poster type) detailing the improved photosensor. The LRC also developed a PowerPoint presentation of the photosensor tutorial that can be used for educational activities at the LRC.

### **5.5 Presentations in Seminars, Technical Meetings, or Similar Events**

The LRC is making a presentation at Lightfair International, an annual lighting tradeshow, in May 2003. This tradeshow is attended by manufacturers, lighting specifiers, builders, lighting designers and other

representatives of the lighting industry. The LRC also presented the technology and the findings of the evaluation to its Partners (a presentation was given at Partner's Day in May 2002, and at California Energy Commission, Genlyte Thomas, OSRAM SYLVANIA).

### **5.6 Other Technology Dissemination Activities**

The LRC sent a prototype photosensor to Watt Stopper, Inc. and Lawrence Berkeley National Laboratory for it to be included in a photosensor evaluation project. This evaluation project is sponsored by the California Energy Commission PIER project. The LRC continues to work with Rensselaer's Office of Technology and Commercialization to find manufacturers interested in the technology.

### **5.7 Commercialization**

Discussions with Sensor Switch and the LRC continue to explore full commercialization and manufacture of the photosensor. Sensor Switch doesn't see an immediate market for the photosensor for dimming fluorescent lighting because dimming ballast costs are too high to make the systems economically attractive. However, Sensor Switch expressed interest in participating in further demonstrations of the technology and keeping informed with future developments. It may be necessary to seek additional developmental funding to complete the necessary manufacturing engineering tasks and to conduct a full-scale demonstration and evaluation of the photosensor before manufacturers such as Sensor Switch will invest in the photosensor technology. These are deemed the next steps necessary for successful commercialization.

The LRC is working to keep Sensor Switch interested in bringing the photosensor to market, but since Sensor Switch is unwilling to move forward with the manufacturing of the photosensor, the LRC is seeking other manufacturers. Two other lighting control manufacturers have expressed interest in the technology.

The LRC is also seeking sponsors to conduct a larger demonstration project using these improved photosensors.

#### **5.7.1 Patent Progress**

Rensselaer Polytechnic Institute has filed with the U. S. Patent and Trademark Office for patent protection on the concepts and their implementation as developed in this project. Sensor Switch, Inc., a Connecticut lighting controls manufacturer, has negotiated a non-exclusive license on the technology as a condition of their contributions to the project by supplying technical support and construction of the 15 prototype devices. The project sponsor advised Rensselaer to pursue patent protection on the advice as means of providing control over the technology so that it may be distributed widely to parties interested in bringing commercial products to the market based on the technology.

On February 5, 2003 the U.S. Patent and Trademark Office provided a Notice of Allowance for the claims made on Rensselaer's patent application. Barring any further revisions to this patent, and provided Rensselaer pays the issue and publication fees, Rensselaer expects a patent to be granted within 28 weeks of the Notice of Allowance.

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## Appendix A. Occupant survey questions

### Think back to before the photosensor was installed

What did you used to do to control your electric lighting?

- Switch it on when I arrived and leave it on until I left
- Only switch it on after dark
- Switch it on and off as necessary for work
- Switch in on and off as I entered and left the office during the day
- Other

What did you used to do the control daylight?

- Kept the blinds closed all the time
- Keep the blinds open at all times
- Close the blinds only when the sun is shining on the window
- Adjust the angle of the blinds to cut off sunlight
- Other

How easy was it for you to achieve comfortable lighting conditions?

- Easy during the day and after dark
- Easy during the day but difficult after dark
- Difficult during the day but easy after dark
- Difficult during the day and after dark

If you had difficulty in achieving comfortable lighting conditions at any time, in what situation did the discomfort occur and what was the cause of the discomfort?

- Too much light
- Too little light
- Too much variation in light on your desk
- Shadows
- Glare from the window
- Glare from the electric lighting
- Difficulty in seeing the computer monitor
- Flicker from the electric lighting
- Noise from the electric lighting

Overall, how would you have rated the quality of the lighting in your office before the photosensor was installed?

Awful / Bad / Adequate / Good / Excellent

Any other comments about the lighting of your office before the photosensor was installed?

**Now, since the photosensor was installed**

What do you do to control your electric lighting?

- Switch it on when I arrive and leave it on until I leave
- Only switch it on after dark
- Switch it on and off as necessary for work
- Switch in on and off as I enter and leave the office during the day
- Other

What do you do to control daylight?

- Kept the blinds closed all the time
- Keep the blinds open at all times
- Close the blinds only when the sun is shining on the window
- Adjust the angle of the blinds to cut off sunlight
- Other

How easy is it for you to achieve comfortable lighting conditions?

- Easy during the day and after dark
- Easy during the day but difficult after dark
- Difficult during the day but easy after dark
- Difficult during the day and after dark

If you have difficulty in achieving comfortable lighting conditions at any time, in what situation does the discomfort occur and what is the cause of the discomfort?

- Too much light
- Too little light
- Too much variation in light on your desk
- Shadows
- Glare from the window
- Glare from the electric lighting
- Difficulty in seeing the computer monitor
- Flicker from the electric lighting
- Noise from the electric lighting

Overall, how would you rate the quality of the lighting in your office now the photosensor has been installed?

Awful / Bad / Adequate / Good / Excellent

Any other comments about the lighting of your office now the photosensor has been installed?

**Finally, some questions about the operation of the photosensor**

Do you notice the lamps dimming? Yes / No  
If you do, is it distracting? Yes / No

Do you notice when the lamps automatically switch on and off? Yes / No  
If you do, it is distracting? Yes / No

Has having a photosensor changed the way you control your lighting? Yes / No  
If it has, how so?

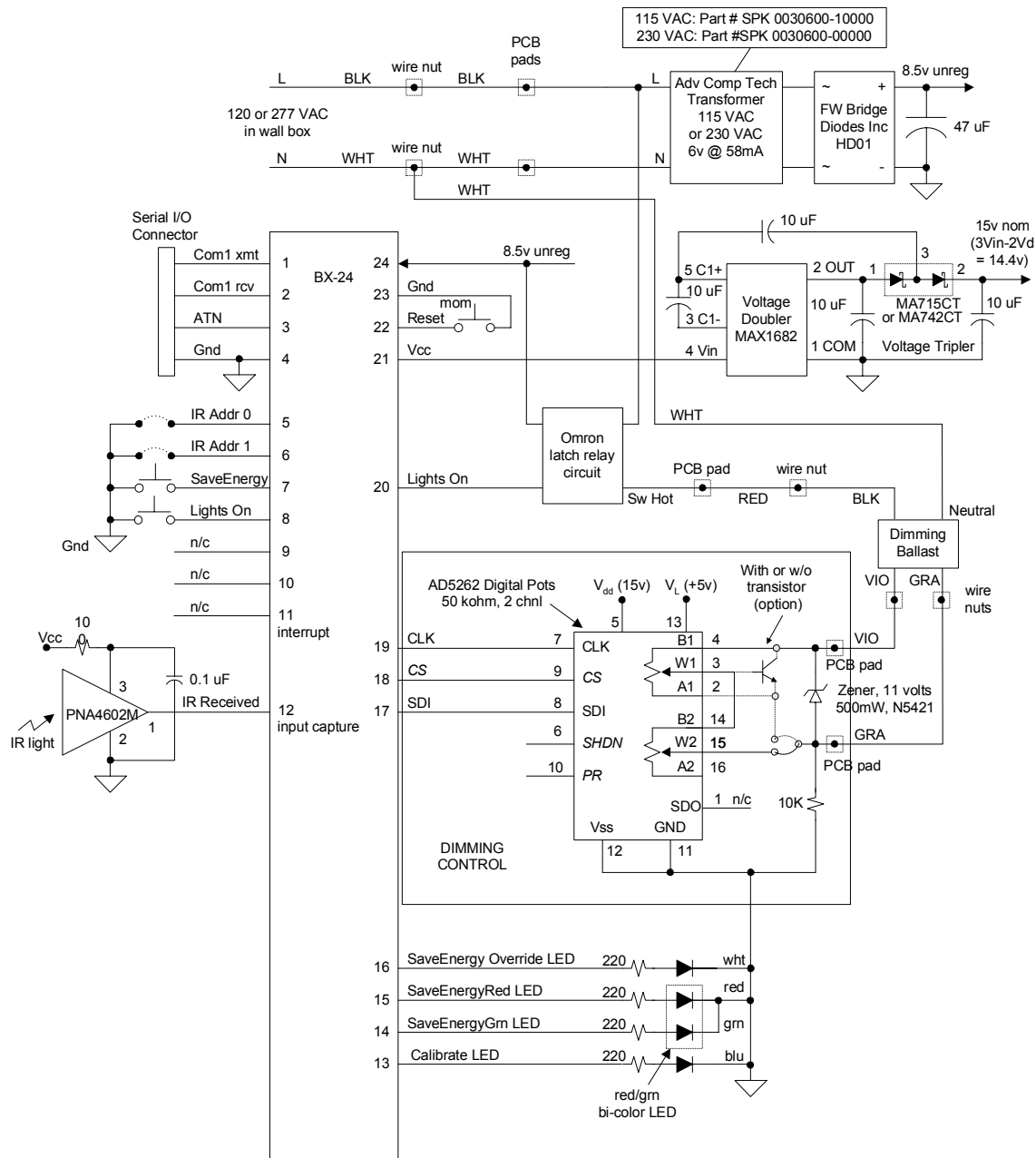
Do you feel you have more or less control over your lighting? More / Less

What if anything would you change about the lighting of your office?

If you changed offices, would you want a photosensor in your new office?

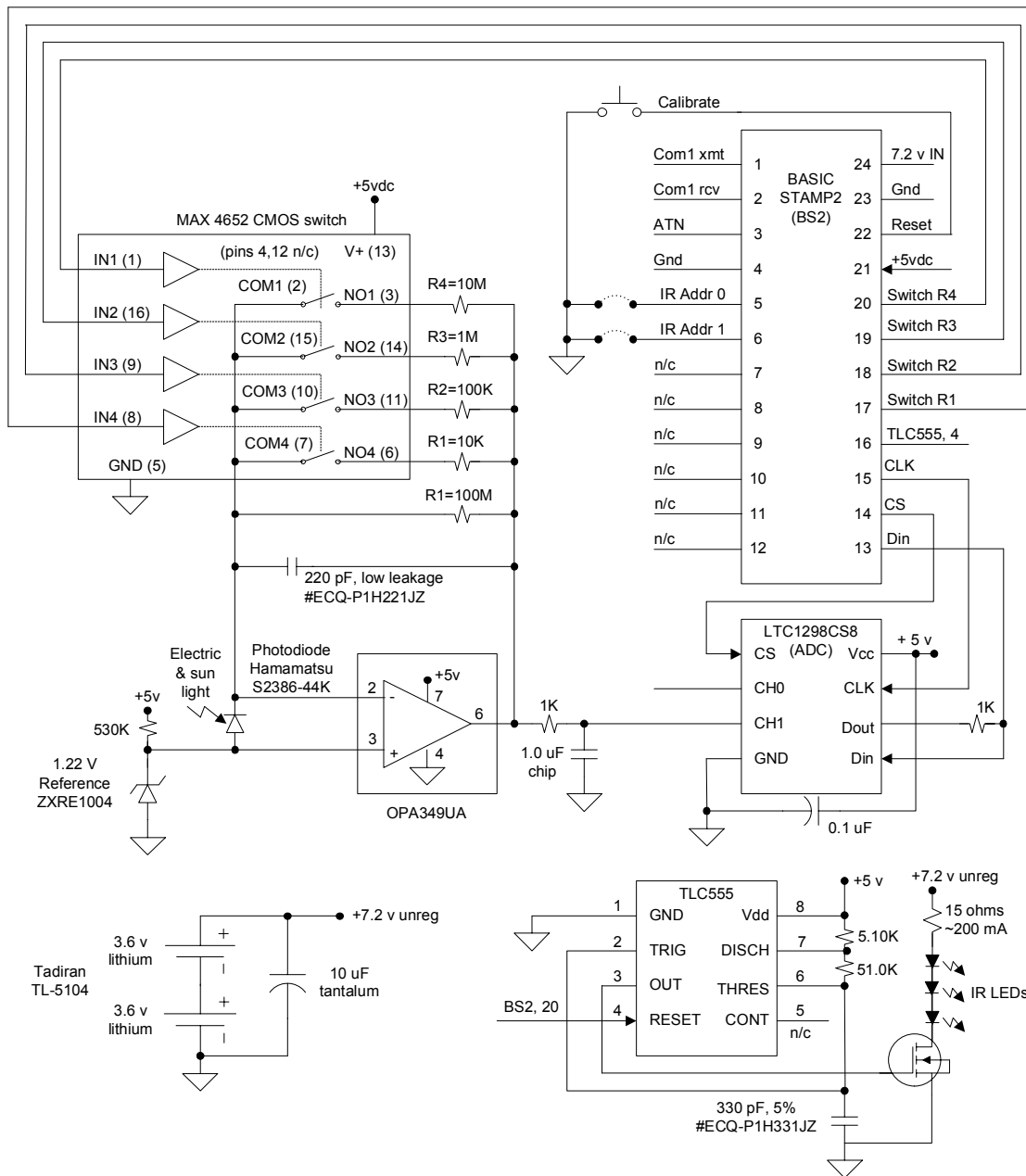
## Appendix B. Photosensor Wall-box Device Schematic

PHOTOSENSOR PROJECT - Wall Unit 06/21/01, latest rev 10/11/01 rmp



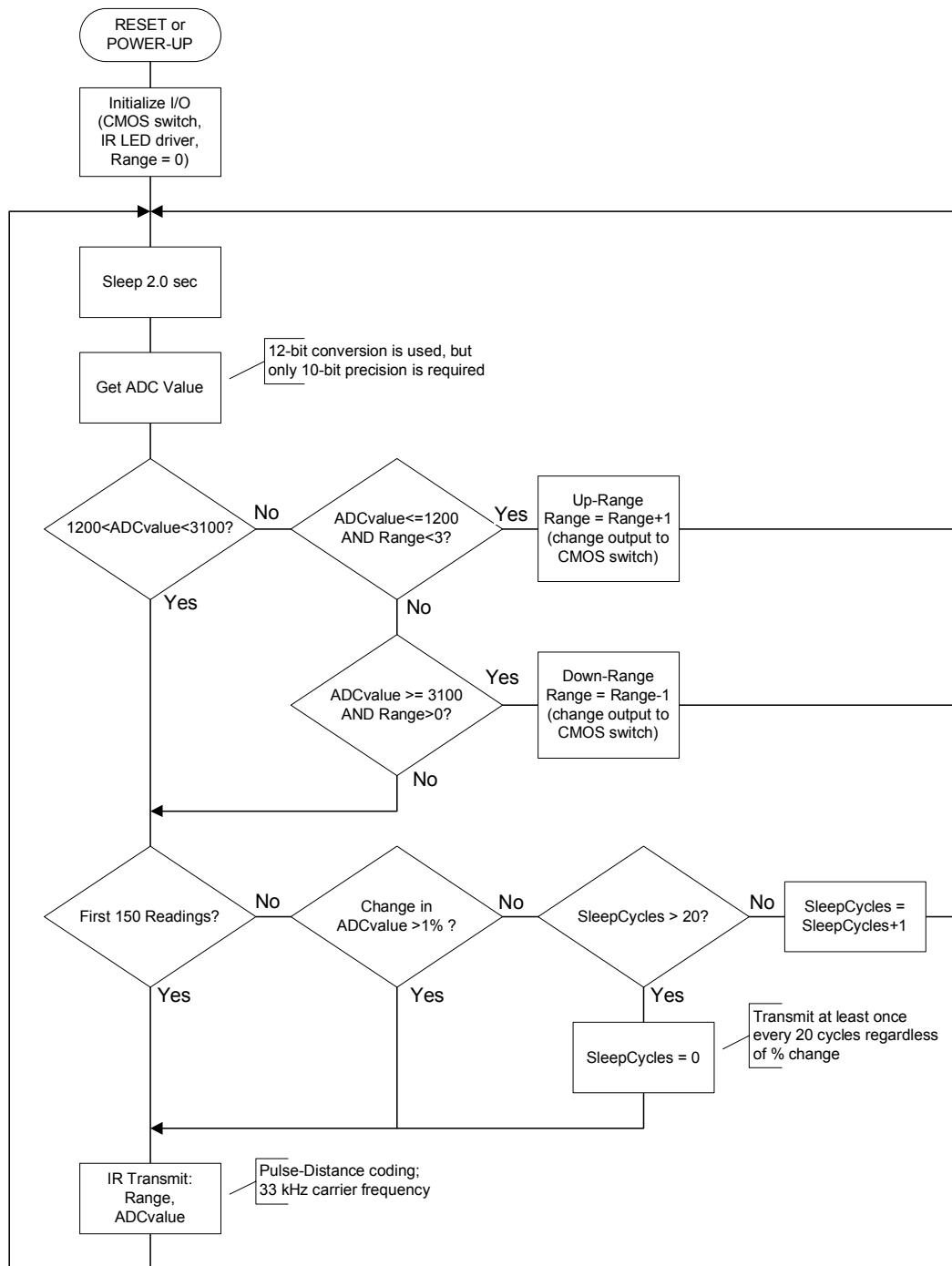
## Appendix C. Photosensor Remote Sensor Device Schematic

PHOTOSENSOR PROJECT - Ceiling Unit (BS2) 07/09/01, latest rev 10/12/01



Appendix D. Software Flowchart for Remote Sensor Device

Sensor Module Algorithm drawn 10/31/02



## Appendix E. Software Code for Wall-box Device

```

*****
'*****      The Main control program receives sensor readings transmitted by the Ceiling Unit, *****
'*****      calculates & outputs the resistance required to control the ballast dimming input, *****
'*****      executes the Calibrate task when the CAL button on the Ceiling Unit is pressed, *****
'*****      controls the SaveEnergy button, turns the ballast on/off, and controls the LEDs. *****
'*****      The code for all modules is based on Andy Bierman's algorithm concepts. *****
*****
'*****      This version of the program also logs power usage and transmits the log, via a *****
'*****      serial protocol, using the Calibrate LED coupled to a photo receiver of a Log Unit. *****
'*****
'*****      Sub Main(), 10/24/01; latest rev 03/19/02 9:00 am *****
*****
'*****
'*****      Do not change the order of declaration of these persistent (EEPROM) variables!
Private Fper As New PersistentByte           'Flag for loading initial EEPROM cal values
Private Dper As New PersistentSingle         'D persistent
Private Eper As New PersistentSingle         'E persistent
Private LightAtTaskper As New PersistentSingle 'LightAtTask persistent
Private LACEcalper(1 To 16) As New PersistentSingle 'LACEcal persistent values
Private AlphaPer As New PersistentSingle     'Range 0-1; Example: Lo(0.0),Md(0.2),Hi(0.4)
Private EEPROMptr As New PersistentLong      'Pointer to energy-saving data log

Public Const EEPROMbgn As Long = 8468        '7568 (2800 data points x 4 bytes per point)
Public Const EEPROMend As Long = 30067      '=(32768-7568)/9bytes*8bytes + 7567
Public Const EEPROMalphaBgn As Long = 30068  '=(EEPROMend + 1 (2800 data points x 1 byte per point)
Public Const EEPROMalphaEnd As Long = 32767  '=(32767 (max memory location)
'Because of sqr() function program uses 7837 bytes. The number of data pts is 2700
Public IRaddrSet As Byte                     'IR address of Wall Unit, set by jumpers
Public IRaddr As Byte                        'IR addr rcvd (2 bits)
Public IRmode As Byte                        'IR mode rcvd (2 bits)
Public IRrng As Byte                         'IR range rcvd (2 bits)
Public IRdata As New UnsignedInteger         'IR data rcvd (10 bits)
Public IRmeas As Single                      'Function of IRdata and Gain

Public Const OverflowValue As Long = 65535
Public Const MaxPulses As Integer = 34
Public PulseTrain(1 To MaxPulses) As New UnsignedInteger
Public Rindex As Integer
Public RindexPrev As Integer

Public LightAtTaskD As Single                'Variables in basic equations
Public LightAtTaskE As Single                'LightAtTaskD variable is re-used in main
Public LightAtTaskDE As Single
Public LightAtCeilingD As Single
Public LightAtCeilingE As Single
Public LightAtCeilingDE As Single
Public LightAtCeilingEcalc As Single

Public LightStatus As Byte                   'LightsOnPin state (0 or 1)
Public Const OprMode As Byte = &H00         'Operating Mode code
Public Const NopMode As Byte = &H01         'No-operation Mode code
Public Const LogMode As Byte = &H02         'Logging Mode code
Public Const CalMode As Byte = &H03         'Calibration Mode code
Public Const CalRnge As Byte = &H00         '2-bit "rng" in CalMode
Public Const NopRnge As Byte = &H01         '2-bit "rng" in NopMode
Public Const LogRnge As Byte = &H02         '2-bit "rng" in LogMode
Public Const CalData As Integer = &H155     '10-bit "data" in CalMode
Public Const LogData As Integer = &H2AA     '10-bit "data" in LogMode
Public Const AlphaLo As Single = 0.0        'Dimming aggressiveness (Lo, Mid, Hi)
Public Const AlphaMd As Single = 0.33

```

Public Const AlphaHi As Single = 0.67

```

Public UpdateIR As Boolean
Public ReadLightGate As Boolean
Public CalPressed As Boolean
Public LogUpload As Boolean
Public CalInProgress As Boolean
Public SaveEnergyOverride As Boolean
Public SaveEnergyStates As Byte
Public NewData As Boolean

read

Public CalError As Boolean

Private Const LightsOnPin As Byte = 20
Private Const SaveEnergyPin As Byte = 7
Private Const LightSwitchPin As Byte = 8
Private Const SaveEnergyGmLEDPin As Byte = 14
Private Const SaveEnergyRedLEDPin As Byte = 15
Private Const SaveOverrideLEDPin As Byte = 16
Private Const CalibrateLEDPin As Byte = 13

Const RLStackSize As Integer = 65
Const SaveEnergySize As Integer = 50
Dim ReadLightStack(1 To RLStackSize) As Byte
Dim SaveEnergyStack(1 To SaveEnergySize) As Byte

Private LoopCounter As New UnsignedInteger
Private DeltaT As Single
Private Const CalTimeout As Single = 15.0
Private Const R0 As Single = 1.0
Private Const R1 As Single = 10.0
Private Const R2 As Single = 100.0
Private Const R3 As Single = 1000.0
'Private Rfb0 As Single
'Private Rfb1 As Single
'Private Rfb2 As Single
'Private Rfb3 As Single
Private InitSELEDs As Boolean

Public Const Icom3BufR As Integer = 2
Public Const Ocom3BufR As Integer = 16
Public Icom3(1 To Icom3BufR) As Byte
Public Ocom3(1 To Ocom3BufR) As Byte

'-----
Public Sub Main()
'Debug.Print "Got to Main"
Dim EnergyW As Single
Dim EnergyWO As Single
Const LogInterval As Long = 3600
Const WattsMax As Single = 188.00

'Dim i As Integer
'For i = 1 To RLStackSize
' ReadLightStack(i) = &HAA
'Next
'For i = 1 To SaveEnergySize
' SaveEnergyStack(i) = &HAA
'Next
'Updated IR comm. data flag (GetIRinfo())
'ReadLightTask semaphore
'Did user press Cal button on Ceiling Unit?
'Log Unit placed into position for upload?
'Used in GetIRinfo() to wait for new data
'Override SaveEnergy
'Save states of Wht, Red, Gm LEDs
'SET in ReadLightTask() after new data rcvd
'RESET in GetIRinfo() after new data

'Set true if Cal routine errors

'Turn lights on/off
'Operator button - Save Energy
'Operator button-Light Switch (on/off man'l)
'LED indicator - GRN: max energy saved
'RED: min energy saved, ORN: mod energy saved
'LED indicator - White: Save Energy overridden
'LED indicator - BLU: calibration progress

'Task stack sizes

'Task declarations

'For timing lights off delay and override period
'Main loop execution time and Cal. timeout
'Timeout period(seconds) for IR comm. during Cal.
'Gain resistors, Ceiling Unit photodiode amp

'Feedback resistance (parallel combo's)

'Queue buffer size for COM3 IN (not used)
'Queue buffer size for COM3 OUT (8+8 overhead)
'Queue buffer for COM3 IN
'Queue buffer for COM3 OUT

```

```

' Rfb3 = R3
' Rfb2 = (Rfb3*R2)/(Rfb3+R2)
' Rfb1 = (Rfb2*R1)/(Rfb2+R1)
' Rfb0 = (Rfb1*R0)/(Rfb1+R0)

' Debug.Print "Rfb3 = "; Cstr(CLng(Rfb3))
' Debug.Print "Rfb2 = "; Cstr(CLng(Rfb2))
' Debug.Print "Rfb1 = "; Cstr(CLng(Rfb1))
' Debug.Print "Rfb0 = "; Cstr(CLng(Rfb0))

Const IRadr0Pin As Byte = 5 'Wall/Ceiling Unit IR address bits
Const IRadr1Pin As Byte = 6
IRaddrSet = GetPin(IRadr1Pin)*2 + GetPin(IRadr0Pin)
CalPressed = False
CalInProgress = False
CalError = False
LogUpload = False
ReadLightGate = False
NewData = False
SaveEnergyOverride = False
InitSELEDs = True
LoopCounter = 0
EnergyW = 0.0
EnergyWO = 0.0
LightAtTaskD = 1.0
Rindex = 510
RindexPrev = Rindex

Call InitPersistent
LightAtCeilingE = LightAtTaskper/(Eper-Dper) 'Initialize to maximum value
IRdata = 250 'Initialize to zero for light level reading
IRmge = 3 'Initialize to most sensitive range (gain =
1010.1)
CallTask "ReadLightTask", ReadLightStack 'Start tasks
CallTask "SaveEnergyTask", SaveEnergyStack
Call OpenWatchdog(7)

'Cycle lights on and off to make sure latching relay is initially in correct state

Call PutPin(LightsOnPin,bxOutputHigh) 'Switch lights on
Call Delay(0.5)
Call PutPin(LightsOnPin,bxOutputLow) 'Switch lights off
Call Delay(0.5)
Call PutPin(LightsOnPin,bxOutputHigh) 'Switch lights on
LightStatus = 1
Call Delay(0.5) 'Delay to let latching relay cap charge
Call WatchDog()
DeltaT = Timer 'Main loop execution time initialize

Do 'Main program loop
'For i = 1 to RLStackSize 'Temporary to check stack overflow
' Debug.Print Cstr(i); " ";Cstr(ReadLightStack(i))
'Call Watchdog()
'Next

Call GetIRinfo
If (GetPin(LightSwitchPin)=1) Then 'If LightSwitchPin OFF (high) ...
Call PutPin(LightsOnPin, bxOutputLow) 'Turn OFF lights
LightStatus = 0 'No need to control lights
LightAtCeilingE = IACEalper(16) 'Reset to make lights come on at full power
ElseIf CalPressed Then
Call Calibrate

```

```

ElseIf LogUpload Then
    Call Delay(0.1)                                'Allow time for ReadLight
    Call LogTransmit
    CallTask "ReadLightTask", ReadLightStack       'Restart tasks
    CallTask "SaveEnergyTask", SaveEnergyStack
ElseIf SaveEnergyOverride Then
    Call PutPin(LightsOnPin,bxOutputHigh)         'Switch lights on
    LightStatus = 1
    Call SetRcode(510)                             'Full light output
    LoopCounter = LoopCounter + 1                 'for timing override period
Else
    LightAtCeilingDE = IRmeas
'Debug.Print "LightAtCeilingDE = "; CStr(CLng(LightAtCeilingDE ))
    LightAtCeilingEcalc = (LightAtTaskper - Dper*(1.0-AlphaPer)*LightAtCeilingDE)/(Eper-Dper)
    'Slow the rate of changes; make electric light component increment faster than decrement
    If NewData Then
        LightAtTaskD = LightAtCeilingE           'Re-use variable to store LightAtCeilingEprevious
    End If
    NewData = False                               'ReadLightTask() sets this true if IR recvd.
    Select Case (LightAtCeilingEcalc < LightAtCeilingE)
        Case True
            If (abs(LightAtTaskD-LightAtCeilingE) < (0.15*LACEcalper(16))) Then
                'If LightAtCeilingE > (LightAtTaskD - 0.15*abs(LightAtTaskD)) Then
                    LightAtCeilingE = LightAtCeilingE + 0.01*(LightAtCeilingEcalc-LightAtCeilingE)
                'Else 'slowly increase to full power DO NOT INCREASE! CAUSES OCSILLATIONS!
                    'LightAtCeilingE = LightAtCeilingE + 0.01*(LACEcalper(16)-LightAtCeilingE)
            End If
        Case False
            LightAtCeilingE = LightAtCeilingE + 0.02*(LightAtCeilingEcalc-LightAtCeilingE)
    End Select

'A NEGATIVE LightAtCeilingE means that there is "too much" light on the sensor
'Although "excess" light cannot be removed, the lights can be shut off, so .....
'When LightAtCeilingE < -50% of full scale, switch the lights off
'However, don't switch lights back on until (LightAtCeilingE > 0) [hysteresis]
If LightAtCeilingE < LACEcalper(16)*(-0.5) Then'Dim level less than negative 50%?
    If LoopCounter < 2400 Then                    '2400 cycles = 10 minutes
        LoopCounter = LoopCounter + 1
    Else
        Call PutPin(LightsOnPin,bxOutputLow)     'Switch lights off
        LightStatus = 0
        LightAtCeilingE = LACEcalper(16)*(-0.51) 'Keep from going excessively low
    End If
ElseIf LightAtCeilingE > 0.0 Then                'Dim level greater than zero?
    Call PutPin(LightsOnPin,bxOutputHigh)        'Switch lights on
    LightStatus = 1
    LoopCounter = 0                               'Reset LoopCounter
End If
Call DriveLights
End If
If CalError Then
    CalPressed = False
    CalInProgress = False
    SaveEnergyOverride = True                    'Go into override mode
    Call PutPin(SaveOverrideLEDpin,bxOutPutHigh) 'Turn on indicator LED (white)
End If

Call PutPin(26,bxOutputLow)                      'Turn on onboard Green LED
Call Delay(0.10)                                 'Control the loop rate (was 0.5)
Call PutPin(26,bxOutputHigh)                    'Turn off onboard Green LED
Call Delay(0.15)                                 'Second part of loop rate delay

```

```

DeltaT = (Timer - DeltaT)
If DeltaT < 0.0 Then                                     'In the event of timer rollover
    DeltaT = 0.264                                     'approximate loop period (was 0.514)
End If
If Rindex < 40 Then
    EnergyW = EnergyW + (37.9 * DeltaT * CSng(LightStatus))
ElseIf Rindex > 374 Then
    EnergyW = EnergyW + (WattsMax * DeltaT * CSng(LightStatus))
Else
    EnergyW = EnergyW + ((0.4481*CSng(Rindex) + 20.387) * DeltaT * CSng(LightStatus))
End If
EnergyWO = EnergyWO + (WattsMax * DeltaT * CSng(Not (GetPin(LightSwitchPin)) AND &H01))
DeltaT = Timer

If ((CLng(Timer) MOD LogInterval) = 0) Then           'If Timer=multiple of LogInterval, log data
'Debug.Print "EnergyW/EnergyWO = "; CStr(CLng(EnergyW)); " "; CStr(CLng(EnergyWO))
    Call PutEEPROM(EEPROMptr, EnergyW, 4)
    Call PutEEPROM(EEPROMptr + (EEPROMend-EEPROMbgn)\2+1, EnergyWO, 4)
    Select Case CByte(AlphaPer*100.0)
        Case CByte(AlphaLo*100.0)
            SaveEnergyStates = &H01
        Case CByte(AlphaMd*100.0)
            SaveEnergyStates = &H03
        Case CByte(AlphaHi*100.0)
            SaveEnergyStates = &H02
    End Select
    If SaveEnergyOverride Then
        SaveEnergyStates = SaveEnergyStates OR 4
    End If
    Call PutEEPROM(EEPROMalphaBgn + (EEPROMptr-EEPROMbgn)\4, SaveEnergyStates, 1)
    EEPROMptr = EEPROMptr + 4
    If EEPROMptr > (EEPROMbgn + (EEPROMend-EEPROMbgn)\2-3) Then
        EEPROMptr = EEPROMbgn
    End If
    'If NewData = False Then                             'No IR communication for entire log interval
        'IRdata = 250                                     'Set light level reading to zero
        'IRmge = 3                                       'Set to most sensitive range (gain =
1010.1)
    'End If
    'NewData = False                                     'Reset, ReadLightTask sets it true again
    Call WatchDog()
    Call Delay(0.75)                                     'This delay + loop rate > 1 sec
    End If                                             'to avoid logging again on next loop cycle
    Call Watchdog()
Loop
End Sub

'*****
'This routine ensures that the order of persistent variable declarations matches the order of their
'first access.
'*****
Private Sub InitPersistent()
    Dim i As Integer                                     'Index variable
    Const EEPROMflag As Byte = &H47                   'EEPROMflag set to &HAA after EEPROM init'd

    If Fper <> EEPROMflag Then                         'Do not change the order of these statements
        Dper = 1.0
        Eper = 5.0
        LightAtTaskper = 1000000.0
        For i = 1 to 16
            LACEcalper(i) = CSng(i) * 15625.0         '(rough function for operating prior to cal)
                                                    'Ecal(16) = LightAtTask/(E-D) = 1E6/4 = 2.5E5
        Next
    End If

```

```

AlphaPer = 0.0
EEPROMptr = EEPROMbgn
Fper = EEPROMflag
Else
  IRmeas = Dper
  IRmeas = Eper
  IRmeas = LightAtTaskper
  For i = 1 to 16
    IRmeas= LACEcalper(i)
  Next
  IRmeas= AlphaPer
  IRmeas= CSng(EEPROMptr)
End If
End Sub

'*****
' This routine gets the latest IR information sent by the Ceiling Unit. *****
'*****
Private Sub GetIRinfo()
  Dim Gain As Single
  If CalInProgress Then
    'Debug.Print "NewData ";Cstr(NewData)
    DeltaT = Timer
    Do Until NewData
      Sleep(0.0)
      Call Watchdog()
      If ((Timer - DeltaT) > CalTimeOut) OR ((Timer - DeltaT) < 0.0) Then
        'The 'OR' condition if Timer rollover occurs at 86400 seconds (midnight)
        CalError = True
        Exit Sub
      End If
    Loop
    'Debug.Print "NewData ";Cstr(NewData)
  End If
  Do
    UpDateIR = Semaphore(ReadLightGate)
    If UpDateIR Then
      If (IRaddr=IRaddrSet) AND (IRmode=OprMode) Then
        'Update if AddrOK, OprMode, & semaphore free
        'Debug.Print "Updating IRmeas"
        CalPressed = False
        LogUpload = False
        Select Case IRmge
          Case 0
            Gain = 1.0 'without 100M Gain = 1.0
          Case 1
            Gain = 10.009 'Rfb1/Rfb0 Temp constants to free memory
          Case 2
            Gain = 100.1 'without 100M Gain = 101.0 Rfb2/Rfb0
          Case 3
            Gain = 1010.1 'without 100M Gain = 1111.0 'Rfb3/Rfb0
          Case Else
            Gain = 1010.1 'Default case, lowest light reading
        End Select
        If IRdata < 250 Then
          IRdata = 250
        End If
        IRmeas = (CSng(IRdata-250) / Gain) * 1010.1 '0 < IRmeas < 781,817.4
        'Subtract 250 counts due to 1.22V Vref on Ceiling Unit (1.22 *1024 = 250)
        'Debug.Print "IRmeas= ";Cstr(Clng(IRmeas))
        'Debug.Print "IRmge= ";Cstr(IRmge)
        'Debug.Print "IRdata= ";Cstr(IRdata)
      ElseIf (IRaddr=IRaddrSet) AND (IRmode=CalMode) AND (IRmge=CalRnge) _

```

```

        AND (IRdata=CuInt(CalData)) Then                                'If Cal button pressed, CalPressed = True
        CalPressed = True
        LogUpload = False
    ElseIf (IRmode=LogMode) AND (IRrng=LogRnge) AND (IRdata=CuInt(LogData)) Then
        LogUpload = True
        IRmode = NopMode                                            'Prevent repeated set of LogUpload flag
        IRrng = NopRnge
    End If
    ReadLightGate = False
End If
Call WatchDog()
Loop Until UpdateIR
End Sub

'*****
'*****      When the user presses the Calibrate button on the Ceiling Unit, this task      *****
'*****      executes. Refer to the MS Word file "equations & procedures.doc" for details.  *****
'*****
'*****      Sub Calibrate(), 06/20/01; latest rev 09/05/01, rmp      *****
'*****

Private Sub Calibrate()
    Const SafetyFactor As Single = 0.10                            'Maintain LightAtTask = (LightAtTaskE + 10%)
    Dim i As Integer

    'To Calibrate, the user places the Ceiling Unit in the Task area and presses the Cal button.
    'The Ceiling Unit then transmits <IRaddr> <CalMode> <IRrng> <CalData> to the Wall Unit.

    CalInProgress = True
    CalError = False
    Call PutPin(CalibrateLEDPin, bxOutputHigh)                    'Turn on Calibrate LED
    Call PutPin(LightsOnPin, bxOutputHigh)                        'Turn on electric lights ...
    LightStatus = 1
    Call PutPin(SaveOverrideLEDPin,bxOutPutLow)                  'Turn off if on
    Call SetRcode(510)                                           '... to full brightness
    For i = 1 to 20                                              'Wait 20 sec for light to stabilize
        Call Delay(1.0)
        Call Watchdog()
    Next
    NewData = False
    Call GetIRinfo                                               '<<<<< Get/Save LightAtTaskDEcal >>>>>'
    If CalError = True Then
        Exit Sub
    End If
    LightAtTaskDE = IRmeas
    'Debug.Print "LightAtTaskDE= "; Cstr(CLng(LightAtTaskDE))
    Call PutPin(LightsOnPin, bxOutputLow)                        'Turn off electric lights
    LightStatus = 0
    For i = 1 to 5                                              'Wait 5 seconds
        Call Delay(1.0)
        Call Watchdog()
    Next
    NewData = False
    Call GetIRinfo                                               '<<<<< Get/Save LightAtTaskDcal >>>>>'
    If CalError = True Then
        Exit Sub
    End If
    LightAtTaskD = IRmeas
    'Debug.Print "LightAtTaskD= "; Cstr(CLng(LightAtTaskD))
    Call PutPin(LightsOnPin, bxOutputHigh)                      'Turn on electric lights (full brightness)
    LightStatus = 1

```

```

'The Calibrate LED on the Wall Unit is now turned off ...
'... until the user places the Ceiling Unit on the ceiling & presses the Cal button
Call PutPin(CalibrateLEDpin, bxOutputLow)           'Turn off Calibrate LED
CalInProgress = False                               'Skip over timeout condition in GetIRinfo()
Do
    'NewData = False (not needed since only waiting for CalPressed)
    Call GetIRinfo
    Call WatchDog()
    Call Delay(0.1)                                 'Delay to let other tasks run
Loop Until CalPressed
CalInProgress = True                                'Resume timeout and NewData condition

For i = 1 to 100                                     'Allow user 20 seconds to move the ladder
    Call PutPin(CalibrateLEDpin, bxOutputLow)       'Blink Cal LED (fast) during this time
    Call Delay(0.1)
    Call PutPin(CalibrateLEDpin, bxOutputHigh)
    Call Delay(0.1)
    Call Watchdog()
Next
Call PutPin(LightsOnPin, bxOutputLow)              'Turn off electric lights
LightStatus = 0
For i = 1 to 5                                       'Wait 5 seconds
    Call Delay(1.0)
    Call Watchdog()
Next
NewData = False
Call GetIRinfo                                       '<<<<< Get/Save LightAtCeilingDcal >>>>>
If CalError = True Then
    Exit Sub
End If
LightAtCeilingD = IRmeas
'Debug.Print "LightAtCeilingD= "; Cstr(CLng(LightAtCeilingD))
Call PutPin(LightsOnPin, bxOutputHigh)             'Turn on electric lights
LightStatus = 1
For i = 1 to 5                                       'Wait 5 seconds
    Call Delay(1.0)
    Call Watchdog()
Next
NewData = False
Call GetIRinfo                                       '<<<<< Get/Save LightAtCeilingDEcal >>>>>
If CalError = True Then
    Exit Sub
End If
LightAtCeilingDE = IRmeas
'Debug.Print "LightAtCeilingDE= "; Cstr(CLng(LightAtCeilingDE))

For i = 16 to 1 Step -1
    Rindex = (i-1) * 34
    Call SetRcode(Rindex)
    'Debug.Print "Rindex ";Cstr(Rindex)
    Call Delay(0.8)
    NewData = False
    Call GetIRinfo
    If CalError = True Then
        Exit Sub
    End If
    LACEcalper(i) = IRmeas-LightAtCeilingD           'Save LACEcalper(1-16) in EEPROM
    Call Delay(0.1)
    'Debug.Print "LightAtCeilingE= "; Cstr(CLng(LACEcalper(i)))
    If i < 16 Then                                     'Check for monotonicity of lookup table
        If LACEcalper(i) > (LACEcalper(i+1) + 0.15*LACEcalper(16)) Then 'Allow 15% variation

```

```

        CalError = True
        Exit Sub
    End If
End If
Call Watchdog()
Next
Call PutPin(LightsOnPin, bxOutputLow)           'Turn off electric lights
LightStatus = 0
Call Delay(1.0)
NewData = False
Call GetIRinfo                                 '<<<<< Check Daylight not changed >>>>>
If LightAtCeilingD = 0.0 Then                   'Avoid divide by zero
    CalError = True
    Exit Sub
End If
If abs(IRmeas - LightAtCeilingD)/LightAtCeilingD > 0.15 Then 'Allow 15% change
    CalError = True
    Exit Sub
End If

'Calculate D, E, and LightAtTask
Dper = LightAtTaskD / LightAtCeilingD
If (LightAtCeilingDE - LightAtCeilingD) = 0.0 Then 'Avoid divide by zero
    CalError = True
    Exit Sub
End If
Eper = (LightAtTaskDE - LightAtTaskD) / (LightAtCeilingDE - LightAtCeilingD)
If Eper < 1.2 * Dper Then
    Eper = 1.2 * Dper
End If

LightAtTaskper = (LightAtTaskDE - LightAtTaskD) * (1.0 + SafetyFactor)
'Debug.Print "D*100,E*100,IAT = "
'Debug.Print Cstr(CLng(Dper*100.0))
'Debug.Print Cstr(CLng(Eper*100.0))
'Debug.Print Cstr(CLng(LightAtTaskper))
Call PutPin(CalibrateLEDPin, bxOutputLow)     'Turn off Calibrate LED
CalInProgress = False
End Sub

*****
*****      This module drives the lights at a level that maintains LightAtTask at the      *****
*****      desired level, despite changes in the daylight lighting component.  The calling *****
*****      routine, before actually calling this module, gets the latest sensor information *****
*****      from the Ceiling Unit (Call GetIRinfo).  It then copies the sensor data into the *****
*****      variable LightAtCeilingDE and calculates the LightAtCeilingE required to keep the *****
*****      LightAtTask constant.  Finally, it calls this module, which calculates the *****
*****      channel (0 or 1) and code (8 bits) required to set the digital pot to the *****
*****      resistance that will generate the LightAtCeilingE value.  It does this by finding *****
*****      the closest value to LightAtCeilingE in the LightAtCeilingEcal(i) lookup table, *****
*****      (interpolating as necessary) which corresponds linearly to a channel and code. *****
*****      This subprogram then calls SetRcode (below), which transmits the channel and code *****
*****      data to the AD5262 digital pot via 3-wire serial bus. *****
*****
*****      This calling sequence structure is summarized below. *****
*****      Call GetIRinfo *****
*****      LightAtCeilingDE = IRmeas *****
*****      LightAtCeilingE = (LightAtTask - D*LightAtCeilingDE)/(E-D) *****
*****      Call DriveLights *****
*****
*****      Sub DriveLights(), written by mmp 06/20/01; latest rev 09/12/01, mmp *****

```

```

*****
Private Sub DriveLights()
    Dim i As Integer                'Index variable
    Dim n As Integer
    Dim LACEset As Single           'LightAtCeiling setpoint

    If LightAtCeilingE < LACEcalper(16)*0.1 Then 'Do not let dim level go below 10% of max level
        LACEset = LACEcalper(16)*0.1
    Else
        LACEset = LightAtCeilingE
    End If

    i = 1                            'Identify 1 of 30 bands containing LightAtCeilingE
    Rindex = 0
    If (LACEset < LACEcalper(1)) Then 'Min value?
        LACEset = LACEcalper(1)
    ElseIf (LACEset >= LACEcalper(16)) Then 'Max value?
        Rindex = 510
    Else
        Do
            If (LACEset >= LACEcalper(i)) AND (LACEset < LACEcalper(i+1)) Then 'In band?
                Rindex = Rindex + _
                    Cint(34.0*(LACEset-LACEcalper(i)) / (LACEcalper(i+1)-LACEcalper(i))) 'Interpolate
                Exit Do 'Done
            Else 'Go to next band
                i = i + 1
                Rindex = Rindex + 34
            End If
        Loop While i < 16
    End If
    If Rindex > RindexPrev + 9 Then 'Avoid sudden light changes due to non-monotonic
        Rindex = RindexPrev + 9 ' LACEcalper calibration
    ElseIf Rindex < RindexPrev - 9 Then
        Rindex = RindexPrev - 9
    End If
    If Rindex < 0 Then
        Rindex = 0
    ElseIf Rindex > 510 Then
        Rindex = 510
    End If
    RindexPrev = Rindex
    Call SetRcode(Rindex)
End Sub

*****
***** This subprogram transmits Rindex to the AD5262 digital pot via a 3-wire serial bus *****
*****
***** Sub SetRcode(), written by nmp 06/20/01; latest rev 09/13/01, acb *****
*****
'Enter with Rindex
'Note: ShiftOut procedure shifts out MSB first

Private Sub SetRcode(ByVal Rindex As Integer)
    Const SDIPin As Byte = 17 '3 wires - Clock, Chip Select, Serial Data In
    Const CSpin As Byte = 18 'Digital pot, with SPI, controls brightness
    Const ClkPin As Byte = 19
    Dim RDAC0 As Byte
    Dim RDAC1 As Byte

```

```
'Each RDAC gets 1/2 of req'd R
RDAC0 = CByte(Rindex\2)
RDAC1 = RDAC0 + CByte(Rindex MOD 2)

Call PutPin(Clkpin, bxOutputLow)           'Clk initially low
Call PutPin(CSpin, bxOutputLow)           'CS low: Enable adr/data shift into DAC reg
Call ShiftOut(SDIpin, ClkPin, 1, &H00)    'Shift out RDAC number 0
Call ShiftOut(SDIpin, ClkPin, 8, RDAC0)   'Shift out 8 bits from RDAC0
Call PutPin(CSpin, bxOutputHigh)         'CS high: Decode/load adr/data into DAC reg

Call PutPin(CSpin, bxOutputLow)           'CS low: Enable adr/data shift into DAC reg
Call ShiftOut(SDIpin, ClkPin, 1, &H80)    'Shift out RDAC number 1
Call ShiftOut(SDIpin, ClkPin, 8, RDAC1)   'Shift out 8 bits from RDAC1
Call PutPin(CSpin, bxOutputHigh)         'CS high: Decode/load adr/data into DAC reg
End Sub

*****
***** The Ceiling Unit makes scheduled measurements of the light falling on its photo- *****
***** sensor. It encodes and transmits these results to the Wall Unit, using an IR LED. *****
***** This program receives the transmitted data using an IR receiver/processor IC. *****
*****
***** The IR signal has the following format: *****
***** Burst-Data-Burst-Data ... Burst-Data (17 bursts, 16 data bits between bursts) *****
***** Burst is 20 cycles of a 38 kHz carrier; (~26 usec period * 20 cycles = 512 usec) *****
***** Data = logic 0 if time between bursts is "short" (~1200 usec, 1000 to 1800 usec) *****
***** Data = logic 1 if time between bursts is "long" (~2400 usec, 1800 to 2600 usec) *****
*****
***** The receiver, a Panasonic #PNA4602M, removes the carrier. Its output pin is a HIGH *****
***** voltage when it detects a carrier burst, and a LOW voltage when no carrier is *****
***** present. The output of the receiver is connected to the input capture pin (pin 12) *****
***** of the EX-24. The EX-24 interprets the TIME DURATION of the LOW voltage states as *****
***** either logic 0 or logic 1 data. The resulting 16 data bits are then stored as a *****
***** 16-bit unsigned integer, IRvalue, which has 4 fields: (1) a 2-bit address field, *****
***** (2) a 2-bit mode field (Opr or Cal), (3) a 2-bit rangefield, and *****
***** (3) a 10-bit data field. *****
*****
***** Sub ReadLightTask(), based on NetMedia IRcodes; mp mod 06/20/01; latest rev 09/05/01 *****
*****
***** NOTE: Later, MinValue, MaxValue, & TripPoint, and/or the logic, should be improved. *****
*****
Private Sub ReadLightTask()
  Dim I As Integer, Success As Boolean, BitValue As Byte
  Dim IRvalue As New UnsignedInteger
  Dim ByteL As Byte, ByteH As Byte
  Dim IRaddrTemp As Byte           '2 bits
  Dim IRmodeTemp As Byte          '2 bits
  Dim IRmgeTemp As Byte           '2 bits
  Dim IRdataTemp As New UnsignedInteger '10 bits

  Do
    Call InputCapture(PulseTrain, MaxPulses, 0) 'Record IR pulses on the input capture pin
    Call ErrorCheck(Success)
    If (Success) Then 'Decode the spaces between each pulse
      IRvalue = 0 ' (stored in even-numbered array elements)
      I = 2
      Do
        Call DecodeSpace(PulseTrain(I), BitValue, Success)
        If (Success) Then
          IRvalue = IRvalue * 2 'Right shift
          IRvalue = IRvalue + CuInt(BitValue) 'Add LSB
          I = I + 2
        Else

```

```

        Exit Do
    End If
    Loop While I <= (MaxPulses - 1)
End If

If (Success) Then
    'Call PutPin(25, bxOutputLow)           'Turn On Red LED to indicate IR rcvd.
    Call PutPin(SaveOverrideLEDPin, bxOutputHigh) 'Turn On White LED to indicate IR rcvd.
    ByteL = FlipBits(CByte((IRvalue AND &HFF00&)\256)) 'Swap bits on unsigned integer IRvalue
    ByteH = FlipBits(CByte(IRvalue AND &HFF))
    IRvalue = CuInt(ByteH)*256 + CuInt(ByteL)

    IRaddrTemp = CByte(IRvalue\16384)           'Done reading data; parse into fields
    IRmodeTemp = CByte(IRvalue\4096) AND &H03
    IRmgeTemp = CByte(IRvalue\1024) AND &H03
    IRdataTemp = IRvalue AND &H03FF
    'Debug.Print "IRmge = ";Cstr(IRmgeTemp); " IRdata = ";Cstr(IRdataTemp)
    Do
        Success = Semaphore(ReadLightGate)
        If Success Then
            IRaddr = IRaddrTemp
            IRmode = IRmodeTemp
            IRmge = IRmgeTemp
            IRdata = IRdataTemp
            ReadLightGate = False
        End If
    Loop Until Success
    'Call PutPin(25, bxOutputHigh)           'Turn Off Red LED indicating IR rcvd.
    If Not CalError Then
        Call PutPin(SaveOverrideLEDPin, bxOutputLow) 'Turn Off White LED to indicate IR rcvd.
    End If
    NewData = True
    If (IRmode=LogMode) AND (IRmge=LogRnge) AND (IRdata=CuInt(LogData)) Then
        Exit Do 'Avoid system conflict
    End If
End If

Loop
End Sub

'-----
Sub ErrorCheck(ByRef Success As Boolean)
    Const MaxValue As Single = 700.0E-6           'Each carrier pulse must be within this range
    Const MinValue As Single = 300.0E-6
    Const UnitConversion As Single = 135.63368E-9 '(1.0/7372800.0)
    Dim PulseWidth As Single, I As Integer

    'The last space is not followed by a burst, so it must equal OverflowValue
    If (PulseTrain(MaxPulses) <> CuInt(OverflowValue)) Then
        Success = False
    Else
        I = 1 'Check IR carrier pulses (odd array elements)
        Do
            PulseWidth = CSng(PulseTrain(I)) * UnitConversion
            If (PulseWidth < MinValue) Or (PulseWidth > MaxValue) Then
                Success = False
                Exit Do
            Else
                I = I + 2
                Success = True
            End If
        Loop While I <= (MaxPulses - 1)
    End If
End Sub

```

End Sub

```

'-----
Sub DecodeSpace(ByVal Space As UnsignedInteger, ByRef BitValue As Byte, ByRef Success As Boolean)
    'Translates the specified space to a binary digit. If the space width is within tolerances, the
    'Success flag is set to true; otherwise Success is false.

    Const MaxValue As Single = 2600.0E-6           'Each space must be within this range
    Const MinValue As Single = 1000.0E-6
    Const TripPoint As Single = 1800.0E-6         'Crossover point between logic 0 and 1
    Const UnitConversion As Single = 135.63368E-9  '(1.0 / 7372800.0)
    Dim SpaceWidth As Single

    SpaceWidth = CSng(Space) * UnitConversion
    If (SpaceWidth < MinValue) Or (SpaceWidth > MaxValue) Then      'Check time constraints
        Success = False
        Exit Sub
    Else
        Success = True
    End If
    If (SpaceWidth > TripPoint) Then
        BitValue = 1
    Else
        BitValue = 0
    End If
End Sub

```

```

*****
*****      This task checks whether the Save Energy button has been pressed.  If it has, the *****
*****      task then checks whether the button is held for at least 2 seconds.  If it has, *****
*****      the task interprets this as a "Save Energy Override"; otherwise, it interprets *****
*****      this as either a "Remove EnergySave Override" or "Change SaveEnergy Level" *****
*****      (alpha).  Alpha is a number between 0 and 1, inclusive, but is here restricted *****
*****      to three levels - low, mid, and high.  An Alpha of 0.0 results in the most *****
*****      aggressive operation, while an alpha of 1.0 does not cause any controlled *****
*****      operation (electric light always ON). *****
*****
*****      Sub SaveEnergyTask(), written by rmp 09/05/01; latest rev 09/12/01, rmp *****
*****

```

```

Private Sub SaveEnergyTask()
    Dim n As Byte

    Do
        If LogUpload Then                                     'Avoid system conflict
            Exit Do
        End If

        If NOT((GetPin(SaveEnergyPin)=0) OR InitSELEds _
        OR (SaveEnergyOverride AND (LoopCounter > 65500))) Then
            Call Sleep(0)                                     'Allow other tasks to run
        Else
            n = 0                                           'SaveEnergy button being held?
            Do
                Call Delay(0.1)
                n = n + 1
            Loop While (GetPin(SaveEnergyPin)=0) AND (n<20)
            If (n = 20) Then                                  'YES - SaveEnergy override
                SaveEnergyOverride = True
                'Call PutPin(SaveOverrideLEDpin, bxOutputHigh) 'Override LED ON
                Call PutPin(SaveEnergyRedLEDpin, bxOutputLow) 'SaveEnergyLEDs OFF
            End If
        End If
    Loop
End Sub

```

```

Call PutPin(SaveEnergyGmLEDPin, bxOutputLow)
'LoopCounter = 0                                     'Max LoopCounter = 2400, don't
bother to reset

ElseIf (SaveEnergyOverride OR InitSELEDs) Then      'Remove SaveEnergy override
LoopCounter = 0                                     'Reset so lights off delay can reuse
SaveEnergyOverride = False
InitSELEDs = False
'Call PutPin(SaveOverrideLEDPin, bxOutputLow)      'Override LED OFF
If AlphaPer = AlphaLo Then                          'Restore SE LEDs to prev values
Call PutPin(SaveEnergyGmLEDPin, bxOutputHigh)
Call PutPin(SaveEnergyRedLEDPin, bxOutputLow)
ElseIf AlphaPer = AlphaMd Then
Call PutPin(SaveEnergyGmLEDPin, bxOutputHigh)
Call PutPin(SaveEnergyRedLEDPin, bxOutputHigh)
ElseIf AlphaPer = AlphaHi Then
Call PutPin(SaveEnergyGmLEDPin, bxOutputLow)
Call PutPin(SaveEnergyRedLEDPin, bxOutputHigh)
End If
Else                                               'Change SaveEnergy level
If AlphaPer = AlphaLo Then                         ' (AlphaMd; LED yel)
AlphaPer = AlphaMd
Call PutPin(SaveEnergyGmLEDPin, bxOutputHigh)
Call PutPin(SaveEnergyRedLEDPin, bxOutputHigh)
ElseIf AlphaPer = AlphaMd Then                     ' (AlphaHi; LED red)
AlphaPer = AlphaHi
Call PutPin(SaveEnergyGmLEDPin, bxOutputLow)
Call PutPin(SaveEnergyRedLEDPin, bxOutputHigh)
ElseIf AlphaPer = AlphaHi Then                     ' (AlphaLo; LED grn)
AlphaPer = AlphaLo
Call PutPin(SaveEnergyGmLEDPin, bxOutputHigh)
Call PutPin(SaveEnergyRedLEDPin, bxOutputLow)
End If
End If
Do                                               'Wait for release of SE button
Call Sleep(0.1)
Loop Until (GetPin(SaveEnergyPin)=1)
End If
Loop
End Sub

```

```

*****
***** This routine transmits logged data to the Log Unit. EnergyW data is sent first, *****
***** followed by EnergyWO data. Each of these parameters is in Single format (4 bytes *****
***** per point). Data is sent in conventional serial format (8 data bits, 1 stop bit, *****
***** no parity, 19200 baud). This data is transmitted via the Calibrate LED, which is *****
***** coupled to a photosensor on the Log Unit. To start logging, couple the Log Unit *****
***** to the Wall Unit; the Log Unit will send the appropriate, encoded LogUpload command *****
***** to the Wall Unit, and logging will commence. This process takes less than 15 sec. *****
*****
***** Sub LogTransmit(), 10/25/01; latest rev 10/31/01 *****
*****

```

```

Private Sub LogTransmit()
Dim k As Integer
Dim EnergyData As Single
Call LockTask()
Call OpenQueue(ICom3, Icom3BufFr) 'Open input and output queues
Call OpenQueue(OCom3, Ocom3BufFr)
Call DefineCom3(0, CalibrateLEDPin, bx10001000) 'SerInPin, SerOutPin, com parameters
Call OpenCom(3, 19200, ICom3, OCom3) 'Open port 3 at 19200 baud; attach queues

```

```
' Debug.Print ""
For k = 1 To CInt((EEPROMend-EEPROMlogn+1)\8)      'Transmit EnergyDataW log
    Call GetEEPROM(EEPROMlogn + 4*CLng(k-1), EnergyData, 4)
    Call PutQueue(OCOM3, EnergyData, 4)
    Call Watchdog()
'    Debug.Print "Transmitted EnergyDataW: "; CStr(CLng(EnergyData))
Next

For k = 1 To CInt((EEPROMend-EEPROMlogn+1)\8)      'Transmit EnergyDataWO log
    Call GetEEPROM(EEPROMlogn + (EEPROMend-EEPROMlogn)\2 + 1 + 4*CLng(k-1), EnergyData, 4)
    Call PutQueue(OCOM3, EnergyData, 4)
    Call Watchdog()
'    Debug.Print "Transmitted EnergyDataWO: "; CStr(CLng(EnergyData))
Next

EnergyData = Dper
Call PutQueue(OCOM3, EnergyData, 4)                'Transmit calibration parameters
' Debug.Print "Dper: "; CStr(CLng(EnergyData))
EnergyData = Eper
Call PutQueue(OCOM3, EnergyData, 4)
' Debug.Print "Eper: "; CStr(CLng(EnergyData))
EnergyData = LightAtTaskper
Call PutQueue(OCOM3, EnergyData, 4)
' Debug.Print "LightAtTaskper: "; CStr(CLng(EnergyData))
For k = 1 to 16
    EnergyData = LACEcalper(k)
    Call PutQueue(OCOM3, EnergyData, 4)
'    Debug.Print "LACEcalper: "; CStr(CLng(EnergyData))
Next

'Transmit states of override (wht LED) & alpha (red and grn bi-color LEDs)
For k = 1 To CInt(EEPROMalphaEnd-EEPROMalphaBgn+1)
    Call GetEEPROM(EEPROMalphaBgn + CLng(k-1), SaveEnergyStates, 1)
    Call PutQueue(OCOM3, SaveEnergyStates, 1)
    Call Watchdog()
'    Debug.Print "SaveEnergyStates: "; CStr(SaveEnergyStates)
Next

' Debug.Print ""
LogUpload = False
Call UnlockTask()
End Sub
```

## Appendix F. Software Code for Remote Sensor Device

```

*****
****                               CEINING UNIT PROGRAM FOR STAMP2                               ****
**** NOTE: A "cycle" in this program refers to a SLEEP instruction cycle of 2.304 seconds ****
****                               10/05/01                               ****
*****

***** I/O PIN DEFINITIONS *****
CS          con    9      'ADC Chip Select pin (active low)
CLK         con    10     'ADC Clock pin
DIO_n      con    08     'ADC Data I/O pin
SW1        con    15     'MAX 4652 IN1  10M
SW2        con    12     'MAX 4652 IN2  10K
SW3        con    13     'MAX 4652 IN3  100K
SW4        con    14     'MAX 4652 IN4  1M

IRLED      con    11     'Drives 555 Enable Pin to pulse IRLED
Power555   con    02     'Power for 555 oscilator

***** VARIABLE & CONSTANT DEFINITIONS *****
ResetSpec  con    130    'After a reset, # of cycles data MUST be continuously transmitted
ResetCount var    byte   'Count of cycles after a Reset (up to ResetSpec)
CyclesSpec con    20    'Max cycles before data MUST be transmitted
Cycles     var    byte   'Counts cycles that don't result in transmit; reset after transmit
PCchange   con    1     '% change needed before data MUST be transmitted

AD1        var    word   '12-bit ADC result, channel 1
AD1Prev    var    word   'Prior AD1 value

OUIHVar    var    byte   'Output pin states of SW1-SW4
Range      var    nib    'To monitor range setting
RangeChg   var    bit    '0=no change, 1=change from previous measurement
RangeFix   var    nib    'Range after "fixed"

zb         var    bit    'dummy variable to fix SLEEP bug
zz         var    byte   'Sleep period (seconds), needed to fix SLEEP bug

-----
GOTO Main

Bed:
    zb = 15
    Sleep zz
Return

Main:
DIRS = $FFFF      'Initially, set all I/O pins to outputs
LOW   Power555    'Keep 555 oscillator off
LOW   IRLED       'Start with the oscillator stopped (RESET Low)
HIGH  CS          'Shut down ADC
HIGH  SW1         'Init; 10M closed
HIGH  SW2         'Init; 10K closed
HIGH  SW3         'Init; 100K closed
HIGH  SW4         'Init; 1M closed

OUIHVar = %11110000 'Save states of SW4-SW1
Range = 0           'Initial Range, RangeChg, & AD1Prev
RangeChg = 0

```

```

AD1Prev = 0
zz = 2

***** Send Calibration Command *****
AD1 = %1111000101010101 'Calibration command, Address=%11, CalMode=%11, Range=%00, Data=%0101010101
GOSUB Transmit
***** End Calibration Command *****

LTC1298:
  GOSUB Bed 'Wait for OpAmp to settle on new gain
  HIGH DIO_n 'Set data pin for first start bit.
  LOW CS 'Activate the ADC.
  SHIFTOUT DIO_n,CLK,lsbfirst,[%1111\4] 'Send config bits, ch. 1
  SHIFTIM DIO_n,CLK,msbpost,[AD1\12] 'Get data bits.
  HIGH CS 'Deactivate the ADC.
  IF AD1>1200 AND AD1<3100 THEN IRcomm
  ' RangeChg = 1 'Indicate that Range will change
  IF AD1<=1200 AND Range<3 THEN UpRange 'Increase Gain
  IF AD1>=3100 AND Range>0 THEN DownRange 'Decrease Gain
  GOTO IRcomm
UpRange:
  OUTHVar = OUTHVar<<1 'Shift bits left
  OUTH = OUTHVar
  Range = Range + 1
  RangeChg = 1 'Indicate that Range has changed
  GOTO LTC1298
DownRange:
  OUTHVar = OUTHVar>>1 | $80 'Shift bits right; set bit7
  OUTH = OUTHVar
  Range = Range - 1
  RangeChg = 1 'Indicate that Range has changed
  GOTO LTC1298

IRcomm:
  RangeFix = Range
  'Transmit photosensor data if any condition met
  IF (ResetCount<ResetSpec) THEN IRL
  IF (ABS (AD1Prev-AD1))>((AD1Prev*PCchange)/100) THEN IRL
  IF RangeChg THEN IRL
  IF (Cycles=CyclesSpec) THEN IRL
  Cycles = Cycles + 1
  GOTO LTC1298
IR1:
  Cycles = 0
  RangeChg = 0
  AD1Prev = AD1 'Save previous AD1 result to see if sensor changes
  AD1 = %1100000000000000 | (AD1/4) '6-bit header combined with 10-bit ADC value (or logic)
  AD1 = AD1 | (Range*1024) 'Add range to header (shift bits by 2^10 then or with AD1)
  GOSUB Transmit
  IF (ResetCount=ResetSpec) THEN LTC1298
  ResetCount = ResetCount + 1
  GOTO LTC1298

Transmit:
  Low IRLED 'Start with the oscillator stopped
  High Power555 'Power to 555 oscillator
  Pulsout IRLED,250 'Burst length = 250*2us = 500 us
  Pause AD1.bit0
  Pause 0
  Pause 0
  Pause 0
  Pulsout IRLED,250

```

Pause AD1.bit1  
Pause 0  
Pause 0  
Pause 0  
Pulsout IRLED, 250  
Pause AD1.bit2  
Pause 0  
Pause 0  
Pause 0  
Pulsout IRLED, 250  
Pause AD1.bit3  
Pause 0  
Pause 0  
Pause 0  
Pulsout IRLED, 250  
Pause AD1.bit4  
Pause 0  
Pause 0  
Pause 0  
Pulsout IRLED, 250  
Pause AD1.bit5  
Pause 0  
Pause 0  
Pause 0  
Pulsout IRLED, 250  
Pause AD1.bit6  
Pause 0  
Pause 0  
Pause 0  
Pulsout IRLED, 250  
Pause AD1.bit7  
Pause 0  
Pause 0  
Pause 0  
Pulsout IRLED, 250  
Pause AD1.bit8  
Pause 0  
Pause 0  
Pause 0  
Pulsout IRLED, 250  
Pause AD1.bit9  
Pause 0  
Pause 0  
Pause 0  
Pulsout IRLED, 250  
Pause AD1.bit10  
Pause 0  
Pause 0  
Pause 0  
Pulsout IRLED, 250  
Pause AD1.bit11  
Pause 0  
Pause 0  
Pause 0  
Pulsout IRLED, 250  
Pause AD1.bit12  
Pause 0  
Pause 0  
Pause 0  
Pulsout IRLED, 250  
Pause AD1.bit13  
Pause 0

```
Pause 0
Pause 0
Pulsout IRLED,250
Pause AD1.bit14
Pause 0
Pause 0
Pause 0
Pulsout IRLED,250
Pause AD1.bit15
Pause 0
Pause 0
Pause 0
Pulsout IRLED,250
Low Power555      'Switch off power to 555 oscillator
Return
```