SYSTEM FOR GREENHOUSE CLIMATE MONITORING IN THREE DIMENSIONS

by

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ABSTRACT

The greenhouse in Throckmorton Hall at Kansas State University (KSU) has a temperature and humidity monitoring system. The system updates its measurements every thirty minutes online, and air temperature is controlled by an automated system. Each room has one temperature and humidity sensor box, which provides a suitable reference but is insufficient for more detailed plant research. To provide a distribution of temperature and humidity, a sensing system should be composed of a collection of sensors that gather data simultaneously.

The new multi-point greenhouse monitoring system presented here can be helpful for plant research on a low budget. The demonstration system uses 27 sensor boxes in a 3x3x3 sensor grid (nine sensors at the same height and three different heights). Each sensor box contains temperature, humidity and light sensors that record data once per minute.

MATLAB plots of these data indicate that temperature varied between 20 and 25 °C at night. Daytime temperatures are increased by sunlight, and rise to a maximum around noon. Sun-lit areas have higher temperatures than shaded areas, and during cloudy days all areas were almost the same temperature.

Relative humidity is inversely related to temperature changes; when the temperature is stable, humidity is also stable. Humidity drops at noon because of increasing temperature and rises again at night. When researchers water the plants, humidity increases immediately.

Greenhouse light intensity depends on the room design and the angle of the sunlight. Direct sunlight makes an obvious difference in shaded areas, and cloudy days promote even light distribution. Lighting at night time diffuses well at lower heights.

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Acknowledgments

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CHAPTER 1: INTRODUCTION

A. Motivation

Monitoring the greenhouse environment is important for effective plant growth. Three environments exist for experimental plant growth: a field crop, a greenhouse and a growth chamber. A greenhouse is an environment that is more stabilized than a field crop: it uses solar energy but helps plants to avoid natural calamities such as hail, strong winds, and snow [1]. A greenhouse makes a close-to-field environment using solar energy, where a growth chamber is a fully artificially controlled environment [2]. The Kansas State University (KSU) greenhouse in Throckmorton Hall uses a heater and ventilation fan to maintain room temperature during the winter or at night time during cold weather. The KSU greenhouse has 130 rooms, and each room temperature is maintained by an automatic temperature control system. Monitoring temperature is important for plant researchers because moderate temperature changes affect for plant growth, and recording these temperatures is helpful where analyzing research data [1]. The monitoring system for the whole KSU greenhouse was recently upgraded to a digital system which can monitor temperature and humidity. However, the system has one sensor per room. While it is good to know representative climate for a room can benefit from knowing detailed spatial climate changes. Equalization of climate distributions in a greenhouse would aid consistent plant growth, and monitoring climate distributions would provide a research capability suitable for many types of plant studies.

On a side note, the current measurement system in Dr. Vara Prasad's greenhouse room uses stand-alone loggers such as Onset's TidbiT and Hobo U10 systems [3]. TidbiT is a temperature sensor, and the Hobo U10 has two sensors: temperature and humidity. Each U10 device has one sensor, so two devices have to be used to acquire temperature and humidity. To collect data with this Onset system, researchers must bring the devices to their labs after finishing these measurements and then connect each sensor to a computer to download the sensor data. Moreover, a TidbiT is a disposable device because the battery cannot be replaced; therefore, the device itself must be replaced every 1-2 years. For a light meter, Dr. Prasad's lab uses a Spectrum Technologies' Fieldscout with a 6-quantum sensor bar [4]. It is a good device to measure light intensity, but it does not have a logging function. In aggregate, these devices cost more than a thousand dollars total per room and indicate the need for a more flexible, cost-effective solution.

CHAPTER 2: NETWORK PROTOCOL

A. New Digital System

The new greenhouse monitoring system is a digital network that uses the 1-Wire system developed by Maxim Integrated Products, Inc. [5]. A 1-Wire network has the advantage of connecting a sensor in series with a data line and installing different kinds of sensors in the same network; in a greenhouse context, this system enables the addition of a humidity sensor to a temperature-only design. Each sensor has a unique identification (ID) number, and the master device recognizes each sensor device by its ID. A 1-Wire system can be inexpensive because each sensor box is simple, and replacing or adding a sensor can be done easily. Programming each device is not required because the system controls all devices at the master device.

The current 1-Wire monitoring system in the Throckmorton greenhouse uses one sensor box that has been installed in each greenhouse room. The sensor box is placed at the center of the room and measures and records temperature and humidity every thirty minutes. Therefore, only one sample per room is uploaded to the web-accessible database. Taking advantage of the characteristics of a 1-Wire network (See Chapter 2), adding a light meter to the sensor box and measuring climate data at multiple points in the room will provide distributions of temperature, humidity and light intensity that will enable new plant growth research. This research is based on this need.

B. 1-Wire Protocol

The network protocol uses the “1-Wire” bus system developed by Maxim Integrated Products. This is a digital protocol that uses one line to both receive and transmit data. A unique 64-bit identification number on each device enables series connection with other devices. It is easy to add sensor boxes after the system network is built because the master device (in this case a personal computer (PC)), controls all sensor devices and the measurement time intervals.

When using one line for communication, timing is important. The 1-Wire protocol consists of three signals (states): reset, read, and write. A 1-Wire bus is connected to a pull-up resistor to keep it in a high state. Then a microcontroller pulls the signal low for a certain time and waits for signals from a 1-Wire device. Figure 1 is the timing diagram of the reset pulse[6]. The 1-Wire data line must pulled up to 3-to-5 V, and the data line is kept at a normally high condition. For a reset pulse, the master pulls low for at least 480 μS, and then the master is set to high and will wait for the presence pulse from a 1-Wire device after 15-60 μs. The presence signal is low between 60 and 240 μs [6]. This reset pulse has to be used every time before sending a 1-or-2 byte command to a 1-Wire device.

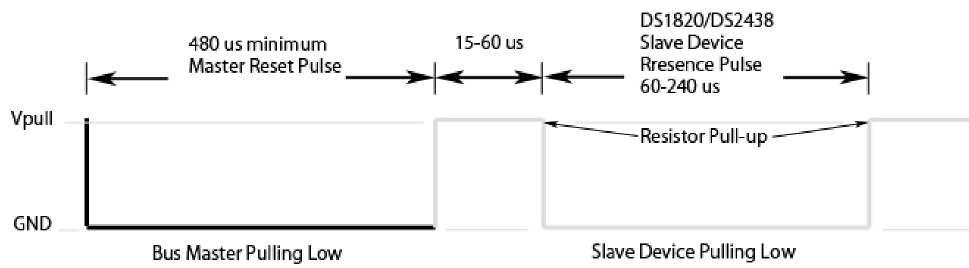

Figure 1. Timing Diagram for 'Reset Pulse' on 1-Wire Bus [6]

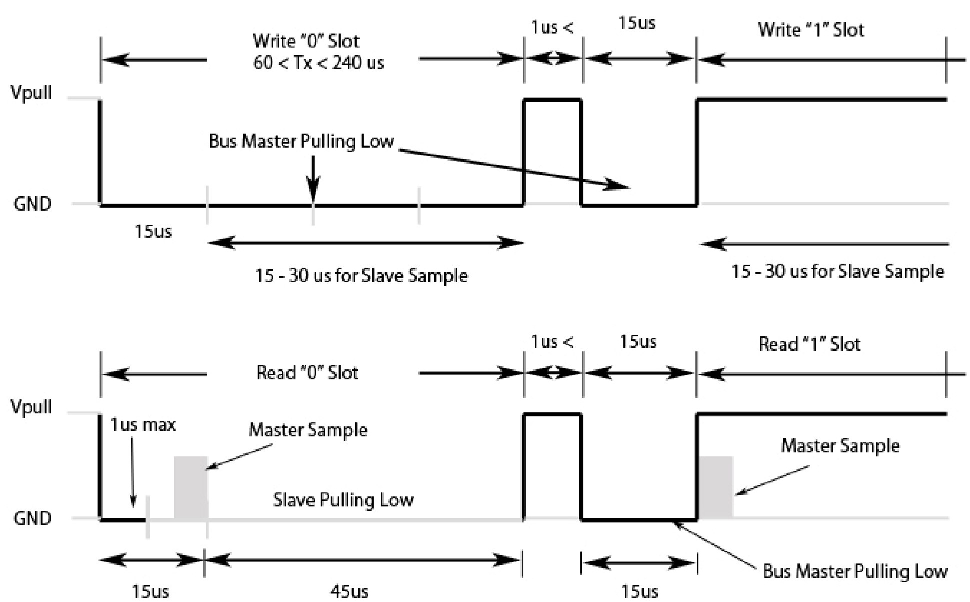

Figure 2. Timing for the Write and Read Bits on a 1-Wire Bus [6]

Figure 2 displays the write and read bits. The write and read bits are controlled in multiples of 15 μs. The figure shows one example of a DS18S20 temperature sensor, but all 1-Wire devices use the exact same timings.

C. Sensor Network

C.1 Wired Network

For this 1-Wire network, CAT5e cable is used to maximize noise suppression. A wired network is used to minimize construction and maintenance costs. A wireless network would be useful, but it would require battery replacement, and each sensor box would be expensive because of the radio frequency (RF) units and microcontrollers.

Pin assignments for the CAT5e cable and sensor box are consistent with assignments at Hobby-Boards.com to make them compatible with other 1-Wire products [7]. Hobby-Boards has many 1-Wire products, and sharing the same network enables the use of aftermarket products. Table 1 shows the pin assignments for the RJ45 jack. There are data, 5 V, 12 V and ground lines on the CAT5e cable.

1	2	3	4	5	6	7	8
GND	5 V	GND	DQ (data)	GND	N/A	9 V-12 V	GND

Table 1. Pin Assignments for the RJ45 jack

The interface device between the computer and the 1-Wire network is shown in Figure 3. It is the DS9490R which Maxim Integrated Products provides. It has a USB input for the computer, and RJ12 6-line phone cable is used to communicate to the 1-Wire network. This device also has a 64-bit ID, and it is recognized as a bus master.

Figure 3. DS9490R 1-Wire USB interface

C.2 Data Management

C.2.1 Software

The software uses the “1-Wire File System” (OWFS) developed by Paul Alfille [5]. This is a Linux-based open source tool installed under Ubuntu 8.04. Before installing the OWFS, the following tools should be installed: gcc, g++, automake, autotools-dev, autoconf, libtools, libusb-dev, libfuse-dev, fuse-utils, swig, python2.4-dev, tcl8.4-dev, and php5-dev [5]. A bash shell script is used to run the OWFS. The code is included in Appendix A.

C.2.2 System Operations

To start the OWFS, enter the command in Figure 4 at the Linux prompt,

```
user$ /opt/owfs/bin/owfs   –u   /user/(desired directory)
```

Figure 4. Script for Starting the OWFS

“/opt/owfs/bin/owfs” starts the OWFS, and “–u”is the option code for USB. “/user/(desired directory)” is the location of 1-Wire folders.

Figure 5 is an example OWFS directory structure for two 1-Wire devices. When the OWFS reads the 1-Wire network, it creates a directory for each ID, and each ID has sub-directories to hold data. Figure 5 implies two DS2438 microcontrollers. The first two digits (26) are the family code of the 1-Wire device. A dot after the first two digits separates the sensor ID and the family code, where in this case 628C78000000 specifies a first humidity device and AD9078000000 specifies second device. Figure 5 shows an expanded directory for ID AD9078000000: “/temperature” is for temperature, “/HIH4000/humidity” is for humidity, “/vis” is for light intensity, “/VAD” is for ADC voltage, and “VDD” is for the DS2438 input voltage. VDD in this network is 5 V, which comes from the 78L05 5 VDC regulator.

```
/user/(specific directory)/81.47ED26000000/
                    |------ /26.628C78000000/
                    |-------/26.AD9078000000/
                                      |----------/temperature
                                      |----------/HIH4000/humidity
                                      |----------/vis
                                      |----------/VAD
                                      |----------/VDD
```

Figure 5. Sample OWFS Directory Structure

To read these data, use a “cat” or “grep” command in a shell script as in the example in Figure 6. When data from many sensors are needed, a wildcard sign (*) can be used, e.g., “/26.*/”.

```
user$ cat /user/(specific directory)/26.AD9078000000/temperature
```

Figure 6. Example for Temperature Reading

CHAPTER 3: THREE-DIMENSIONAL SENSOR SYSTEM

A. Sensor Description

The difference between the 1-Wire sensor network and the original greenhouse system is the use of multiple sensors in one greenhouse. The original system used only one sensor box per room, but this new system uses 27 sensor boxes in a 3x3x3 rectangular grid. Multiple sensors will measure the distribution of room climates versus time in both vertical and horizontal directions. For this system, a light sensor was added to gauge plant growth. It can help researchers compare relative light levels during conditions such as daytime, nighttime, sunny days and cloudy days. Therefore, each sensor box contains temperature, humidity and light sensors, and boxes are placed at three different heights, yielding nine sensors per level. Initial experiments were done at the greenhouse in Throckmorton Hall room SG101J.

B. Sensor Diagram

The reference 1-Wire network uses a 6-channel hub to spread sensor branches and reduce network weight because the system has to manage at least 130 sensor boxes. For the three-dimensional sensor system used here, this 1-Wire hub was not used because the total sensor count is only 27. Figure 7 contains a diagram of the sensor network. Each sensor is connected in series with CAT5e cable, and two 9 VDC power supplies are placed at the beginning and the end of the network without power loss. The interface between the PC and the 1-Wire system is the DS9490R USB adapter in Figure 3.

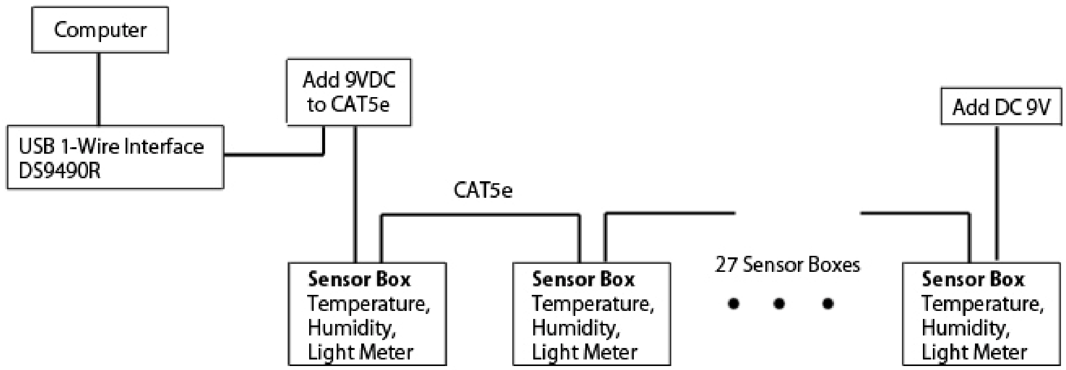

Figure 7. Sensor Network Diagram

C. Sensor Box

The sensor box consists of a 5 V DC regulator and temperature, humidity, and light sensors. Although the CAT5e cable has a 5 V DC line, each sensor box uses 9 V DC input for its internal 5V regulator because multiple sensors will increase power consumption. The DS2438 in each sensor box handles all sensors (the temperature sensor is a built-in sensor in the DS2438). The humidity sensor is Honeywell's HIH-4000. This sensor is a capacitive humidity sensor and has an integrated circuit which converts humidity to linear voltage. This humidity sensor must avoid direct sunlight because of its sensitivity. The light sensor uses a Sharp BS120E0F photodiode. This light sensor has an optical band pass filter which passes visible light over the range of 400-700 nm. Most light meters for plant research have a sensitivity range between these limits and specify Photosynthetic Active Radiation (PAR), a parameter with units of uMolm^{-2}s^{-1}[8]. Figure 7 contains the picture of a sensor box.

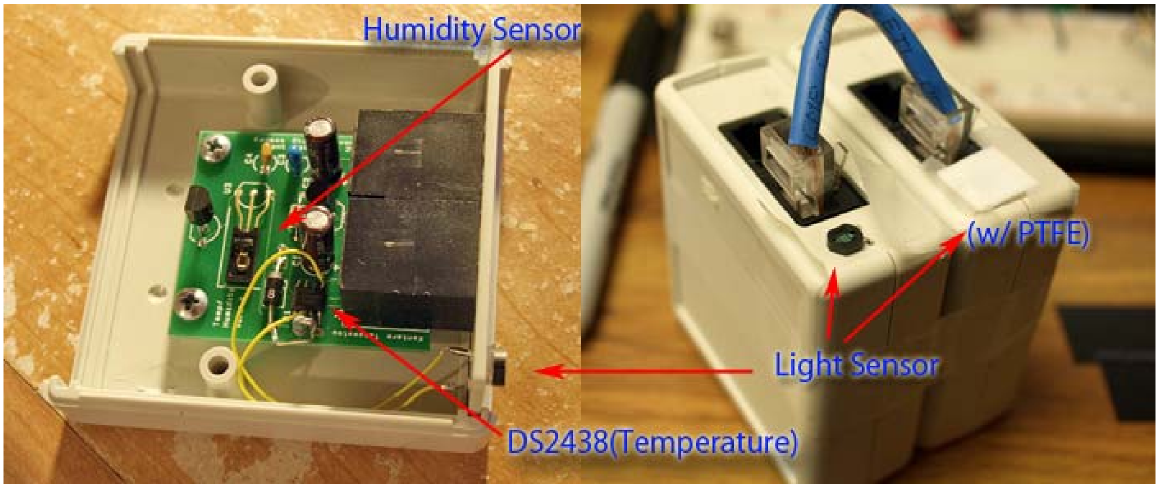

Figure 8. Sensor Box

C.1 DS2438 Microcontroller

The DS2438 microcontroller is a chip to control 1-Wire devices. The OWFS will communicate with this chip to read ID and sensor values. The DS2438 is designed to be a battery monitor integrated circuit. For this system, it is used to interface with temperature, humidity, and light sensors. The DS2438 has an internal temperature sensor which has a 13-bit resolution over the range of -55 to 125 °C yielding 0.03125 °C per bit. The humidity and photodiode sensors are connected to the DS2438's ADC ports [9]. Each DS2438 chip has a unique 64-bit ID. The first two bits are the family code (26), and the last two bits are Cyclic Redundancy Check (CRC) bits. These CRC bits are stored in ROM and are generated from the first 6bytes. The polynomial function for CRC bit generation is shown below [9].

$$CRC = X^8 + X^5 + X^4 + 1$$

These CRC bits are used when the Master device (PC or microcontroller) finds 1-Wire devices. DS2438 RAM has 7 pages, with 8 bytes per page, and this greenhouse system uses page 0 (Table 2). The first byte (0) is the status and configuration byte. Bytes 1 and 2 are temperature values, bytes 3 and 4 are humidity values, and bytes 5 and 6 are light intensity.

Page	Byte	Contents	R/W	NV
0	0	Status/Configuration	R/W	Yes
	1	Temperature LSB	R	No
	2	Temperature MSB	R	No
	3	Voltage LSB	R	No
	4	Voltage MSB	R	No
	5	Current LSB	R	No
	6	Current MSB	R	No
	7	Threshold	R/W	Yes

Table 2. RAM Map on DS2438 Page 0 [9]

Table 3 shows the assignments for byte 0. For this system, the IAD and AD bits are used. The IAD bit enables byte 5 and 6 [9], where “1” is an enable bit and “0” is a disable bit. When this bit is 1, the current ADC is enabled with a 36.41 Hz sampling rate. AD (bit 4) is a general A/D select bit. When this bit is “1”, VDD will be monitored. When the bit is “0”, a general ADC port (pin 4) is selected [9]. The default setting is 1. Therefore, to read a humidity value, the master must set this bit to “0” before reading byte 3 and 4 on page 0.

X	ADB	NVB	TB	AD	EE	CA	IAD

Table 3. Status/Configuration Register [9]

Table 4 below is the list of commands for the DS2438 [9]. “Search ROM” sends 0xF0h; this is used when a master device identifies unknown 1-Wire devices. “Match ROM” sends 0x55h; this is used to talk to a specific device after identifying IDs with the “Search ROM” command. When 0x55h is sent to a 1-Wire bus, only the matched device responds to the master. This command is used to get sensor values from each device. “Write Scratchpad” sends 0x4Exxh; this command sets the IAD and AD bits. “xx” is the number of pages; therefore, for setting these two bits, the command is 0x4E00h. Read Scratchpad is sending 0xBExxh. “xx” is also the number of pages. When the device receives 0xBE00, it sends all eight bytes on page 0 to the master.

Table 4. List of ROM Commands

Command Name	Hex
Search ROM	0xF0h
Match ROM	0x55h
Write Scratchpad	0x4Exxh
Read Scratchpad	0xBExxh

C.1.1 HIH-4000 Humidity Sensor

Honeywell's HIH-4000 (shown in Figure 9. HIH-4000 Humidity Sensor) is used for the humidity sensor. This sensor is a capacitive sensor that has an integrated circuit to convert from capacitance to voltage: its output in linear with humidity. The measurement range is from 0-100%, and the supply voltage should be 5 VDC. Its output is connected to a general ADC port on the DS2438. This sensor is sensitive to light; therefore, the sensor should avoid direct sunlight [10].

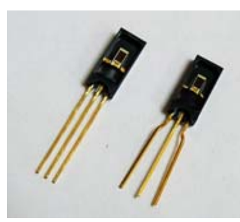

Figure 9. HIH-4000 Humidity Sensor

C.1.2 BS120E0F Photodiode

Sharp's BS120E0F is used for the light meter (Figure 10. BS120E0F Photodiode). This blue enhanced sensor has an optical band pass filter on the top of the package: the wavelength range is 400-700 nm, and the response peaks at 550 nm (Figure 11) [11]. This spectrum is very similar to the spectrum for a Fieldscout 6-Sensor Bar [4], the hand-held wand currently used to obtain light readings in the Throckmorton greenhouse. The curve of voltage versus received light intensity is almost linear, as noted in the Calibration Section in Chapter 4. This sensor is connected to a battery monitor input on the DS2438. The maximum voltage output can be 0.25 V: the limit of the ADC. The voltage sensing resistor was chosen to be 1.78 kΩ so as to not saturate the ADC under the direct sunlight condition; 0 to 0.25 V with 0.0002441 V of resolution has 1024 steps. If the direct sunlight condition will be half of the maximum voltage (0.125 V), it will have 512 steps from 0 V: enough to measure light intensity. For example, if the maximum light intensity is 2000 uMol $m^{-2}s^{-1}$ at 0.125 V, the resolution will be 3.9 uMol $m^{-2}s^{-1}$ per bit.

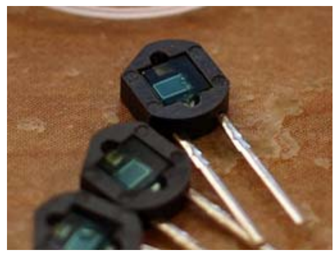

Figure 10. BS120E0F Photodiode

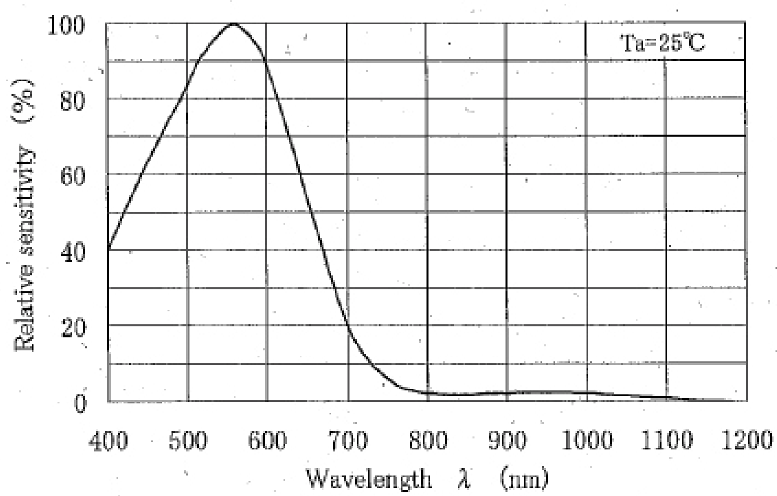

Figure 11. BS120E0F Spectrum [11]

D. 1-Wire Checker/Reader

A standalone 1-Wire Checker/Reader is shown in Figure 12. This was designed to check ID or sensor values on a single sensor box without using a PC, a useful operation when the system is operational. This checker is capable of simultaneously reading up to four 1-Wire devices and supports two types of chips: the DS1820 and the DS2438. When power is on, an 8-byte ID (16 hex numbers) is shown on the top line of the LCD; temperature will be displayed on the bottom line first. By pushing a select button, the bottom line on the LCD cycles between to temperature, humidity, and light intensity. When a new sensor box is available, pushing a reset button acquires its new ID number, and its data can then be viewed. The code for this checker is included in Appendix D.

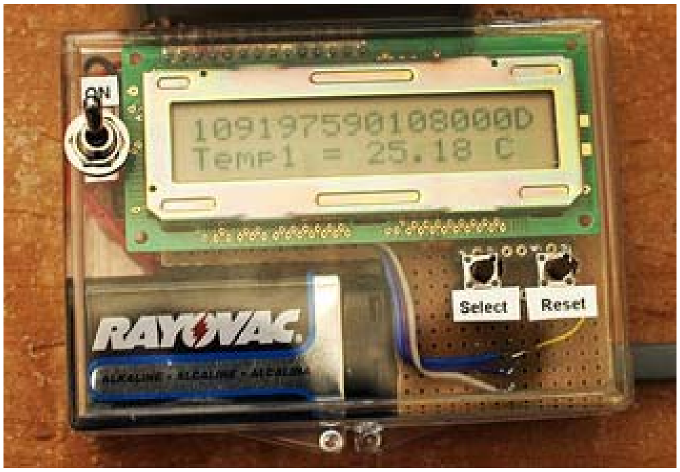

Figure 12. 1-Wire Checker/Reader

CHAPTER 4: CREATING A LIGHT METER

A. Sensor Selection

Each BS120E0F photodiode did not come with a separate calibration curve, so calibration was required for each photodiode in order to gain comparable data from all 27 sensor boxes. The BS120E0F was selected over a plain photodiode: Cliarex's CLD160, which has a typical peak sensitivity at 850 nm, which is in the infrared range and is less sensible for measuring the visible light wavelengths where photosynthesis occurs [12].

Calibration of each photodiode was performed with a Spectrum Technologies, Inc. Fieldscout 3415FX (S/N: 263, MFG Code: 802), a 6-sensor bar quantum line sensor (S/N: 213 MFG Code: 802 - see Figure 13). This light meter can measure up to 2500 uMol $m^{-2}s^{-1}$. Its published sensitivity spectrum is shown in Figure 14 [4].

Figure 13. Fieldscout 3415FX with 6-Sensor Quantum Line Sensor

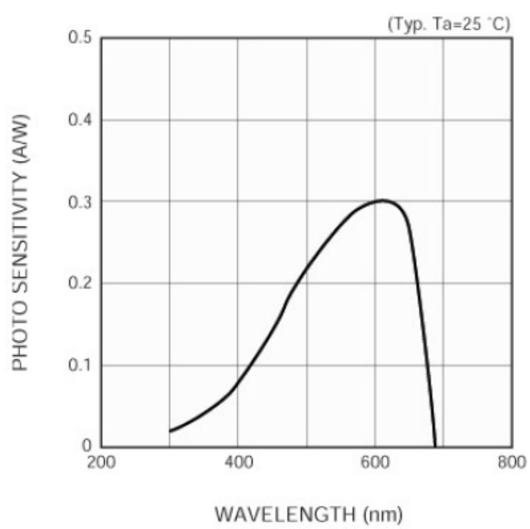

Figure 14. Spectrum of the 6-Sensor Quantum Line Sensor [4]

Figure 15 is a calibration curve for a CLD160 photodiode. The curve is approximately linear from 0 to 700 uMol $m^{-2}s^{-1}$ and exhibits $1-e^{-x}$ behavior over its entire range. This curve indicates this sensor cannot measure more than ~1200 uMol $m^{-2}s^{-1}$. Above 700 uMol $m^{-2}s^{-1}$, the light condition is almost direct sun, and this graph indicates that the plain photodiode is not a proper device for this application because it is too sensitive to the infrared component of direct sunlight. A similar curve for the BS120E0F photodiode is shown in Figure 16. This graph is almost linear versus light intensity and is more appropriate for measurement in direct sunlight.

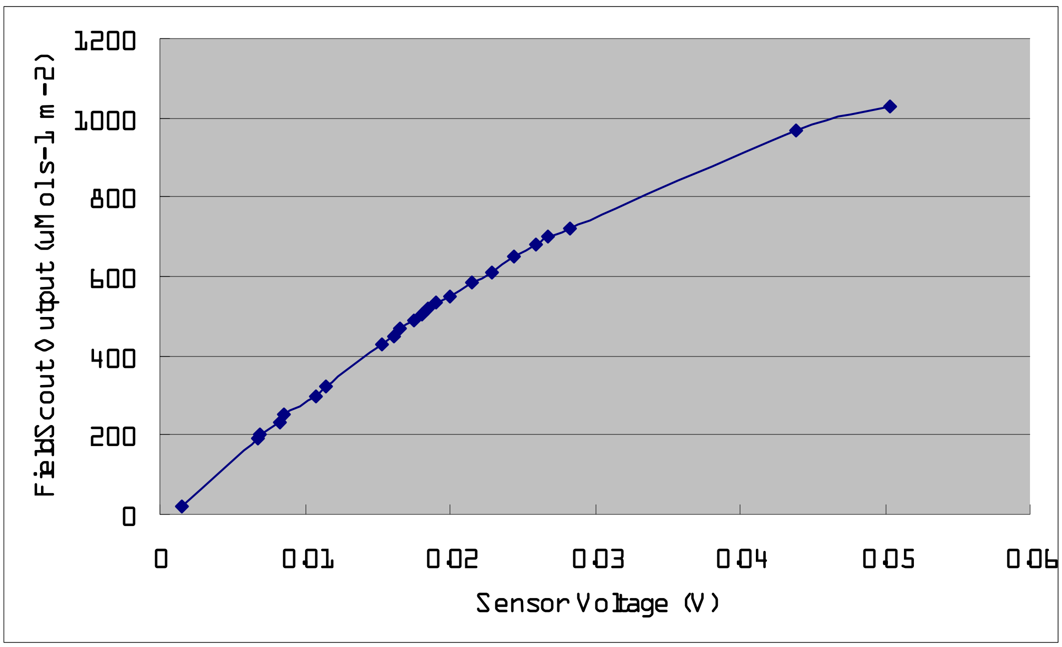

Figure 15. Calibration Curve for a CLD160 with Sunlight

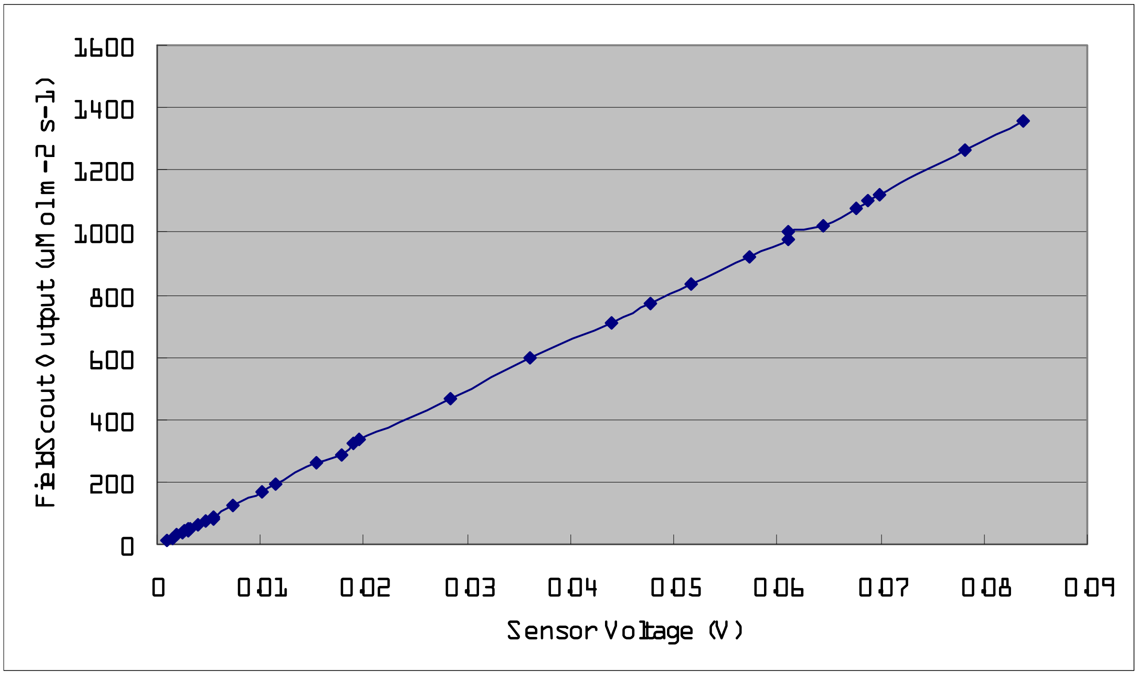

Figure 16. Calibration of BS120E0F with Sunlight

A polytetraflouroethylene (PTFE, or teflon) sheet with a 0.8 mm thickness is used on the top of the photodiode as a light diffuser. It delivers incoming light to the sensing area evenly with a relatively flat wavelength response. PTFE sheets are widely used as bouncers for flash photography due to their optical characteristics [13].

B. Calibration of Light Sensors

B.1: Measurement

The calibration measurement was performed for the 27 sensors at the same time during a clear sunny day. To get all sensor boxes as close to the sensor bar as possible, three 9-sensor box assemblies were created and placed around the sensor bar (Figure 17). The measurements were done from 8:00 AM to 1:00 PM, and the Fieldscout FX3415 was used for a reference light intensity. When the FX3415's intensity value was input to the shell screen, a script automatically recorded the sensor voltages for all 27 light sensors. The overall range of the recorded intensities was from 0 to nearly 1500 uMol $m^{-2}s^{-1}$. A third-order polynomial curve with the Y axis forced to zero was used to generate these calibration for equations. See Appendix C for detailed data.

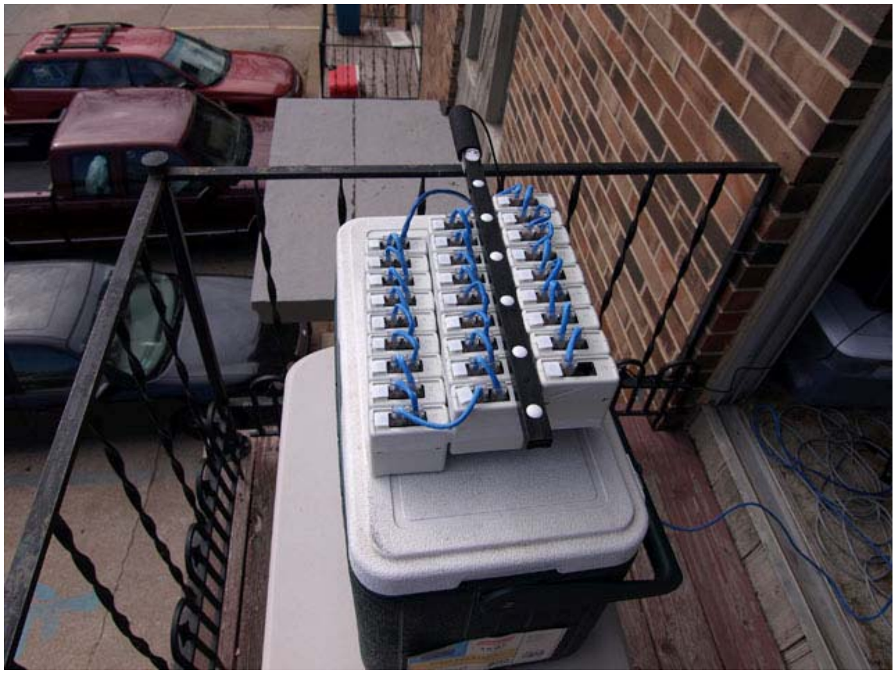

Figure 17. Sensor Calibration Setup

B.2: Fitting Equations

The conversion equations were calculated using MATLAB. A `polyfit()` function in MATLAB cannot be used for this calibration because it cannot accommodate a forced Y intercept. When the Fieldscout shows zero light intensity, the light sensors also show a zero. Therefore, a custom function was used for the polynomial fit with a forced, zero Y-intercept (see Appendix C for the source script) [14]. This computation uses the same technique as the trend line function in Microsoft Excel. Using MATLAB, polynomial coefficients are saved to a text file with each column corresponding to a separate sensor. When using the MATLAB `polyval()` function to plot actual data dots and polynomial curves, there has to be careful implementation of the number "n" in polyval (n=4, not 3) because the polynomials have a zero Y-intercept; therefore, the fourth number is treated as zero. The calibration curves and coefficients are listed in Appendix D.

CHAPTER 5: GREENHOUSE MEASUREMENTS

A. Sensor Box Placement

The three-dimensional measurement system was housed in Throckmorton SG101J, one of the greenhouse rooms in Throckmorton. Sensor boxes were placed in a 3x3x3 grid. Figure 18 contains a top view of the sensor locations. The sensor boxes were numbered around the outside, with the last one in the center. Sensors 1 to 9 were the top layer, sensors 10 to 18 were the middle layer, and sensors 19 to 27 were the bottom layer. Figure 19 is the actual picture of room SG101J. One additional temperature sensor was placed into the blower duct, which is circled in black in Figure 19. This sensor indicated when the blower turned on, and it helped to show how the blowing air affects changing temperature in the greenhouse.

Figures 20 to 22 illustrate the dimensions of the sensor grid. Figure 20 is the horizontal separation: the X direction has a 183 cm interval, and the Y direction has a 200 cm interval. The distance from Sensor 3 to the outside wall is 90 cm. Figure 21 shows the vertical separation: the Z direction has a 70 cm interval, and the distance is measured from the light source at the top.

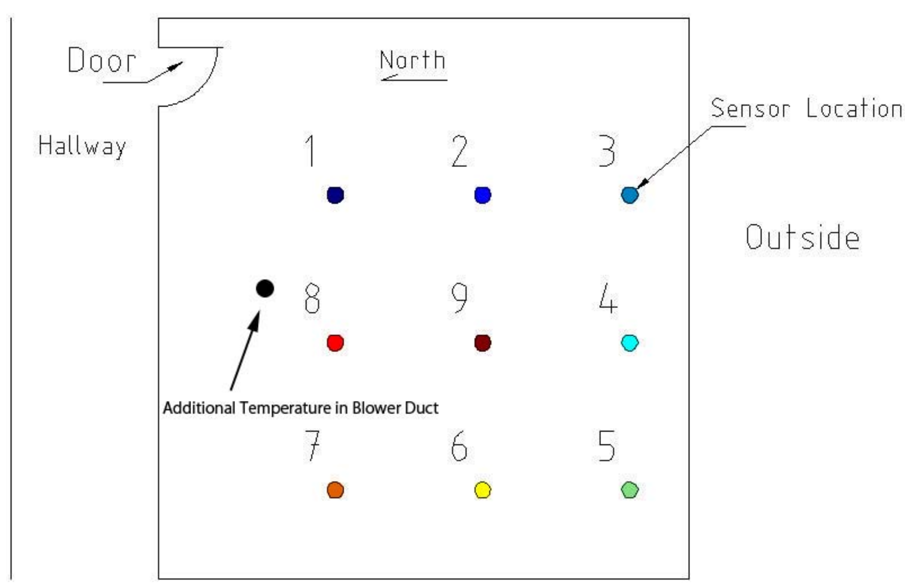

Figure 18. Top View of Sensor Location

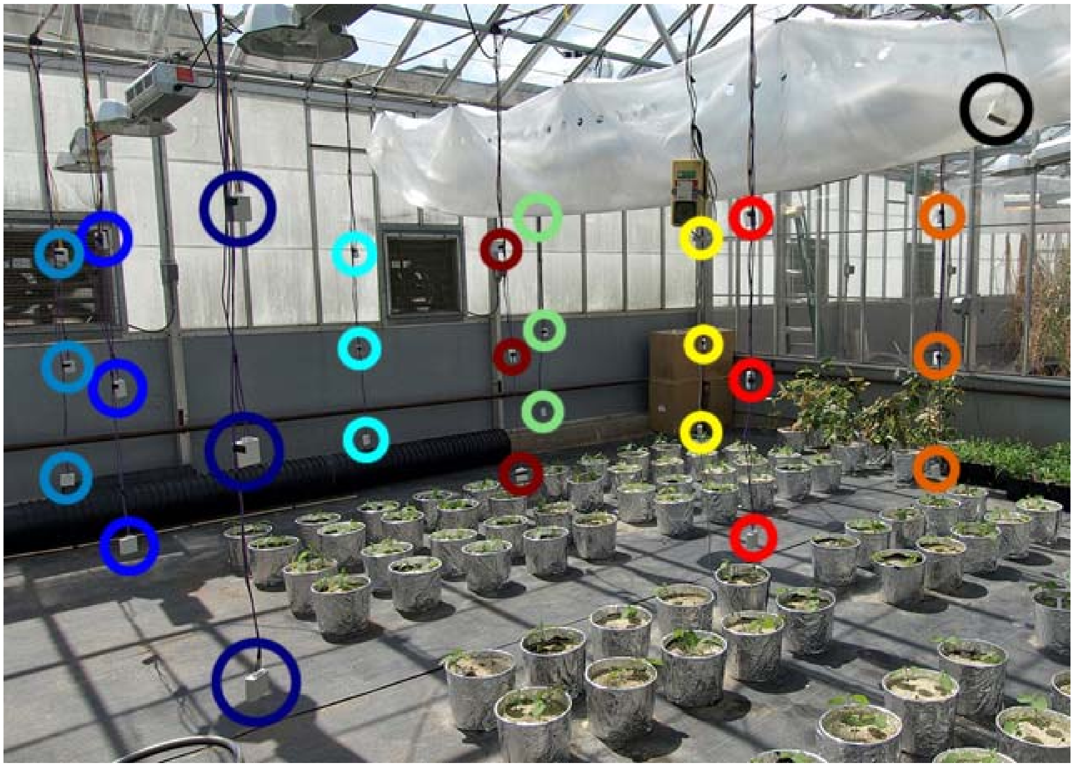

Figure 19. Picture of the Greenhouse for the 3-Dimensional Measurements (corresponding sensors are circled with similar colors)

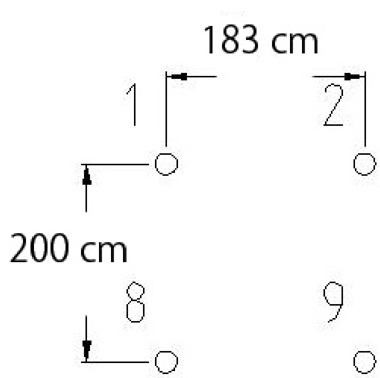

Figure 20. Horizontal Sensor Box Separations

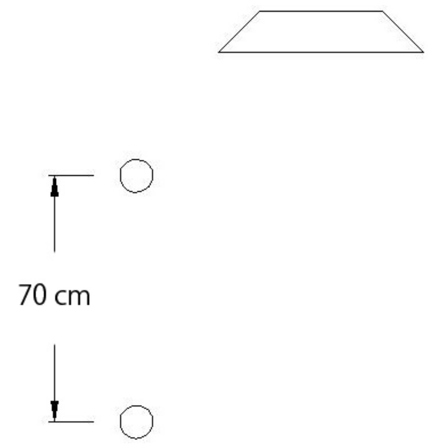

Figure 21. Vertical Sensor Box Separations

Figure 22 is an illustration of the distance between the light source and a sensor box. In the top layer, four sensors are very close to the light source (Sensors 1, 2, 3, and 7). The distance D for Sensors 1, 2 and 5 is 56 cm; the Sensor 3 distance is 67 cm, and the Sensor 7 distance is 77 cm. Because the sunlight is coming from the South, which is opposite the hallway, each light sensor should face the south direction to gather light effectively.

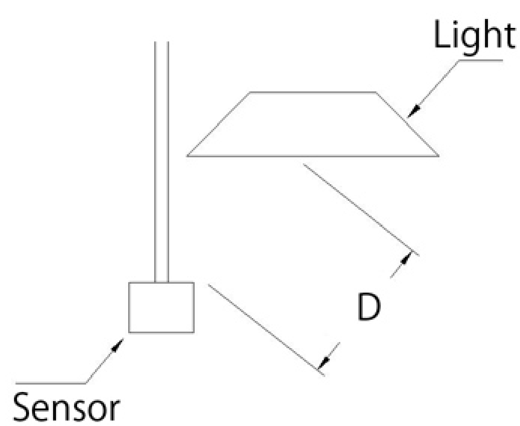

Figure 22. The Distance a Sensor and the Light Source

Measurements were taken from April 3 to 7, 2009. April 3rd was a snow/cloudy day, and April 4-7 were sunny days. The data were taken every minute; therefore, each day yielded 1439 data points for 27 columns, plus time values. A shell script was used to collect data. It created a folder for each day and text files of temperature, humidity and light intensity.

CHAPTER 6: ANALYSIS

A. Plotting

Two dimensional (2D) plotting is good to compare vertical or horizontal sensor groupings or perhaps individual sensor data versus time, but three-dimensional (3D) plots are needed to visualize either (a) data from the entire sensor grid at a given time or (b) data from a linear sensor grouping versus time. For the latter, the `ribbon()` function in MATLAB is used. In this context, the 27 sensors are numbered 1 to 9 respectively for the top, middle, and bottom layers. Figure 23 is an example plot of temperature versus time for the 9 sensors on the top layer. This plot layout is effective for visualizing spatial temperature distributions at the same relative height. Other plots for humidity and light intensity use the same layout.

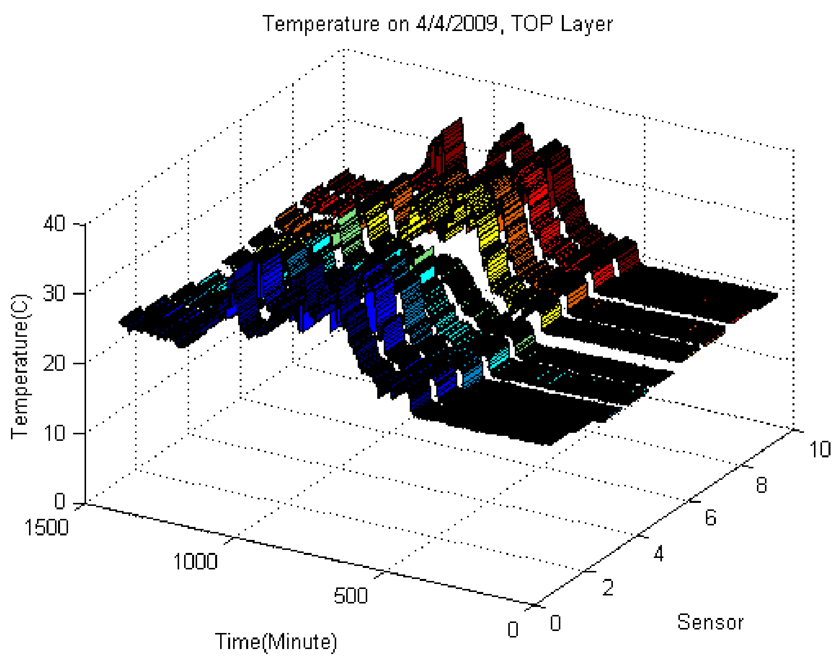

Figure 23. Example Temperature Plot for the Top Layer

B. Nighttime Analysis

B.1 Light Intensity

Usually, the artificial light in the greenhouse turns off at 8:00 PM and turns on at 8:00 AM. However, the light was on all night from April 4, 2009 to the morning of April 5, 2009. This was due to a control error in the temperature control system, but fortunately it was helpful for analyzing the relative effect of the artificial lighting.

Figure 24 is a collection of the layered data for night time on April 4, 2009. As seen in the top layer, Sensors 1, 2, and 5 are the strongest at the completion of the session, nearly 400 uMol $m^{-2}s^{-1}$. The second highest intensity comes from Sensors 3 and 9 at 300 uMol $m^{-2}s^{-1}$. Sensors 6 and 8 are the weakest. Data from Sensors 1, 2, 3, 5, and 7 relate to their proximity to the light. Sensors 1, 2 and 5 are the closest at 56 cm, Sensor 3 is at 67 cm, and sensor 7 is at 77 cm. The middle layer is relatively weaker than the top layer, and the intensity relationships in the middle layer are the same as the top layer; the bottom layer shows the overall weakest light intensity, and this layer is darker but evenly distributed.

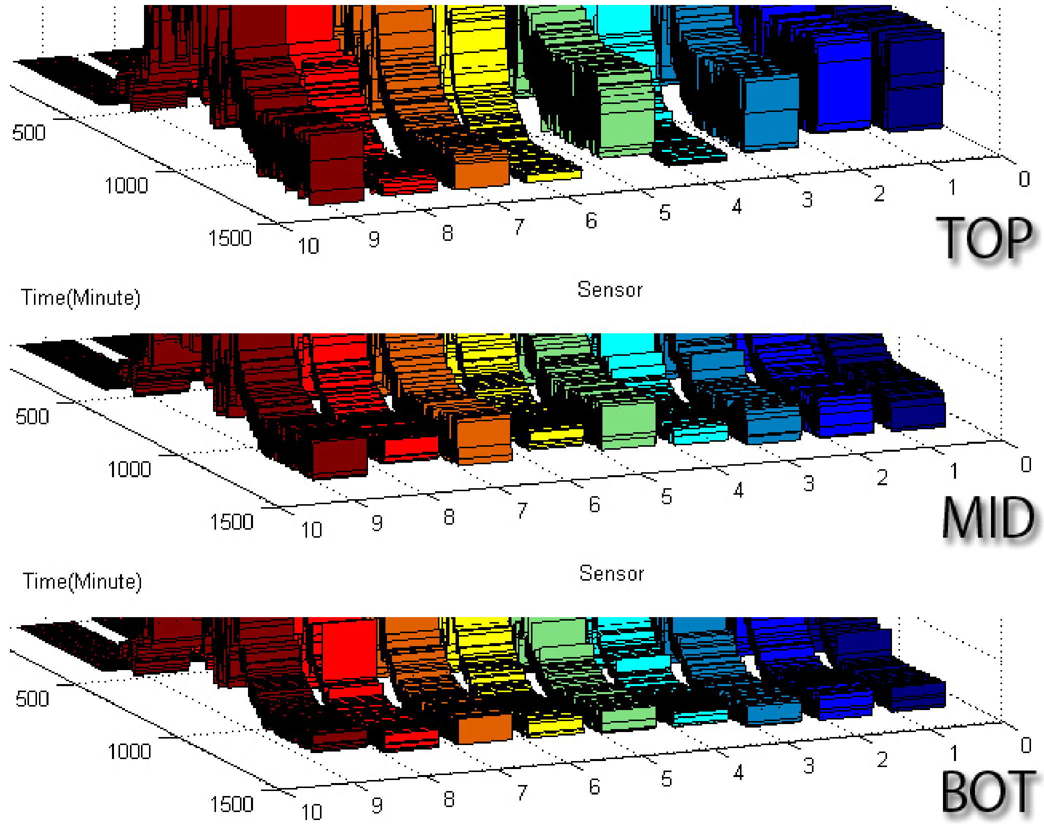

Figure 24. Nighttime Comparison for 4/4/2009

B.2 Temperature and Humidity

Now, for temperature, the difference between light and dark is clear. Figure 25 shows data from Sensors 1, 5, and 9 at night time with a no-light condition. The time is between 1:40 AM and 3:20 AM on April 4. Temperature variations versus time and position are small: 0.5 to 1 °C. Oddly, temperatures on the bottom layer are higher than the corresponding temperatures in the top and middle layers at location 5 and 9. We surmise that this is caused by radiant heat form the ground the night.

Figure 26 is the temperature in the duct tube at the same times as in Figure 25. As seen in this graph, the air blower is turning on during the positive slope and off during the negative slope. This behavior is clearly the cause of the oscillations in Figure 25. The duct temperature is controlled between 20 °C and 30 °C.

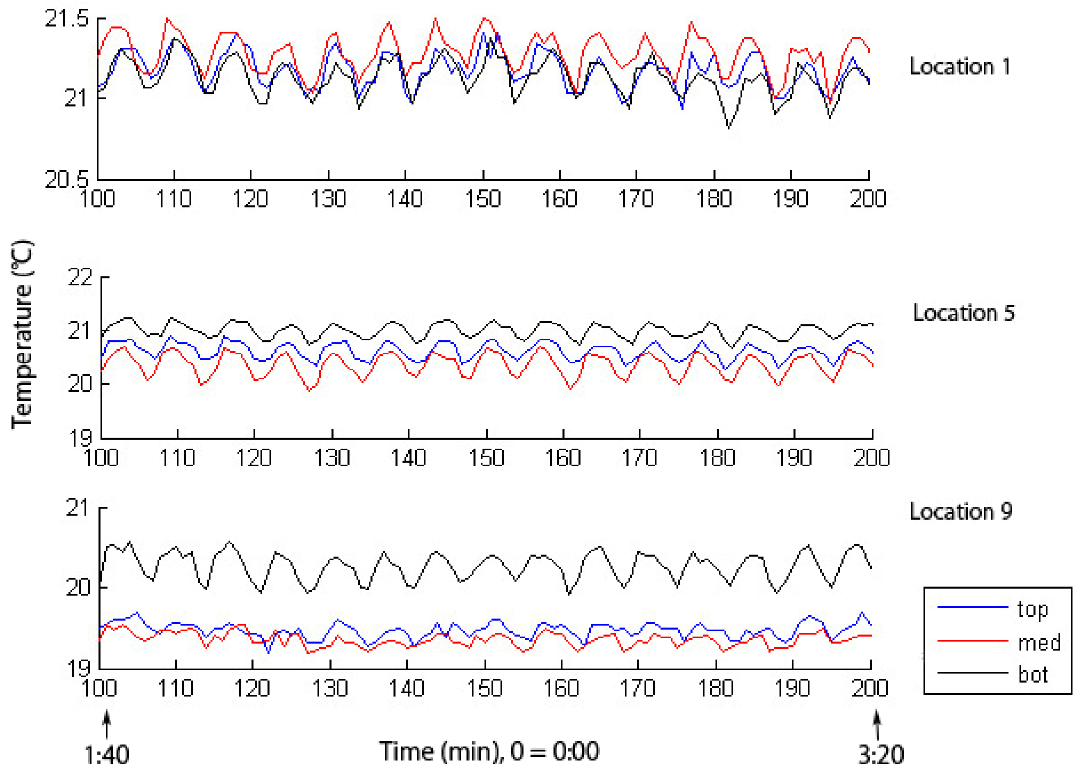

Figure 25. Nighttime Temperature for a Light OFF Condition

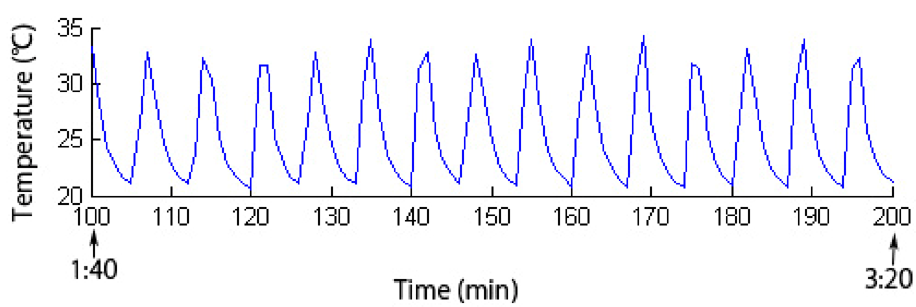

Figure 26. Duct Temperature for a Light OFF Condition

B.2 Temperature and Humidity

Figure 27 contains the temperature plots from 8:00 PM to 12:00 AM on the same day (April 4). The evening of April 4 was warmer than the morning. Locations 1 and 9 indicate that the top sensors are warmer than the others, most likely because of heat radiation from the light source. At location 5, the top and bottom sensor are at almost the same temperature, and the bottom sensor is just a little lower than the other two. Figure

28 displays the temperature in the duct tube over the same time frame as in Figure 27. The air blower is not working at the beginning of this time range because the average room temperature is warmer than in the early morning. This behavior is apparent in Figure 27. The blower frequency increases to keep the temperature above 20 °C as time passes into midnight. This indicates the room temperature is gradually decreasing.

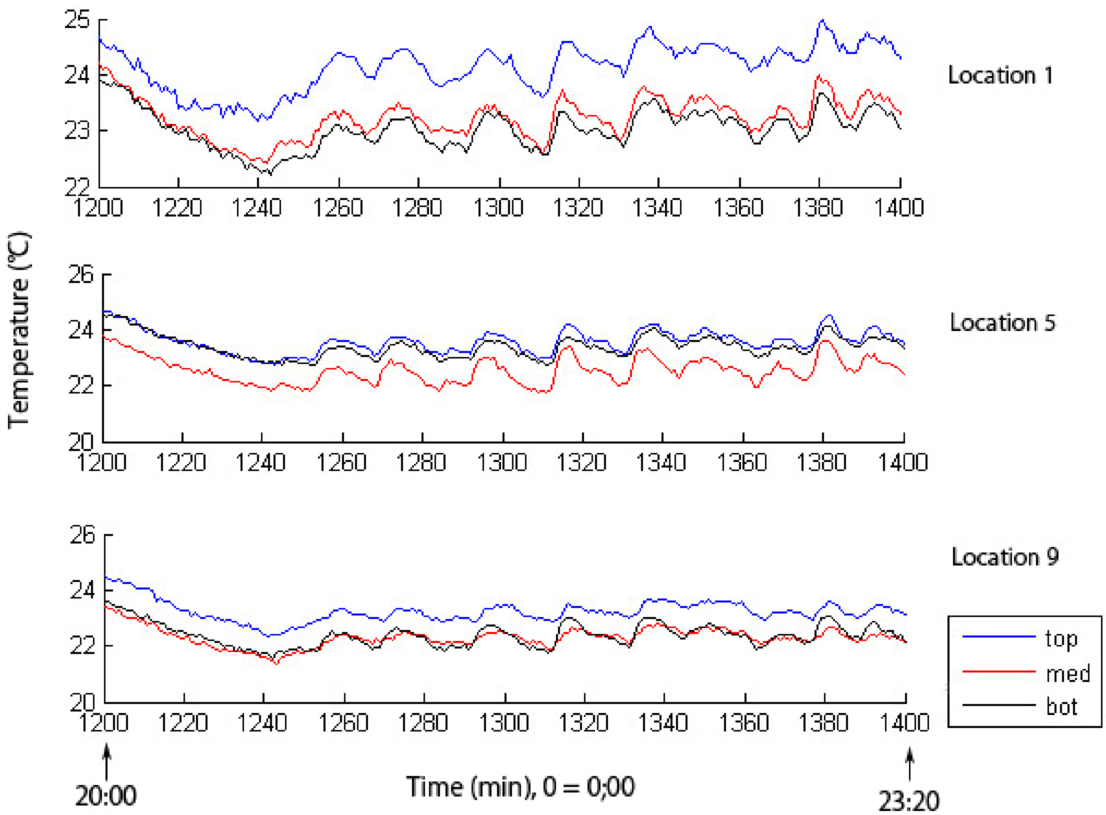

Figure 27. Temperature with the Light ON

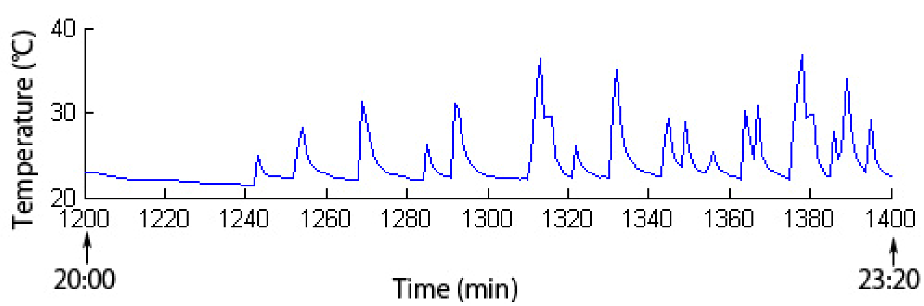

Figure 28. Temperature for a Light ON Condition

C. Daytime Analysis

C.1 Light Intensity

From daytime analyses, sensor locations 3, 4, and 5 are relatively darker than the other locations. These locations are closest to the south wall of the greenhouse. The brightest locations are 1, 2, 6, 7, 8, and 9. Figure 29 compares light intensities on the top layer for April 6th and 7th. These two days were clear sunny days, and their light intensities versus time were very similar. At locations 1, 2 and 6, the light strength dropped at certain times. Locations 1 and 2, the dark blue and cyan ribbons, show a loss in the light intensity from noon until about 3:00 PM. At location 6, the yellow ribbon shows a drop in light intensity during noon. On the same day, the middle and bottom layers in locations 1 and 2 exhibit constantly increasing and decreasing light intensity versus time. According to these plots, locations 1, 2, 6, 7, 8 and 9 were the most efficient positions for plants to gather sun light. Locations 3, 4 and 5 were in shadow all day.

Figure 30 displays the yellow ribbons (location 6) from Figure 29. The red line is from April 6, 2009, and the blue line is from April 7, 2009. As seen in the figure, the shading events happen at the same time. The letter A marks events where shading occurs for about one minute; that happens six times. This is assumed to be due to the ceiling frame of the greenhouse. A similar occurrence happened to letter B at noon for about 30 minutes (event B). This shading would be due to the artificial light because the sensors on the top layer are the closest to that light. If the shade was caused by the vinyl air duct, the shading would affect the lower layers too because of the size of the duct, but the shade at noon happened only to this top layer. The same phenomenon is recognized in other stripes in Figure 29, and other layers had similar shadings.

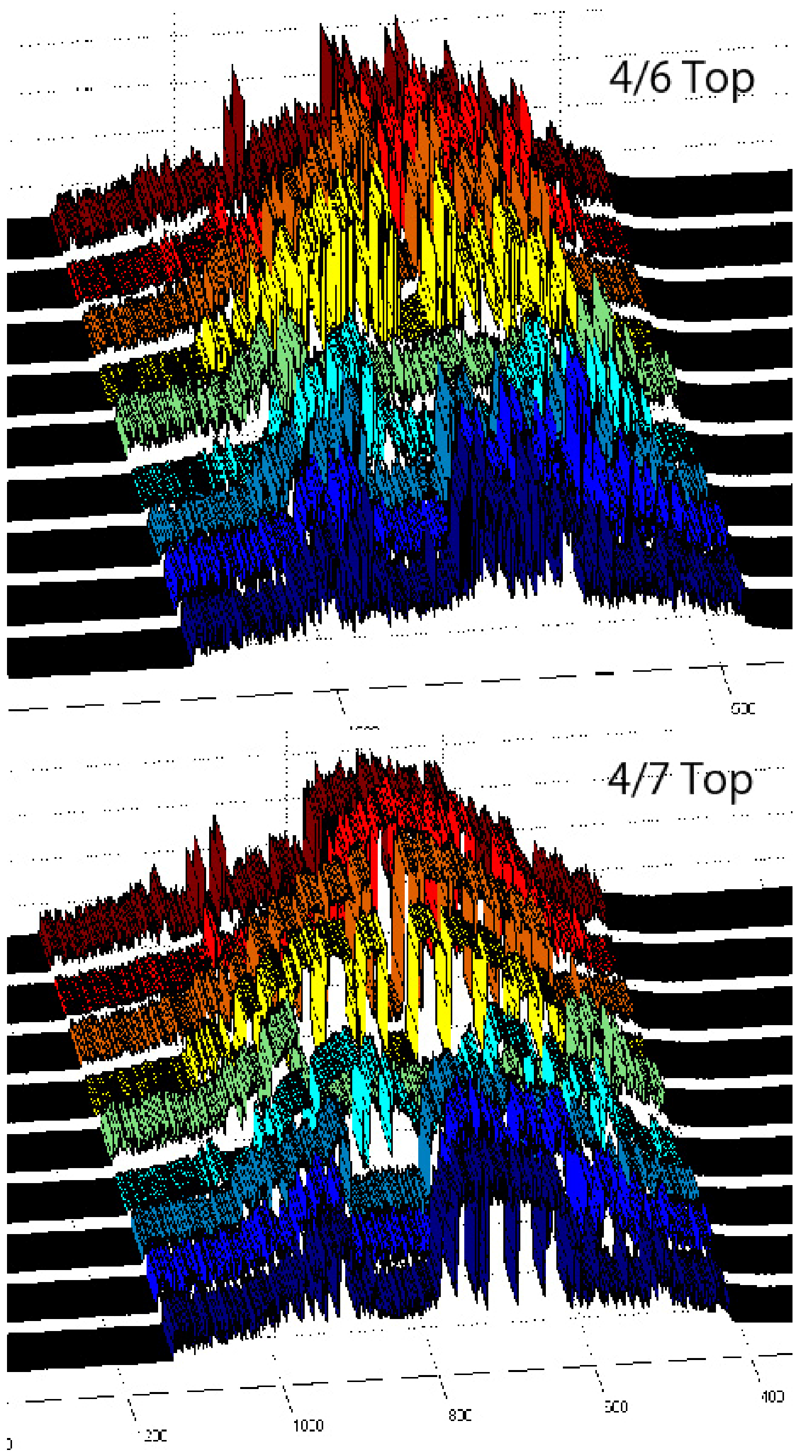

Figure 29. Comparison of Light Intensity on the Top Layer for 4/6 and 4/7

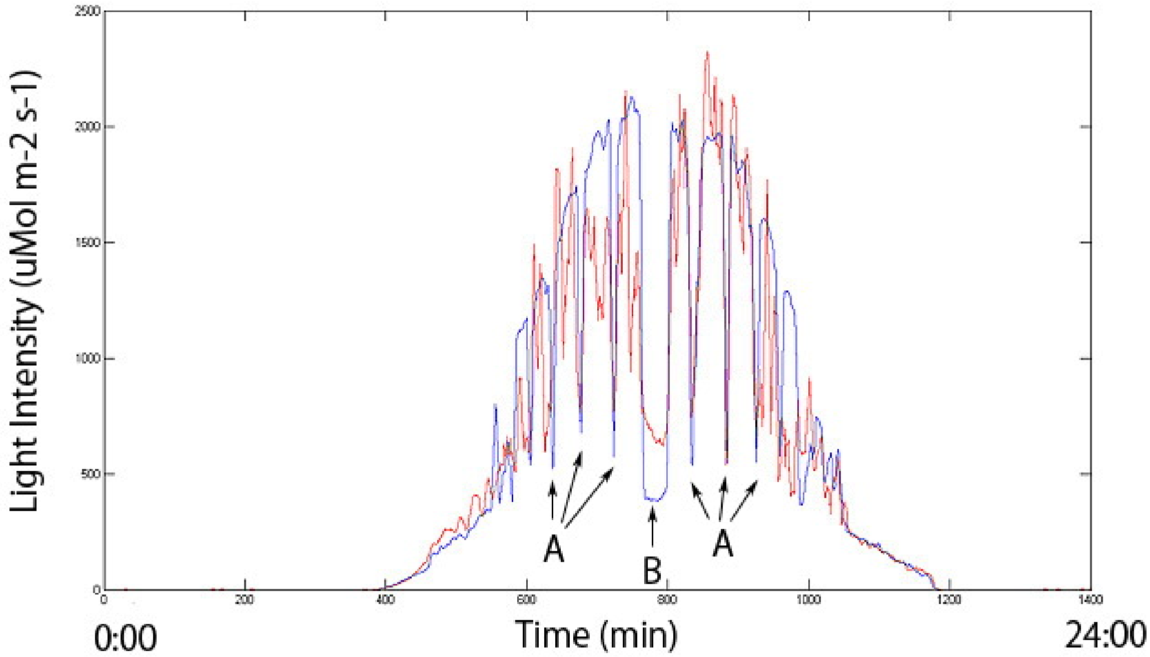

Figure 30. The Comparison of Yellow Ribbons (Location 6) from Figure 29

Figure 31 is a combined plot for sensors 9, 10 and 11 on the bottom layer for April 7th. These three sensors were located next to the outside wall. The graph indicates that the light intensity increased up to 400 uMol m^{-2} s^{-1}. There were some spiked intensities which means direct sunlight was experienced for a few minutes at various times. Overall, the light intensity of the shaded area was moderate and the three sensors recorded almost identical intensities over the course of the day. Also, Figure 31 implies that the drop in light intensity (point B) at noon on Figure 30 was due to the artificial light source, because point B on Figure 30 and the shaded intensity in Figure 31 are the same.

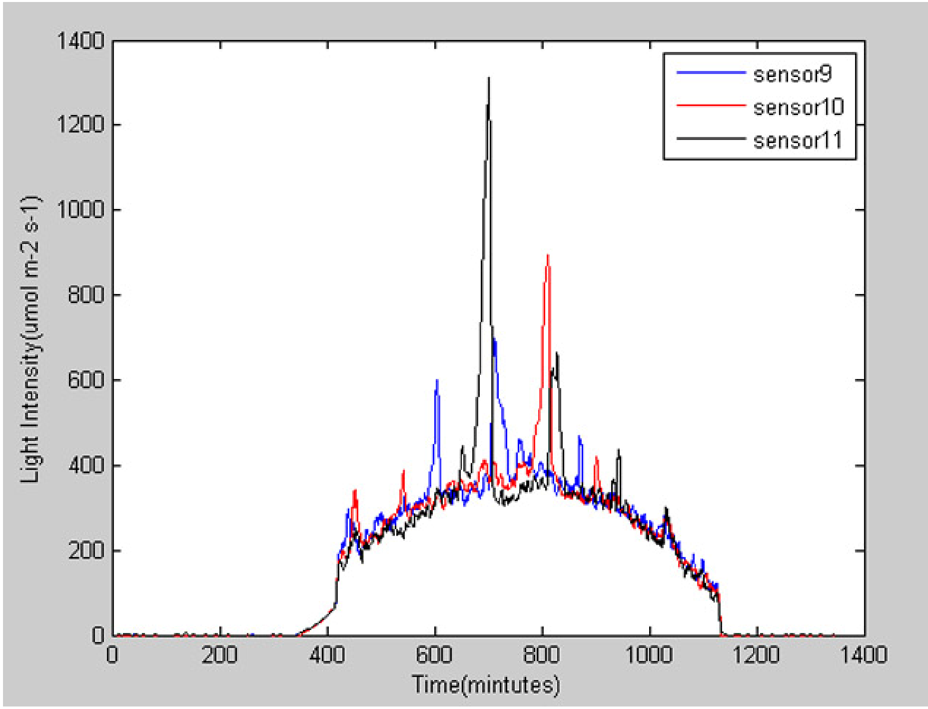

Figure 31. Daytime Intensity Plots for Sensors 9 to 11 (Bottom Layer)

C.2 Temperature and Humidity

During daytime, temperature and humidity have an inverse relationship. Usually, the greenhouse temperature is higher than the outside temperature; therefore, relative humidity is lower. However, the humidity is increased when researchers water plants.

Figure 32 is the 3D graph of humidity on April 6. The graph shows humidity at noon increasing quickly when the plants are watered. Humidity changes are also related to temperature changes. When temperature rises, humidity goes down, and vice versa for decreasing temperatures. Figure 33 is a combined graph of temperature and humidity on Sensor 1: the closest sensor to the greenhouse room entrance. Point A indicates increasing humidity at noon, and point B indicates temperature drop, which implies the greenhouse door was opened. This temperature drop is the largest at the closest sensor to the door. The temperature at Sensor 5, which is the furthest point from the door, had the least change. The increasing humidity at point A is shown at all sensor locations; therefore, it occurred when the plants were watered.

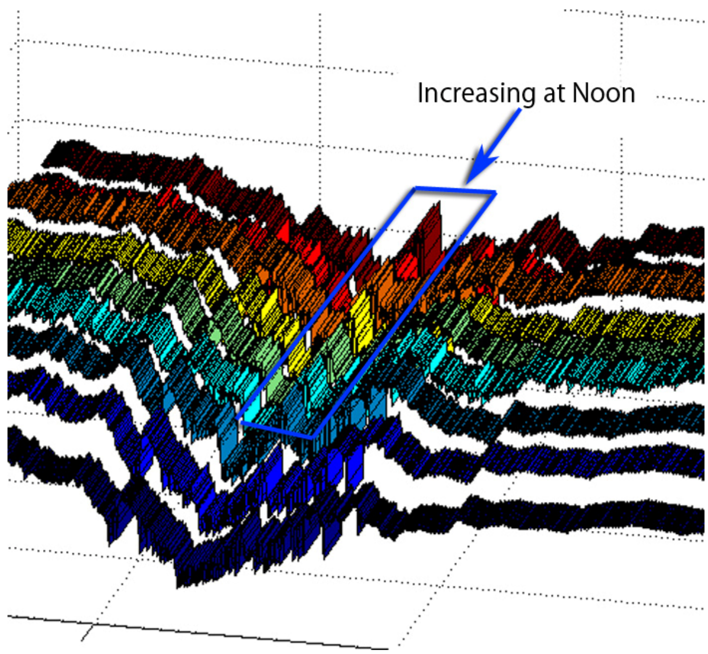

Figure 32. Zoomed Humidity Arround Noon on 4/6/2009

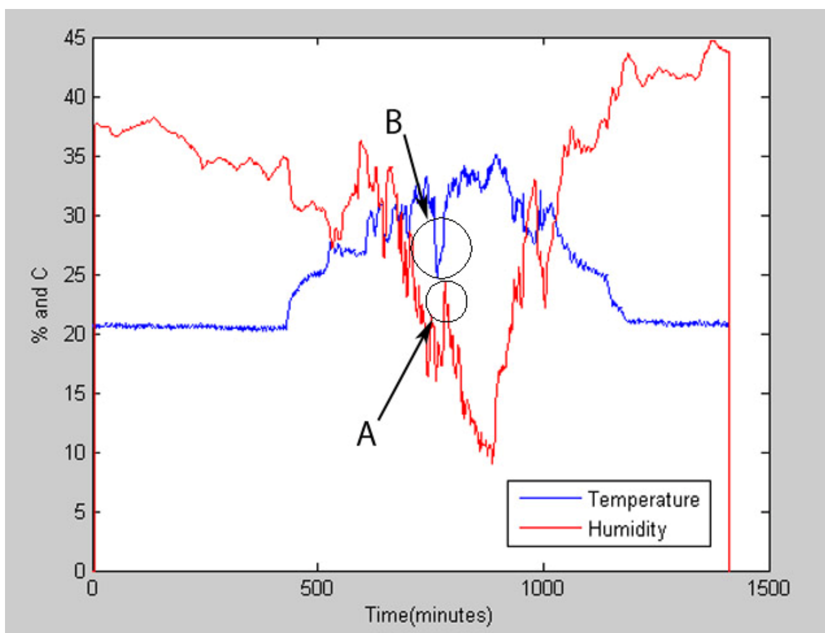

Figure 33. Temperature and Humidity on Sensor 1

D. Data Collection Issues

The system collected data over the time interval of April 4-7, 2009. The number of data points each day should have been up to 1439 points per sensor because the data are taken every one minute. Minor data loss occurred, amounting to 1 or 2 minutes per day: an acceptable amount. Two causes existed for this data loss. The first was a script problem. When a day was begun, the shell script would make a new folder for the day. However, the first couple of minutes for the new day were not recorded until the shell startup process was complete. The second problem was a power problem: data lost during day time due to short power outages. One minute of data was lost during one day, and at times points were recorded for 23 sensors but not all 27 sensors.

Another problem was the light sensor. Although all 27 photodiodes were calibrated correctly, the received light intensity for these devices is sensitive: it changes greatly with small changes in incident light angle (even 1 or 2 degrees). For these experiments, the sensors were hung on CAT5e cable with solid wire, so it was easy to adjust the sensor angle up and to the South. For a more accurate light meter, a level gauge could be used on each sensor box in a manner similar to the Fieldscout unit.

CHAPTER 7: CONCLUSIONS

The 1-Wire protocol network enabled researchers to use several types of sensors on an inexpensive budget. A wired system does not require replacement of batteries like a wireless system, and control is handled by a host computer. This simplifies the change of a measurement time interval or sensor configuration. For all 27 sensors, the total cost was $850, which is a much lower cost than comparable data logging sensor systems. Although specification sheets for the temperature and humidity sensors provided conversion equations and their tolerances, the photodiodes required further calibration to be used as a light meter. For these photodiode sensors, calibration curves for additional light sensors can arguably be chosen from the existing calibration curves for the 27 sensors without using a reference device because all 27 curves are very close to each other. A new PCB for the light meter would be a good next step because the sensor box used for this work had to be modified to use a light sensor. The light diffuser should be improved because the flat Teflon sheet does not receive light equally well from different angles. The best solution for a light diffuser would be to use a semi-spherical Teflon dome. The humidity sensors had a 4-5% offset relative to one another, but corrections can be done with post processing. The standalone 1-Wire data logger would also be useful for small sensing network such as 4-5 sensor boxes.

The temperature in greenhouse room 101J is well controlled, and humidity is also stable. The strength of sunlight is good at high points in the center of the room, and the area near the South wall tends to be in shadow all day. Light intensities on cloudy days are weaker than light intensities on sunny days, but the light is evenly distributed for most areas. The light intensity at the bottom of the room at night time averaged 100 uMol $m^{-2}s^{-1}$. This intensity is bright for artificial lights because it is almost the same as early morning, near sunset or in daytime shadows. This intensity, when compared to direct sunlight, is relatively low, but it is strong enough for artificial light and plants, and even for our eyes.

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APPENDIX A : SHELL SCRIPT FOR COLLECTING DATA

<research.sh>

```
#!/bin/bash
######################################################################
#     Kansas State University, Electrical Engineering
#
#     File name: research.sh
#     Arthur: Kentaro Takamatsu
#     Date   : 03/04/2009
#     Description:     Measure a temperature, humidity, and
#                      light intensity for the greenhouse
#
#
#     Major Professor: Steve Warren, Ph.D
######################################################################

modprobe fuse

# Starting OWFS
/opt/owfs/bin/owfs -u /home/kentaro/1wire

# Loop without ending
while true
do

#create folder each day
if [ -w /home/kentaro/Desktop/$(date '+%m%d%y') ];then
      sleep 0 #skip
else
      mkdir /home/kentaro/Desktop/$(date '+%m%d%y')

      echo 'file created'
fi

n=1
for Data in $sensors
  do Data_a[${n}]=$Data

   X=$( echo /home/kentaro/1wire/uncached/26.* )
   j1=1
   for h1 in $X
      do H1[${j1}]=$h1
      j1=$(( ${j1} + 1 ))
   done
# Time for second
Time=$(date '+%S')

# Time for hour and minute, hhmm
time1=$(date '+%H%M')

      # Read data on 00 minute
```

```
	if  [ $Time -eq 00 ] ;then

	# Record Temperature
		echo    $time1    $(cat    ${H1[1]}/temperature)    $(cat
${H1[2]}/temperature)     $(cat     ${H1[3]}/temperature)     $(cat
${H1[4]}/temperature)     $(cat     ${H1[5]}/temperature)     $(cat
${H1[6]}/temperature)     $(cat     ${H1[7]}/temperature)     $(cat
${H1[8]}/temperature)     $(cat     ${H1[9]}/temperature)     $(cat
${H1[10]}/temperature)     $(cat     ${H1[11]}/temperature)     $(cat
${H1[12]}/temperature)     $(cat     ${H1[13]}/temperature)     $(cat
${H1[14]}/temperature)     $(cat     ${H1[15]}/temperature)     $(cat
${H1[16]}/temperature)     $(cat     ${H1[17]}/temperature)     $(cat
${H1[18]}/temperature)     $(cat     ${H1[19]}/temperature)     $(cat
${H1[20]}/temperature)     $(cat     ${H1[21]}/temperature)     $(cat
${H1[22]}/temperature)     $(cat     ${H1[23]}/temperature)     $(cat
${H1[24]}/temperature)     $(cat     ${H1[25]}/temperature)     $(cat
${H1[26]}/temperature)      $(cat      ${H1[27]}/temperature)       >>
/home/kentaro/Desktop/$(date '+%m%d%y')/Temperature

	# Record Humidity
		echo   $time1   $(cat   ${H1[1]}/HIH4000/humidity)   $(cat
${H1[2]}/HIH4000/humidity)  $(cat  ${H1[3]}/HIH4000/humidity)  $(cat
${H1[4]}/HIH4000/humidity)  $(cat  ${H1[5]}/HIH4000/humidity)  $(cat
${H1[6]}/HIH4000/humidity)  $(cat  ${H1[7]}/HIH4000/humidity)  $(cat
${H1[8]}/HIH4000/humidity)  $(cat  ${H1[9]}/HIH4000/humidity)  $(cat
${H1[10]}/HIH4000/humidity)  $(cat ${H1[11]}/HIH4000/humidity)  $(cat
${H1[12]}/HIH4000/humidity)  $(cat ${H1[13]}/HIH4000/humidity)  $(cat
${H1[14]}/HIH4000/humidity)  $(cat ${H1[15]}/HIH4000/humidity)  $(cat
${H1[16]}/HIH4000/humidity)  $(cat ${H1[17]}/HIH4000/humidity)  $(cat
${H1[18]}/HIH4000/humidity)  $(cat ${H1[19]}/HIH4000/humidity)  $(cat
${H1[20]}/HIH4000/humidity)  $(cat ${H1[21]}/HIH4000/humidity)  $(cat
${H1[22]}/HIH4000/humidity)  $(cat ${H1[23]}/HIH4000/humidity)  $(cat
${H1[24]}/HIH4000/humidity)  $(cat ${H1[25]}/HIH4000/humidity)  $(cat
${H1[26]}/HIH4000/humidity)   $(cat   ${H1[27]}/HIH4000/humidity)   >>
/home/kentaro/Desktop/$(date '+%m%d%y')/Humidity

	# Record Light Intensity
		echo $time1 $(cat ${H1[1]}/vis) $(cat ${H1[2]}/vis) $(cat
${H1[3]}/vis)   $(cat   ${H1[4]}/vis)   $(cat   ${H1[5]}/vis)   $(cat
${H1[6]}/vis)   $(cat   ${H1[7]}/vis)   $(cat   ${H1[8]}/vis)   $(cat
${H1[9]}/vis)   $(cat   ${H1[10]}/vis)   $(cat   ${H1[11]}/vis)   $(cat
${H1[12]}/vis)   $(cat   ${H1[13]}/vis)   $(cat   ${H1[14]}/vis)   $(cat
${H1[15]}/vis)   $(cat   ${H1[16]}/vis)   $(cat   ${H1[17]}/vis)   $(cat
${H1[18]}/vis)   $(cat   ${H1[19]}/vis)   $(cat   ${H1[20]}/vis)   $(cat
${H1[21]}/vis)   $(cat   ${H1[22]}/vis)   $(cat   ${H1[23]}/vis)   $(cat
${H1[24]}/vis)   $(cat   ${H1[25]}/vis)   $(cat   ${H1[26]}/vis)   $(cat
${H1[27]}/vis) >> /home/kentaro/Desktop/$(date '+%m%d%y')/Light

	echo                          $time1                          $(cat
/home/kentaro/1wire/uncached/10A23D1A0108005F/temperature)          >>
/home/kentaro/Desktop/$(date '+%m%d%y')/Duct_Temperature

		if [ $Time -eq 00 ] ;then
			sleep  40
```

```
            fi
      fi
done
done # end while(1)
```

APPENDIX B : SHELL SCRIPT FOR CALIBRATION

<lightcal.sh>

```
#!/bin/bash
####################################################################
#      Kansas State University, Electrical Engineering
#     Title:     ligtcal.sh
#     Arthur:    Kentaro Takamatsu
#     Date: 03/03/2009
#
#     Description:     Script for calibrating 27 photodiodes.
#
#     Major Professor: Steve Warren, Ph.D
####################################################################
modprobe fuse

# Starting OWFS
/opt/owfs/bin/owfs -u /home/kentaro/1wire

# sensor search
sensors=$(ls /home/kentaro/1wire/26.*);

# Creating sensor array
X=$( echo /home/kentaro/1wire/uncached/26.* )
   j1=1
   for h1 in $X
      do H1[${j1}]=$h1
      j1=$(( ${j1} + 1 ))
   done

# Storing Sensor ID
echo 'LightMeter' $(cat ${H1[1]}/address) $(cat ${H1[2]}/address)
$(cat ${H1[3]}/address) $(cat ${H1[4]}/address) >>
/home/kentaro/Desktop/Calibration_Data5/SensorID

# Loop without ending. To end script, press Ctrl+C
while true
do

   # Script is asking to enter a light intensity from Fieldscout
   echo 'input light value then press enter'
   read light

  for i in 1
  do

      # Record sensor voltage, and show data in screen
      echo $light $(cat ${H1[1]}/vis) $(cat ${H1[2]}/vis) $(cat
${H1[3]}/vis) $(cat ${H1[4]}/vis) $(cat ${H1[5]}/vis) $(cat
${H1[6]}/vis) $(cat ${H1[7]}/vis) $(cat ${H1[8]}/vis) $(cat
${H1[9]}/vis) $(cat ${H1[10]}/vis) $(cat ${H1[11]}/vis) $(cat
${H1[12]}/vis) $(cat ${H1[13]}/vis) $(cat ${H1[14]}/vis) $(cat
${H1[15]}/vis) $(cat ${H1[16]}/vis)c□□$(cat ${H1[17]}/vis) $(cat
```

```
${H1[18]}/vis)  $(cat  ${H1[19]}/vis)  $(cat  ${H1[20]}/vis)  $(cat
${H1[21]}/vis)  $(cat  ${H1[22]}/vis)  $(cat  ${H1[23]}/vis)  $(cat
${H1[24]}/vis)  $(cat  ${H1[25]}/vis)  $(cat  ${H1[26]}/vis)  $(cat
${H1[27]}/vis) >> /home/kentaro/Desktop/Lightcal5
      echo  $light  $(cat  ${H1[1]}/vis)  $(cat  ${H1[2]}/vis)  $(cat
${H1[3]}/vis)   $(cat   ${H1[4]}/vis)   $(cat   ${H1[5]}/vis)   $(cat
${H1[6]}/vis)   $(cat   ${H1[7]}/vis)   $(cat   ${H1[8]}/vis)   $(cat
${H1[9]}/vis)   $(cat   ${H1[10]}/vis)   $(cat   ${H1[11]}/vis)  $(cat
${H1[12]}/vis)  $(cat  ${H1[13]}/vis)  $(cat  ${H1[14]}/vis)  $(cat
${H1[15]}/vis)  $(cat  ${H1[16]}/vis)c□□$(cat  ${H1[17]}/vis)  $(cat
${H1[18]}/vis)  $(cat  ${H1[19]}/vis)  $(cat  ${H1[20]}/vis)  $(cat
${H1[21]}/vis)  $(cat  ${H1[22]}/vis)  $(cat  ${H1[23]}/vis)  $(cat
${H1[24]}/vis)  $(cat  ${H1[25]}/vis)  $(cat  ${H1[26]}/vis)  $(cat
${H1[27]}/vis)

      echo '---'
      sleep  0
  done



done # end of while(1)
```

APPENDIX C: MATLAB CODE FOR FINDING COEFFICIENTS

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Kansas State University, Electrical Engineering
%
%   Author: Kentaro Takamatsu
%   Date  : 03/18/2009
%   Desctioption: Find polynomial coefficients for 27 light sensors.
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear
% Load data
data=load('cal27.txt');

[m n]=size(data); % m = y, n = x

% Excract light values for Y-axis
light = data((2:m),1);

% Extract sensor values for X-axis
sensor=zeros(m-1,n-1);
for i = 2 : m
    for j = 2:n
     sensor(i-1,j-1) = data(i,j);
    end
end

% Find coefficients
coef = zeros(n-1,3);
for i = 1:n-1
    coef(i,:) = polyfit2((sensor(:,i)),light,3);
end
temp = zeros(n-1,1);
coef(:,4)=temp;  % Fill zero for polyval

% Examine error
pred_y = zeros(m-1,n-1);
for i = 1:n-1
    pred_y(:,i) = polyval(coef(i,:),sensor(:,i));
end

error = zeros(m-1,n-1);
percent = zeros(m-1,n-1);
for i = 1:m-1
    for j = 1:n-1
        error(i,j) = abs(light(i,1) - pred_y(i,j));
        percent(i,j) = (error(i,j)./light(i,1).*100);
    end
end
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   polyfit2(x,y,N)
%   x: x values
%   y: y values
%   N: number of polynomial
%   03/18/2009
%   This function is to compute polynomial fit with force zero
%     intercept.
%   Refered sorce at
%http://www.mathworks.com/matlabcentral/newsreader/view_thread/53637
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function p = polyfit2(x,y,N)
Nv = repmat(N:-1:1, length(x), 1);
Xm = repmat(x, 1, N);
DataMatrix = Xm.^Nv;
CoefficientVector = DataMatrix\y;
p=CoefficientVector';
```

APPENDIX D : CALIBRATION GRAPHS AND COEFFICIENT CHART

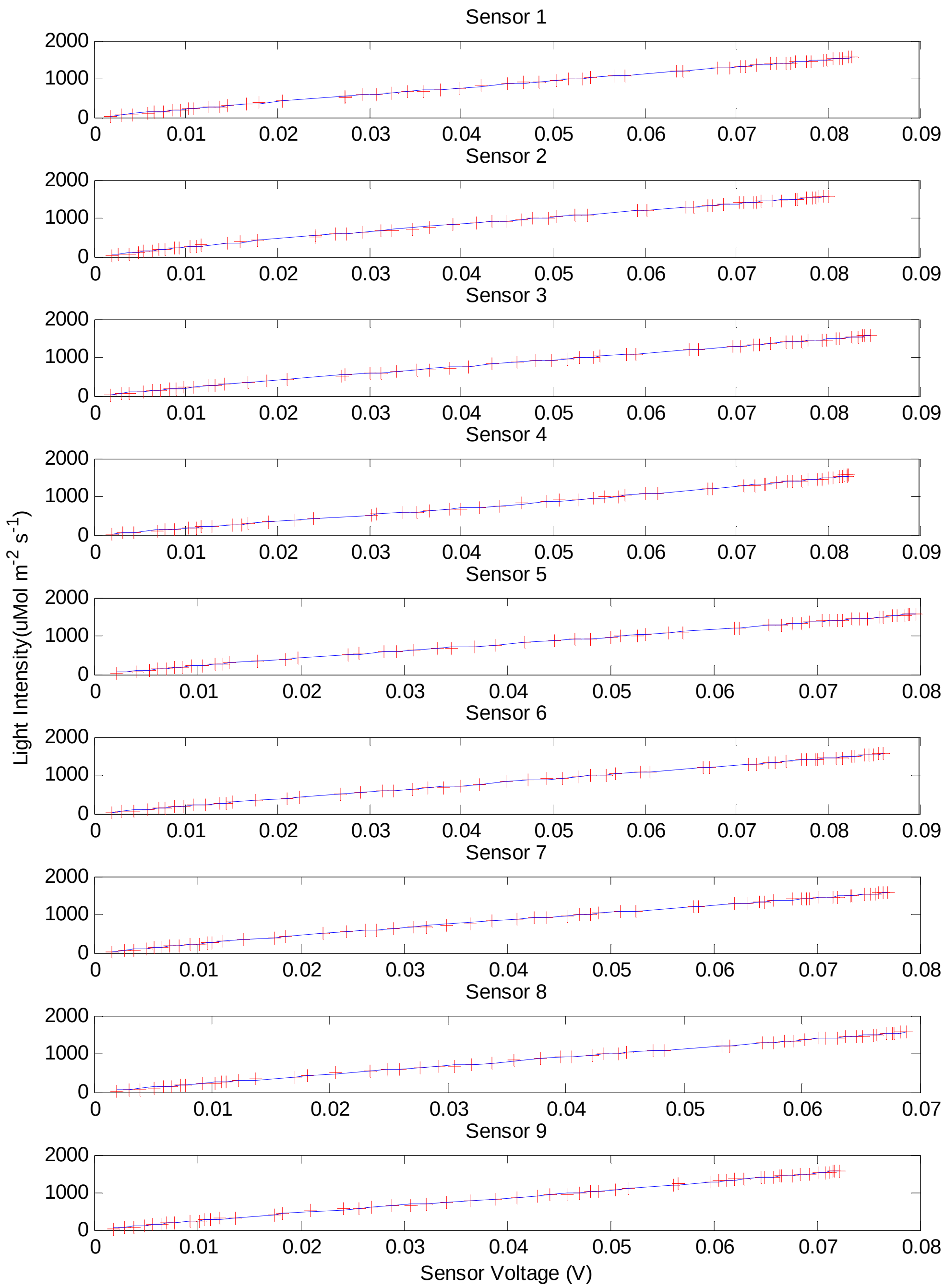

Figure 34. Calibration Curve for Sensors 1 to 9

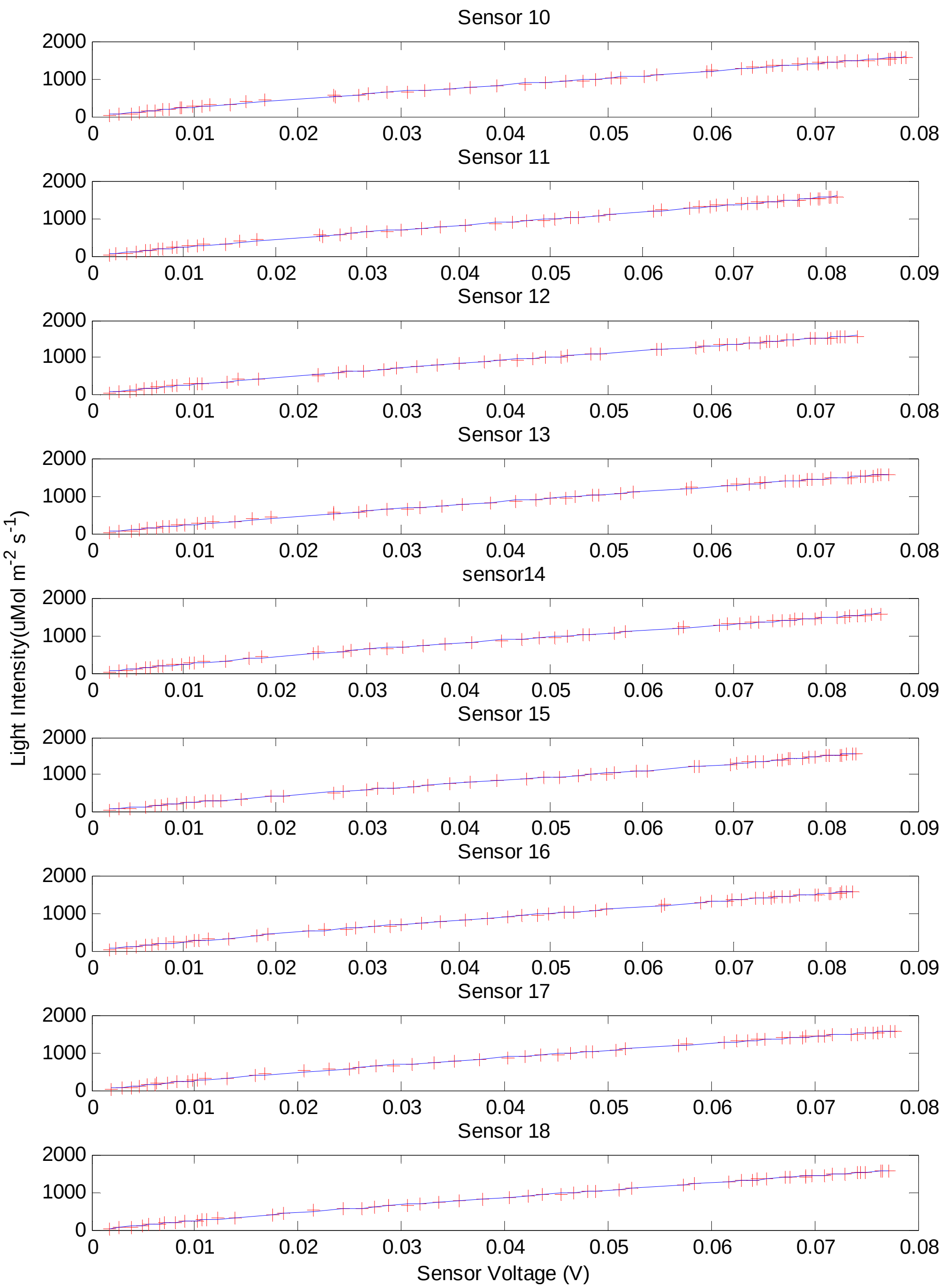

Figure 35. Calibration Curves for Sensors 10 to 18

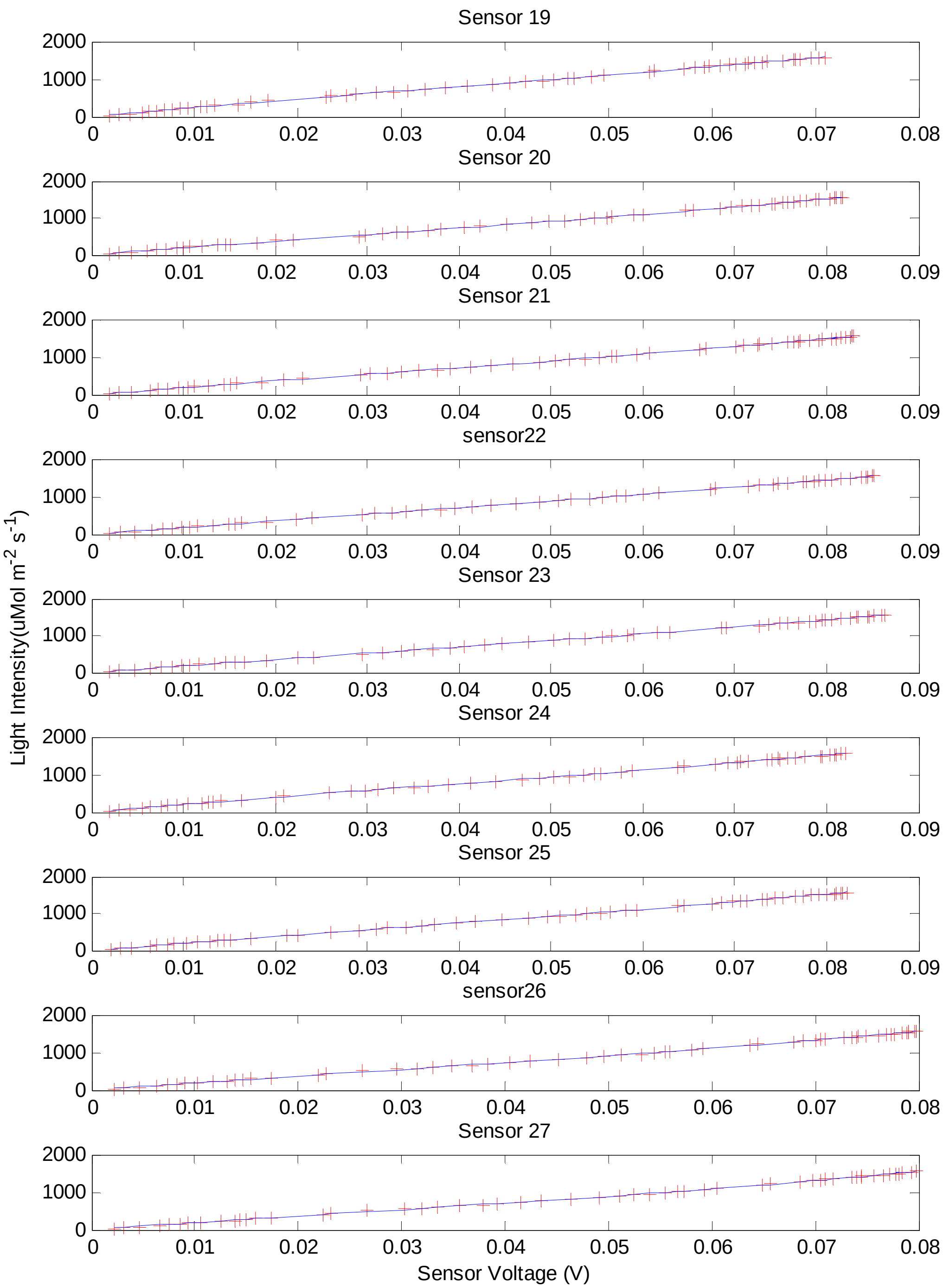

Figure 36. Calibration Curves for sensors 19 to 27.

Table 5. Polynomial Coefficients

Sensor	a0(x)	a1(x^2)	a2(x^3)	a3
1	499084.1	-72113.8	21408.52	0
2	786103.6	-130096	24974.71	0
3	684703.1	-95557.5	21713.55	0
4	685646.1	-49939.8	18256.3	0
5	1130796	-134366	23320.96	0
6	422635.6	-57607.6	19970.78	0
7	571011.5	-91368.7	24039.32	0
8	626367.8	-71875.2	24632.12	0
9	1532175	-158741	25264.28	0
10	1387548	-188281	26360.66	0
11	1141568	-156270	24714.52	0
12	1029683	-158350	27494.18	0
13	942703.5	-136774	25442.61	0
14	957350.4	-155312	24711.44	0
15	1121665	-134211	22239.72	0
16	668292.1	-112038	23681.22	0
17	899304.1	-148864	26443.29	0
18	576771.4	-95958	24417.62	0
19	1127980	-122628	25511.96	0
20	860357.8	-80936.5	20010.26	0
21	617036.2	-55323	19045.07	0
22	315580.7	-26566.5	18178.57	0
23	511649.8	-45929.9	18232.81	0
24	806517	-93267.3	21316.23	0
25	488133.2	-43009.5	19404.3	0
26	931322.3	-77047.2	19739.06	0
27	1163167	-95075.1	19614.73	0

APPENDIX E: DATA PROFILES

E.1 Day 1 - April 4, 2009

E1.1 Temperature

Figures 26 to 28 are 3D temperature plots

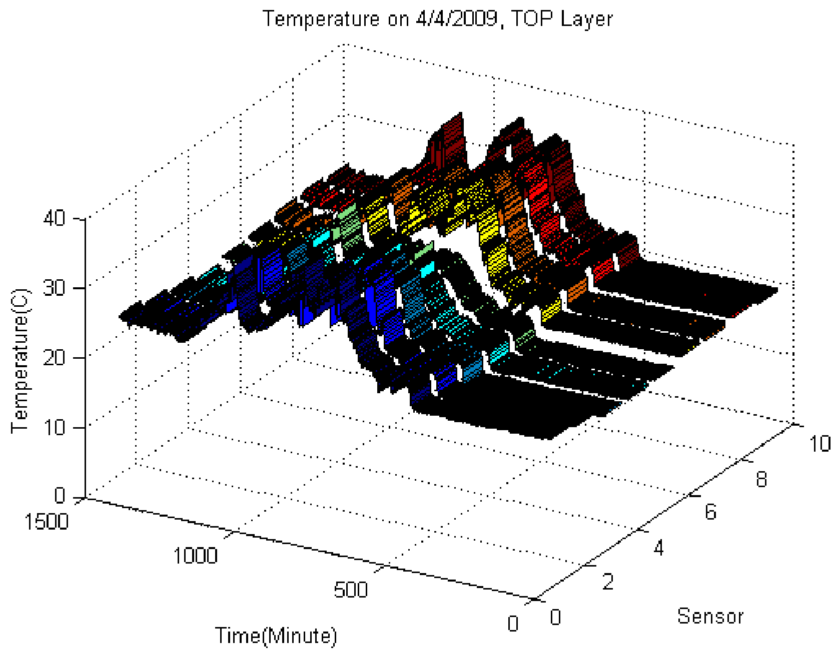

Figure 37. Top Layer of Temperatures on 4/4/2009 – Day 1

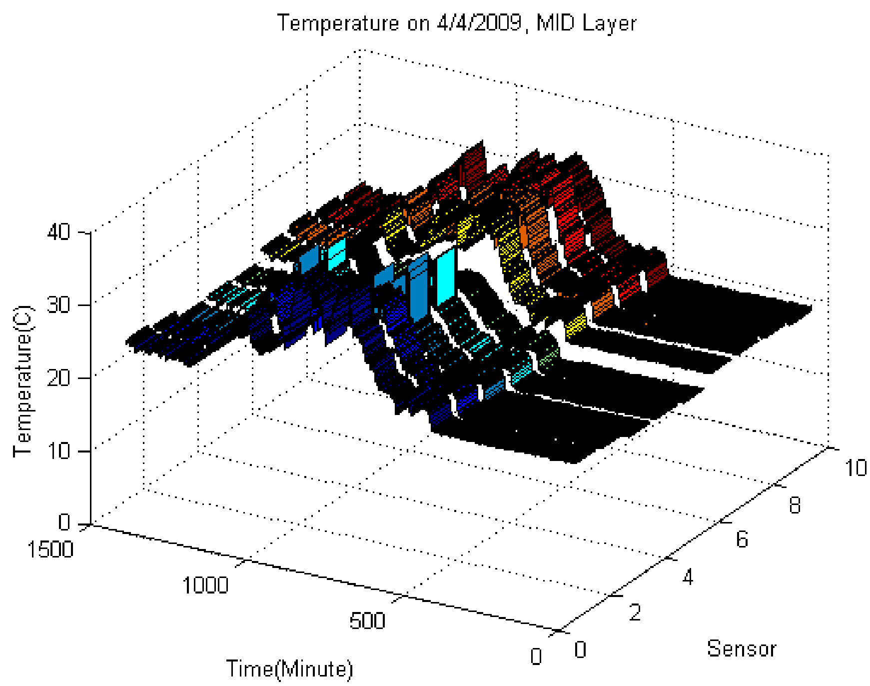

Figure 38. Middle Layer of Temperatures on 4/4/2009

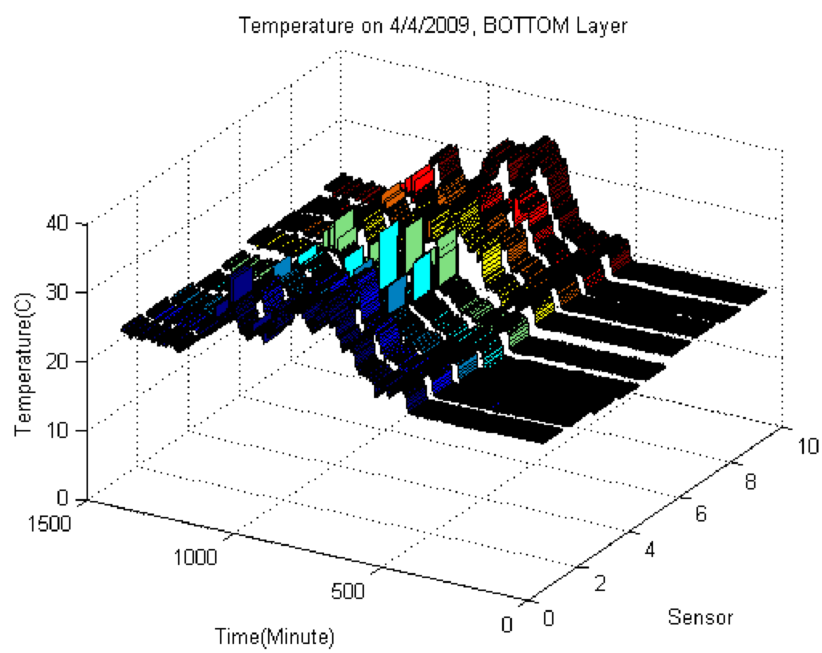

Figure 39. Bottom Layer of Temperatures on 4/4/2009

E.1.2 Humidity

Figures 29 to 31 are 3D humidity plots by layer.

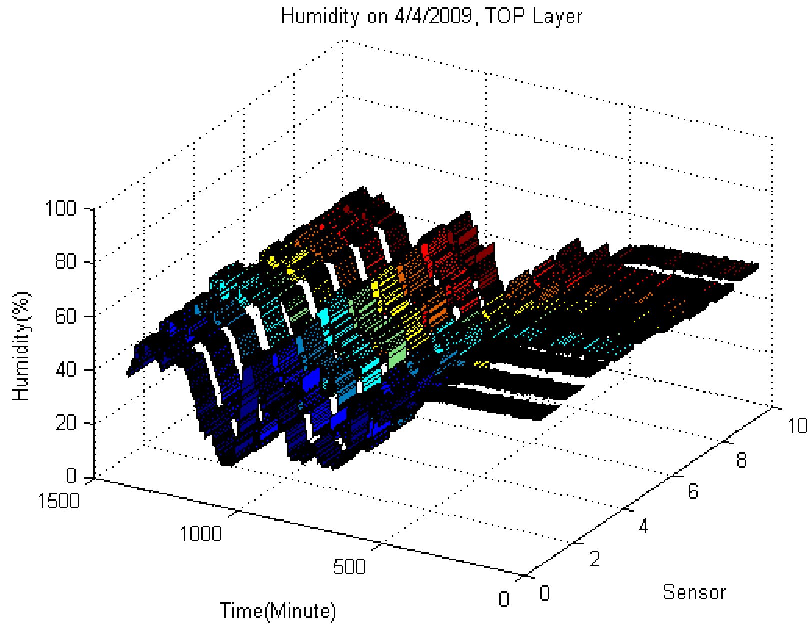

Figure 40. Top Layer of Humidities on 4/4/2009

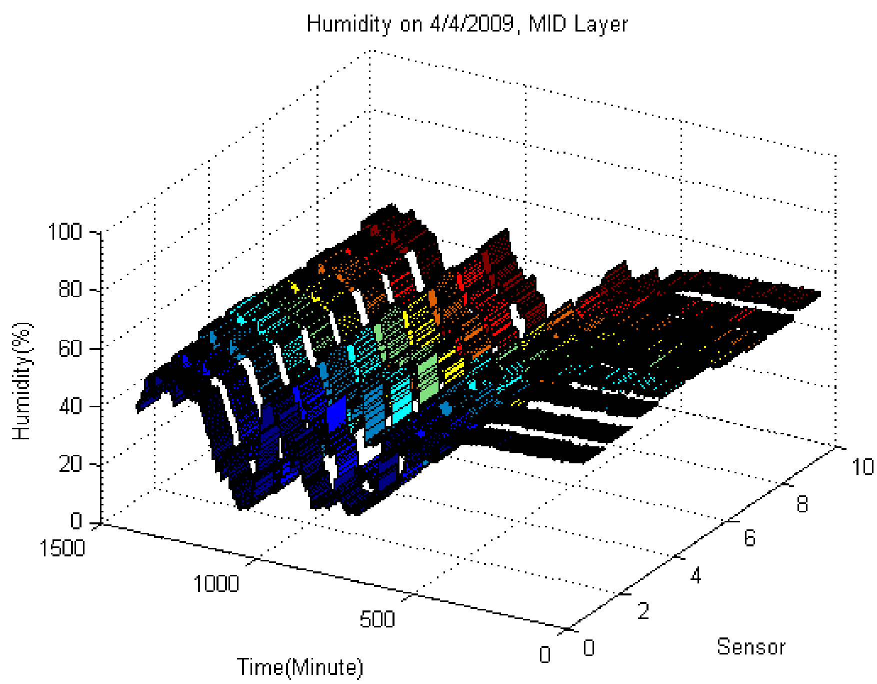

Figure 41. Middle Layer of Humidites on 4/4/2009

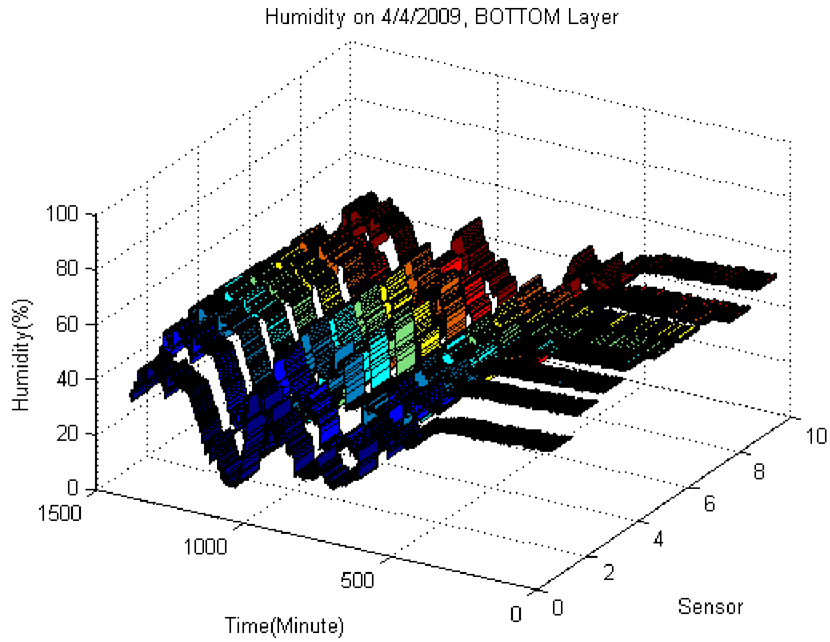

Figure 42. Bottom Layer of Humidites on 4/4/2009

E.1.3 Light Intensity

Figures 32 to 34 are 3D light intensity plots by layer..

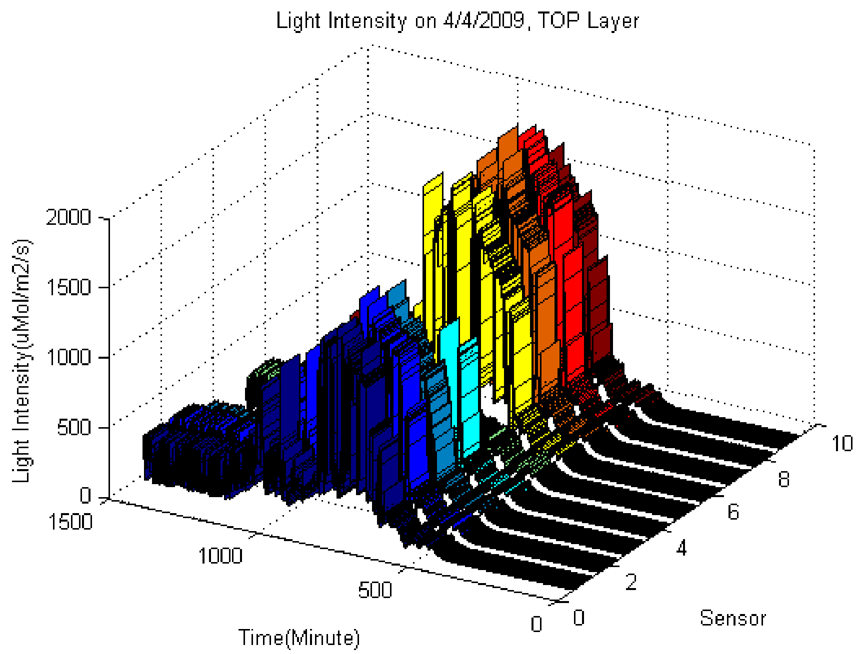

Figure 43 Top Layer of Light Intensities on 4/4/2009

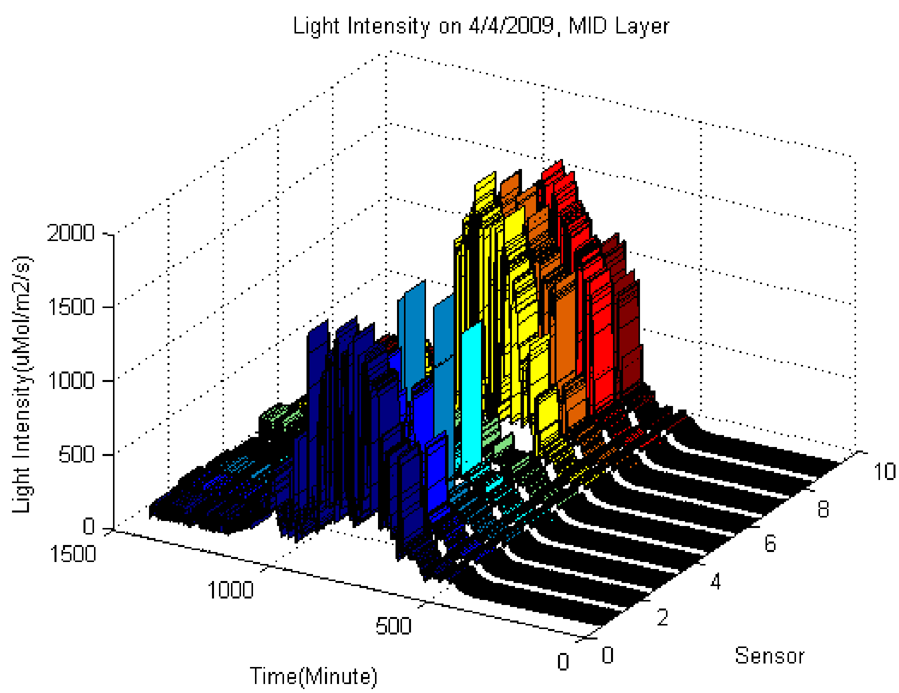

Figure 44 Middle Layer of Light Intensites on 4/4/2009

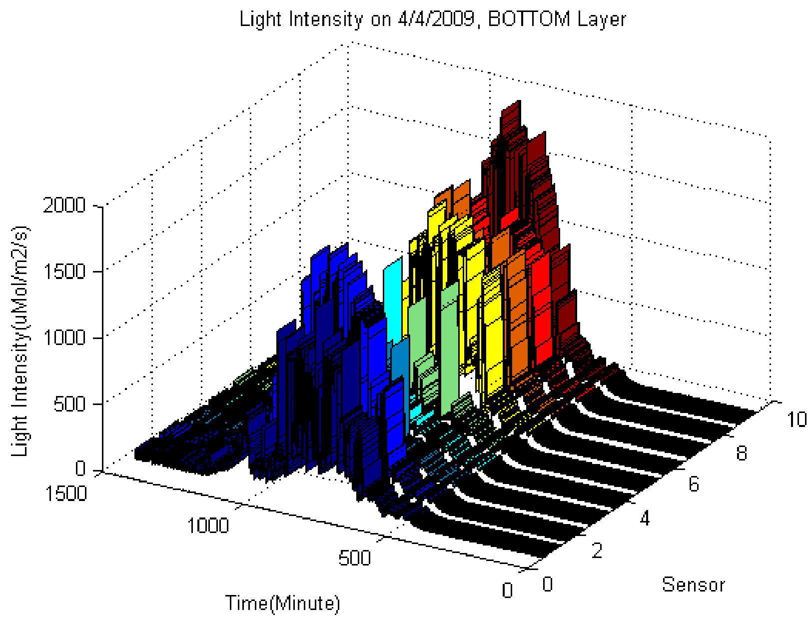

Figure 45. Bottom Layer of Light Intensites on 4/4/2009

E.2 Day 2 - April 5, 2009

E.2.1 Temperature

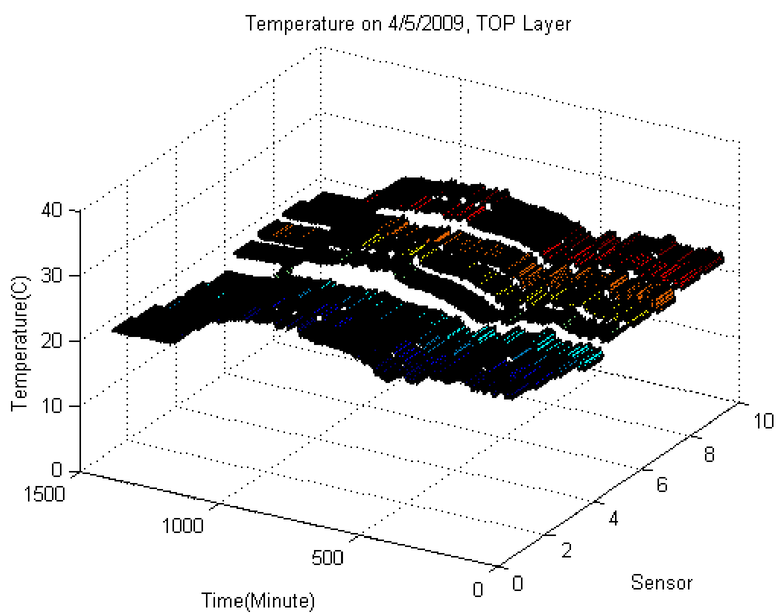

Figure 46. Top Layer of Temperatures on 4/5/2009 – Day 2

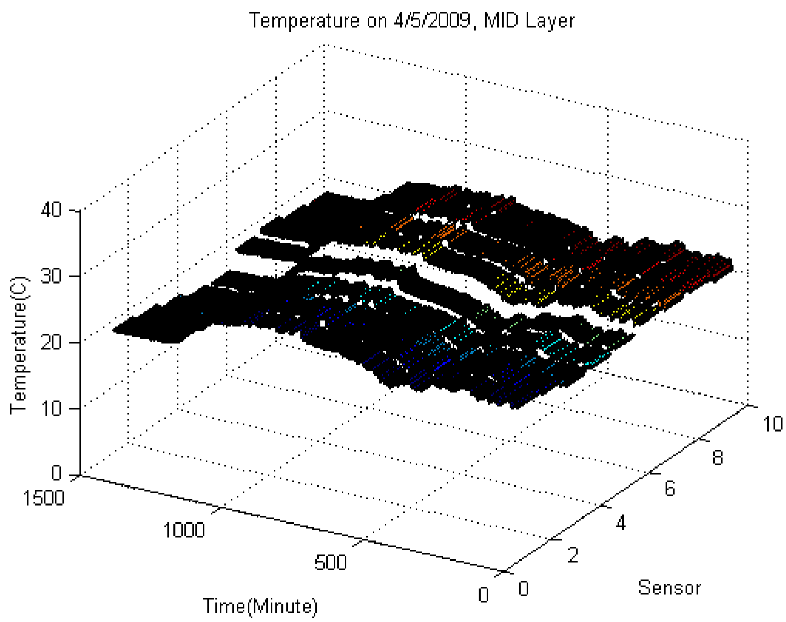

Figure 47. Middle Layer of Temperatures on 4/5/2009

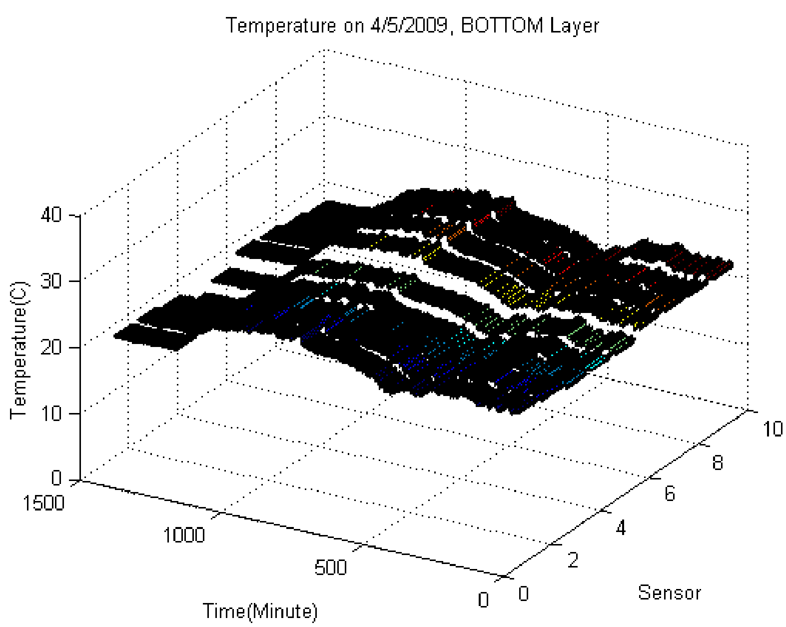

Figure 48. Bottom Layer of Temperatures on 4/5/2009

E.2.2 Humidity

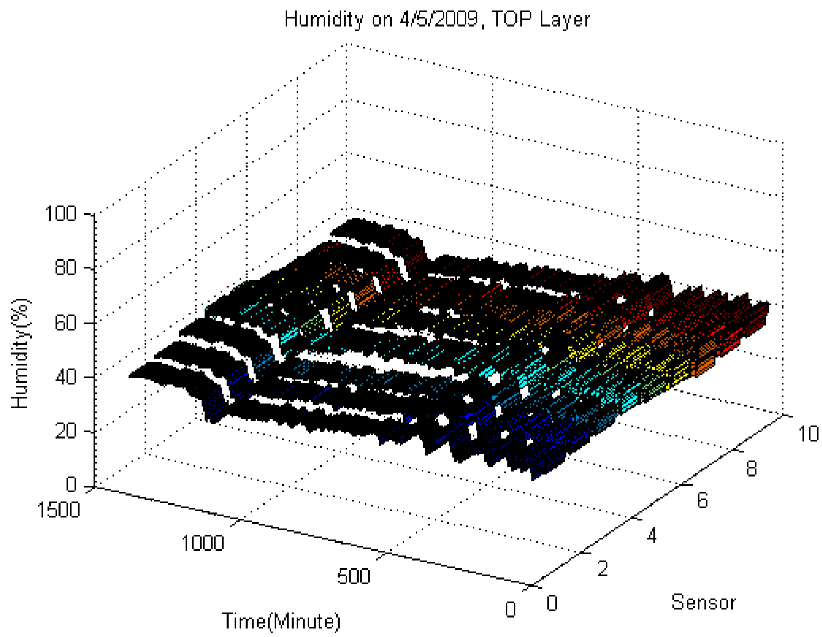

Figure 49. Top Layer of Humidites on 4/5/2009

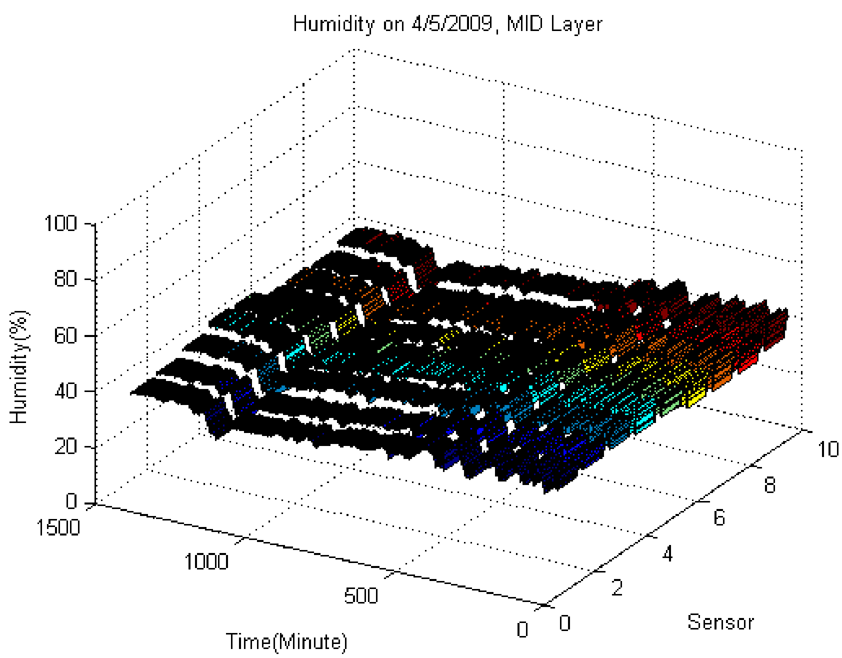

Figure 50. Bottom Layer of Humidites on 4/5/2009

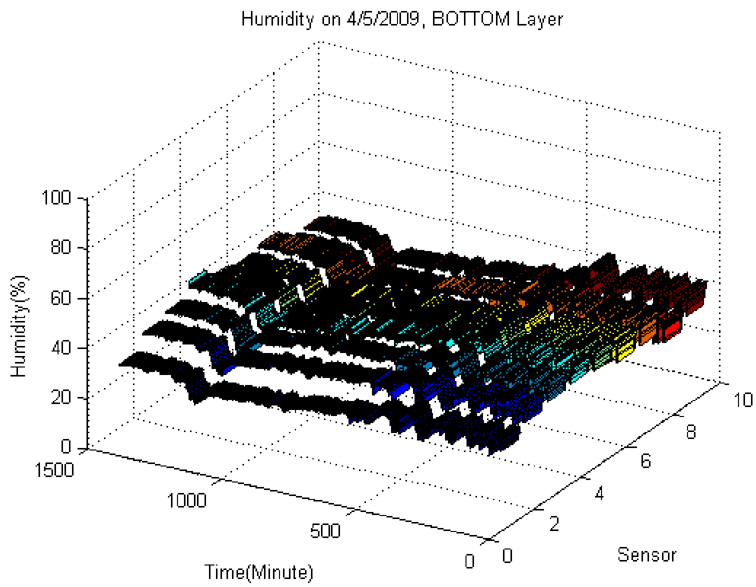

Figure 51. Bottom Layer of Humidites on 4/5/2009

E.2.3 Light Intensity

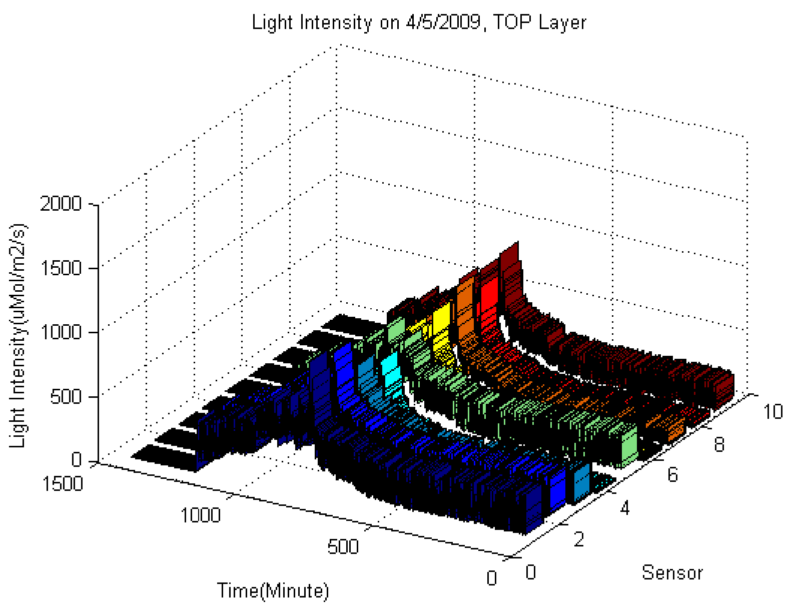

Figure 52. Top Layer of Light Intensites on 4/5/2009

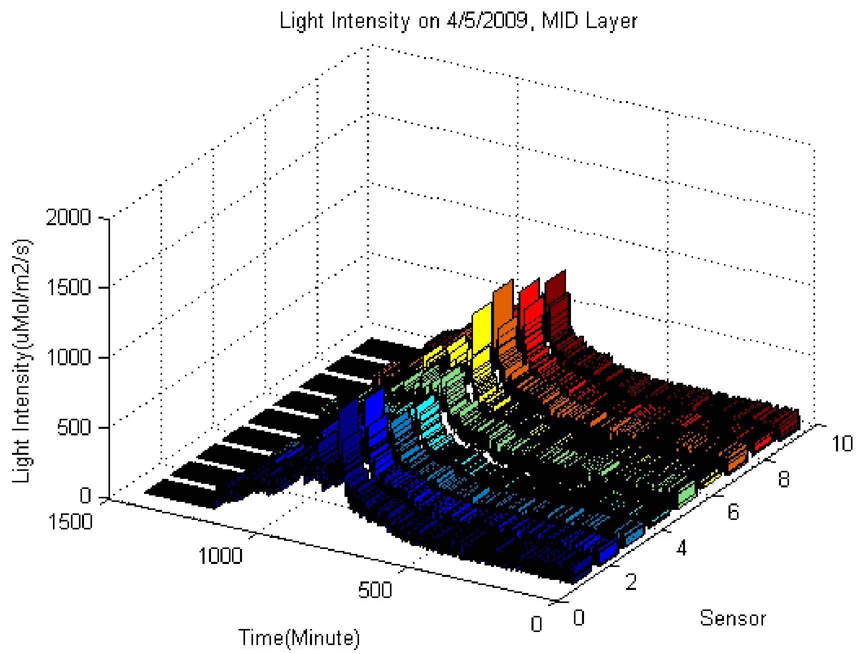

Figure 53. Middle Layer of Light Intensites on 4/5/2009

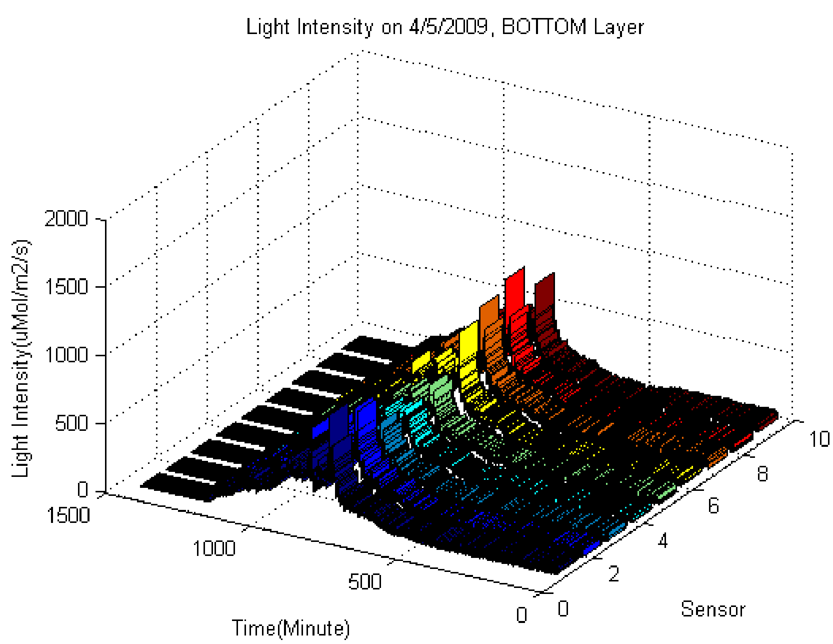

Figure 54. Bottom Layer of Light intensites on 4/5/2009

E.3 Day 3 - April 6, 2009

E3.1 Temperature

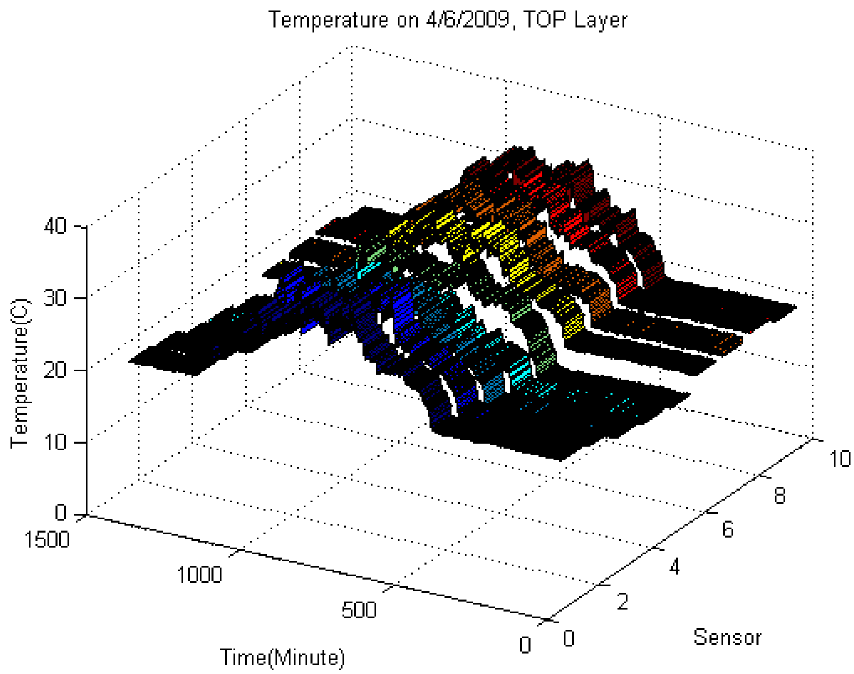

Figure 55. Top Layer of Temperatures on 4/6/2009 – Day 3

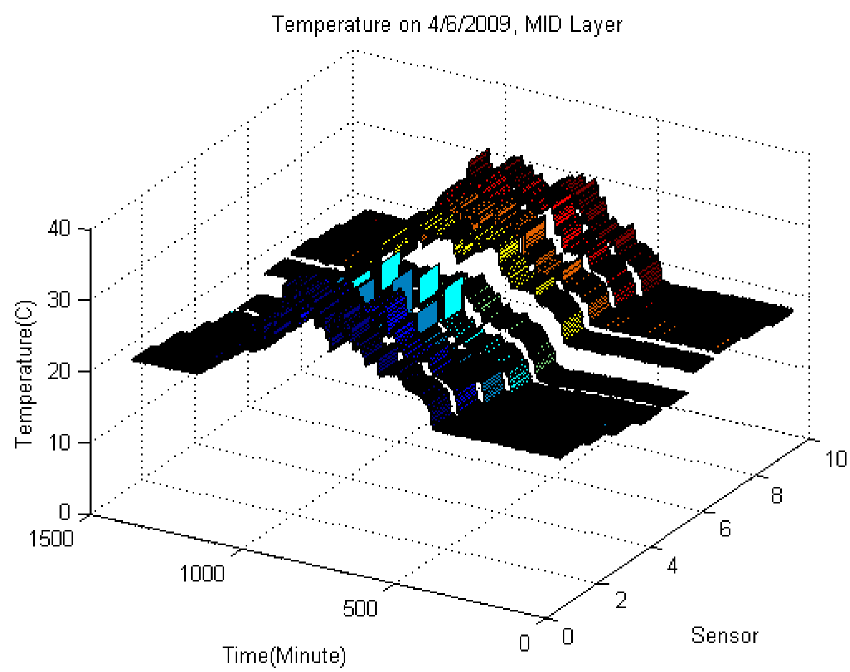

Figure 56. Middle Layer of Temperatures on 4/6/2009

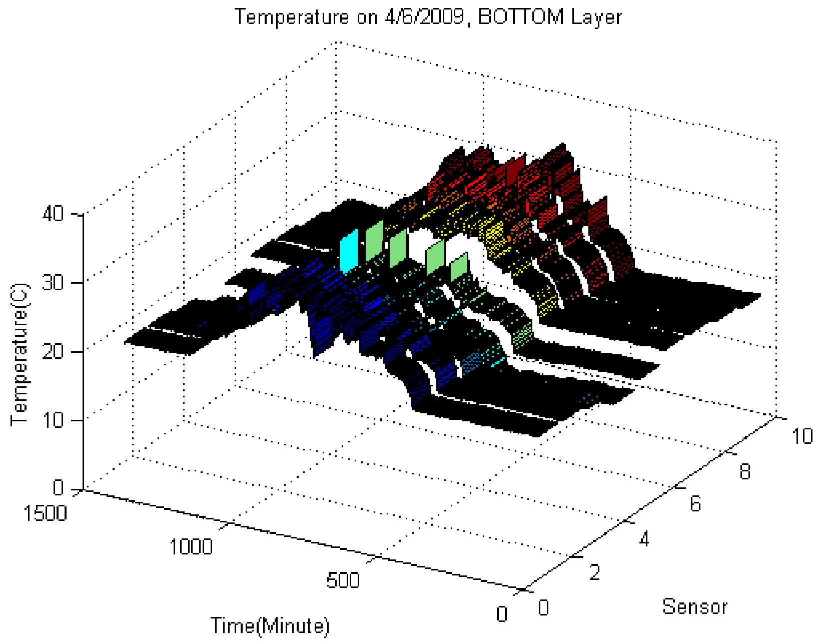

Figure 57. Bottom Layer of Temperatures on 4/6/2009

E.3.2 Humidity

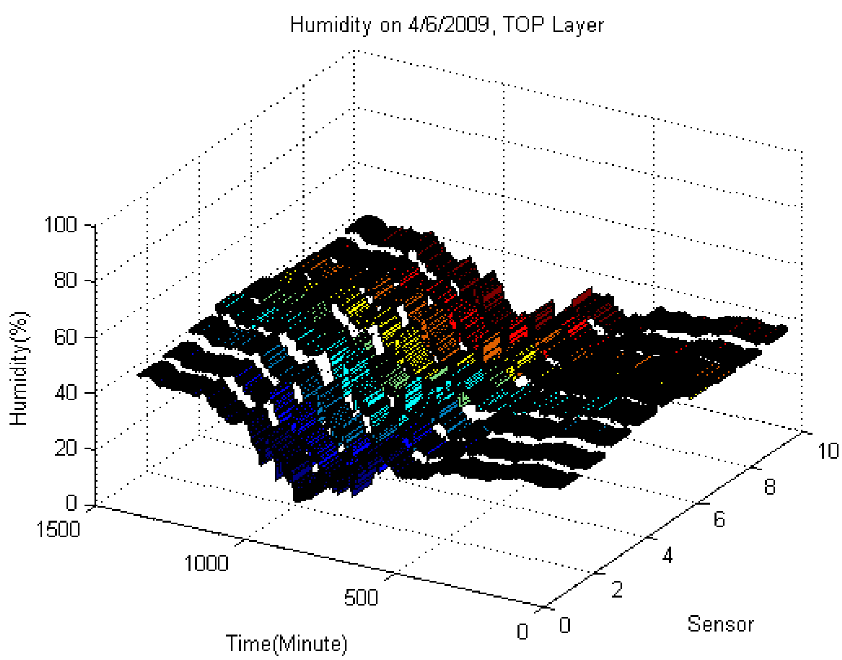

Figure 58. Top Layer of Humidities on 4/6/2009

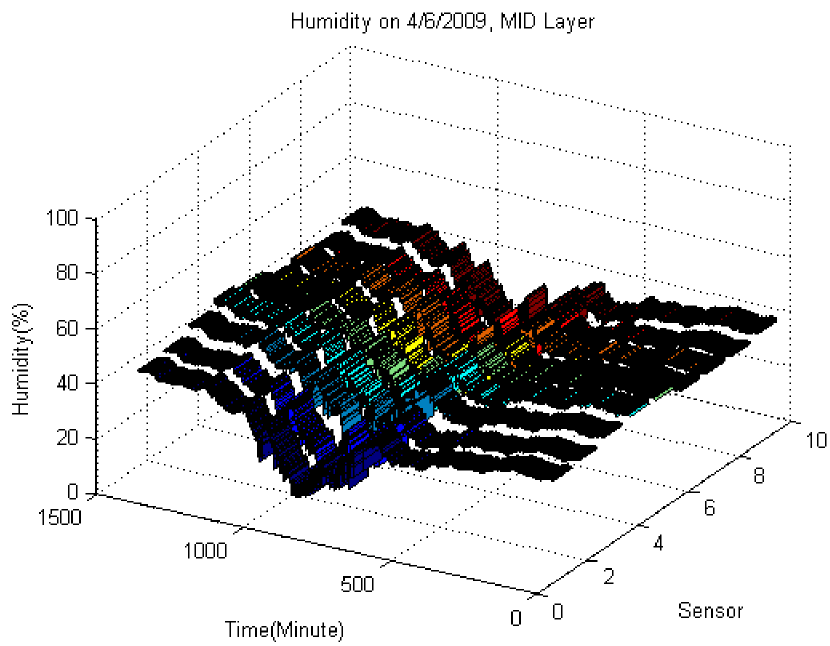

Figure 59. Middle Layer of Humidities on 4/6/2009

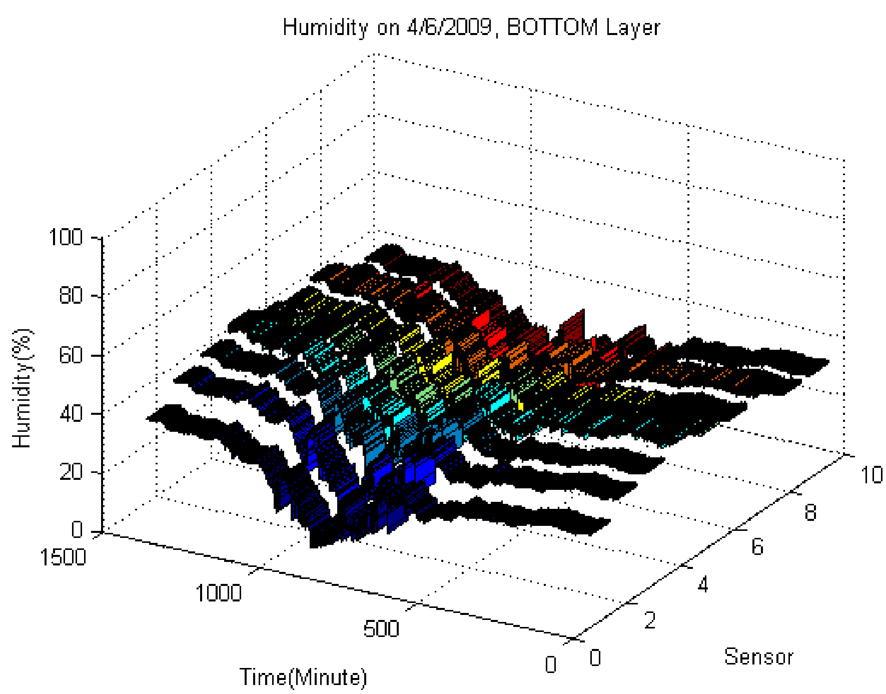

Figure 60. Bottom Layer of Humidities on 4/6/2009

E.3.3 Light Intensity

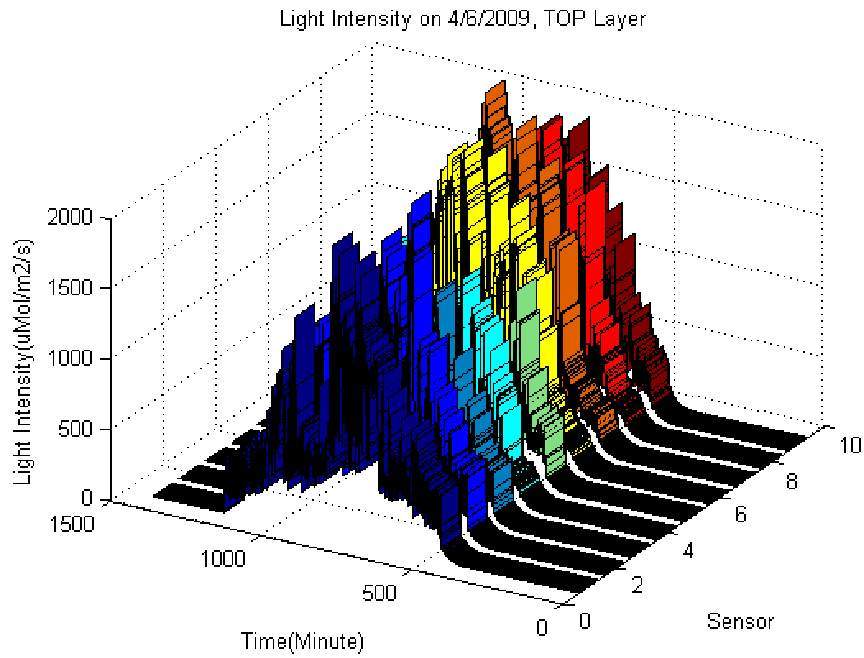

Figure 61. Top Layer of Light Intensities on 4/6/2009

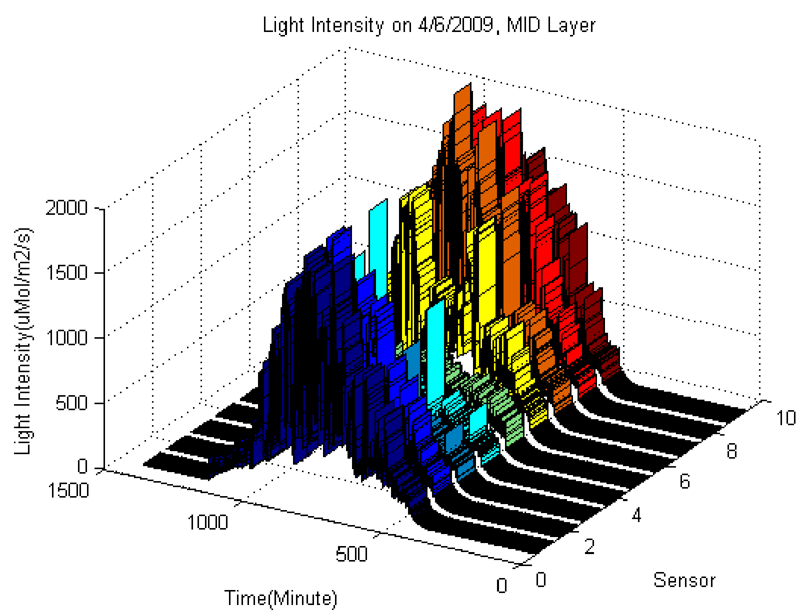

Figure 62. Middle Layer of Light Intensities on 4/6/2009

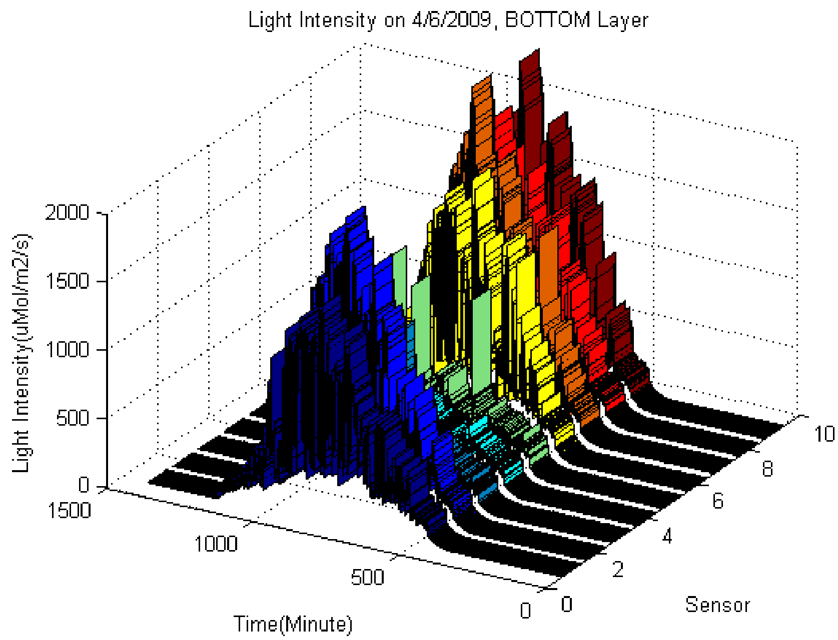

Figure 63. Bottom Layer of Light Intensities on 4/6/2009

E.4 Day 4 - April 7, 2009

E4.1 Temperature

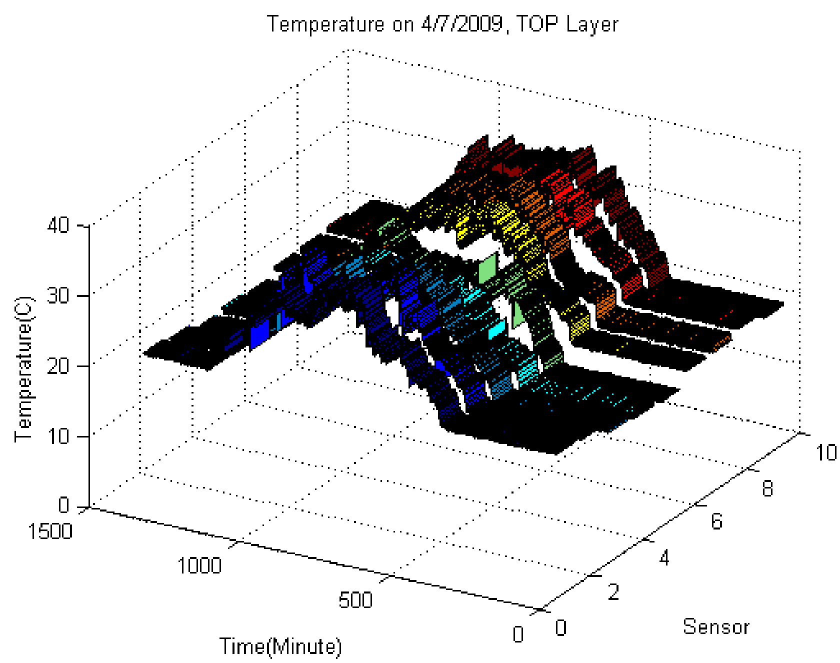

Figure 64. Top Layer of Temperatures on 4/7/2009 – Day 4

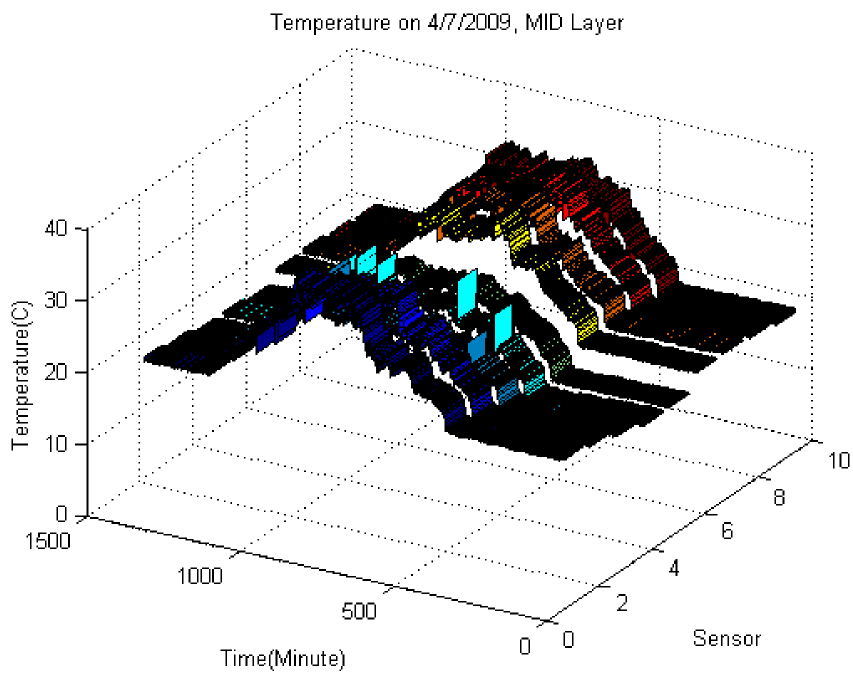

Figure 65. Middle Layer of Temperatures on 4/7/2009

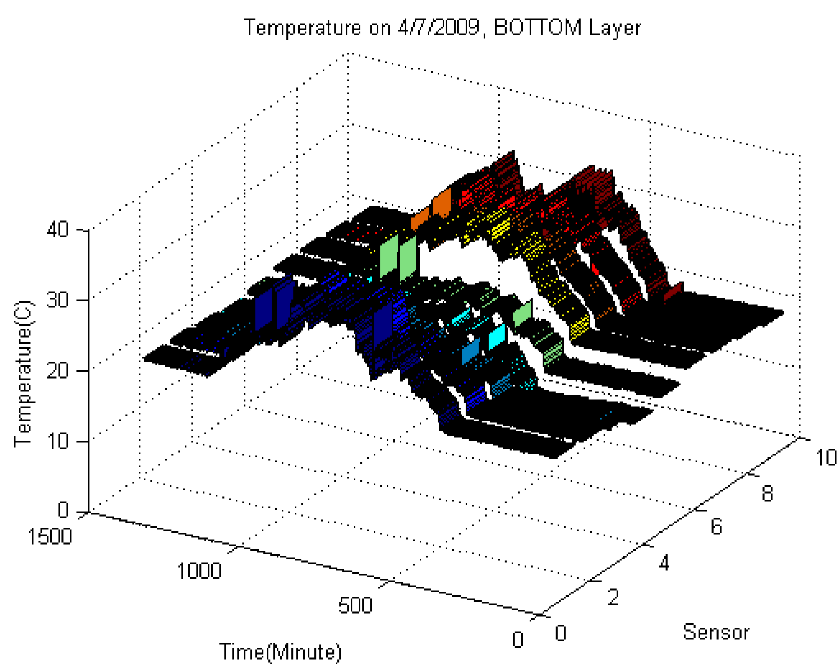

Figure 66. Bottom Layer of Temperatures on 4/7/2009

E.4.2 Humidity

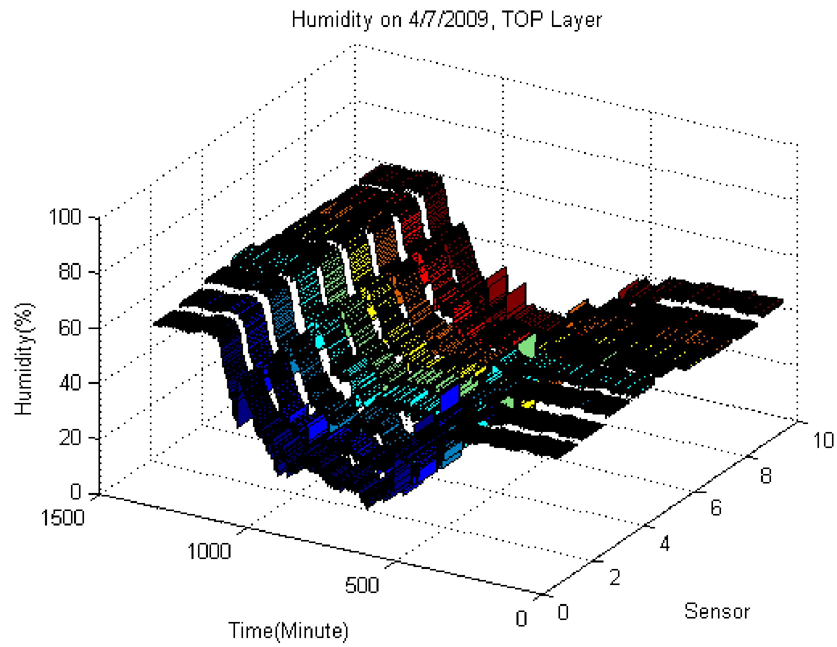

Figure 67. Top Layer of Humidities on 4/7/2009

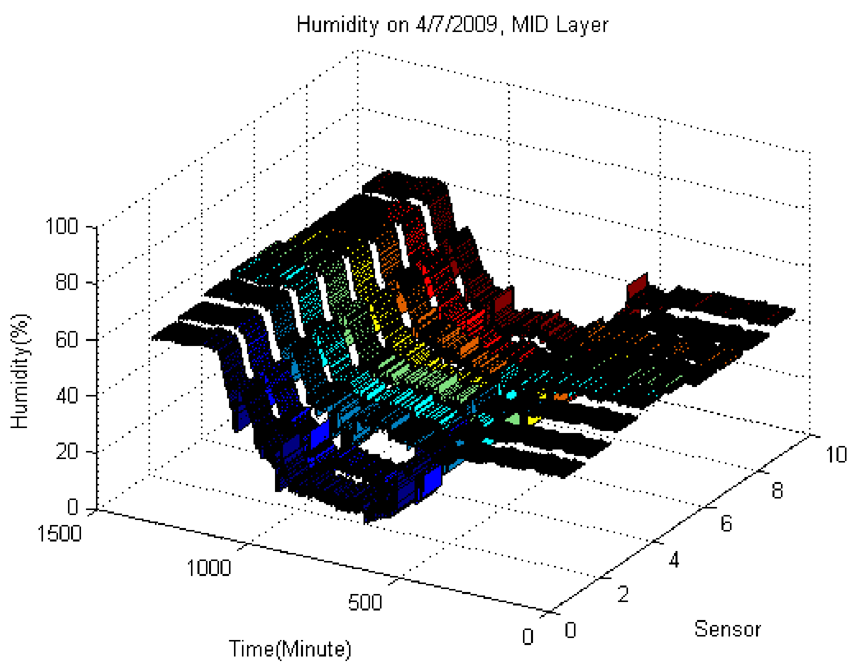

Figure 68. Middle Layer of Humidities on 4/7/2009

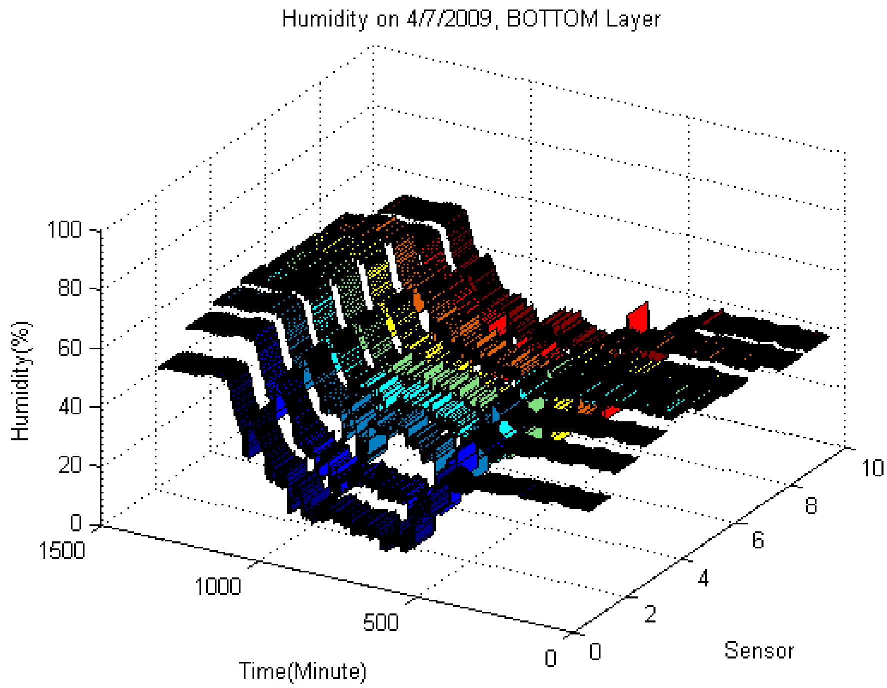

Figure 69. Bottom Layer of Humidities on 4/7/2009

E.4.3 Light Intensity

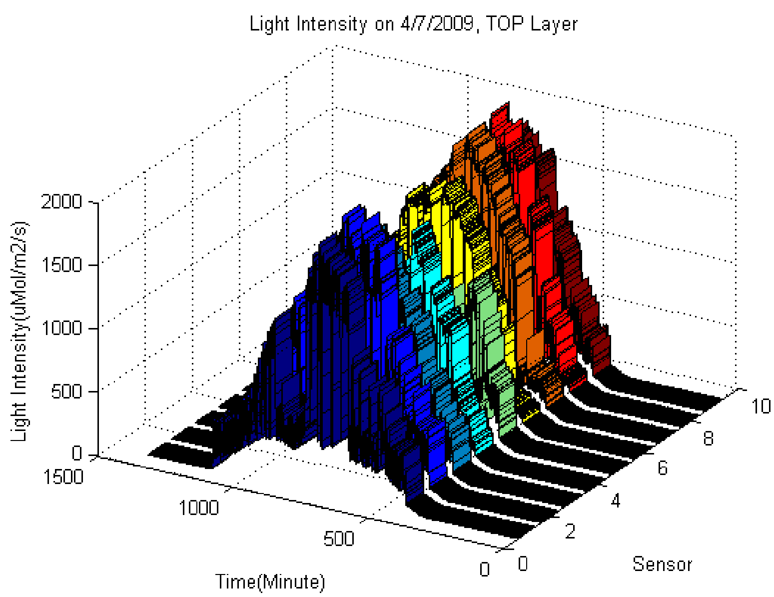

Figure 70. Top Layer of Light Intensities on 4/7/2009

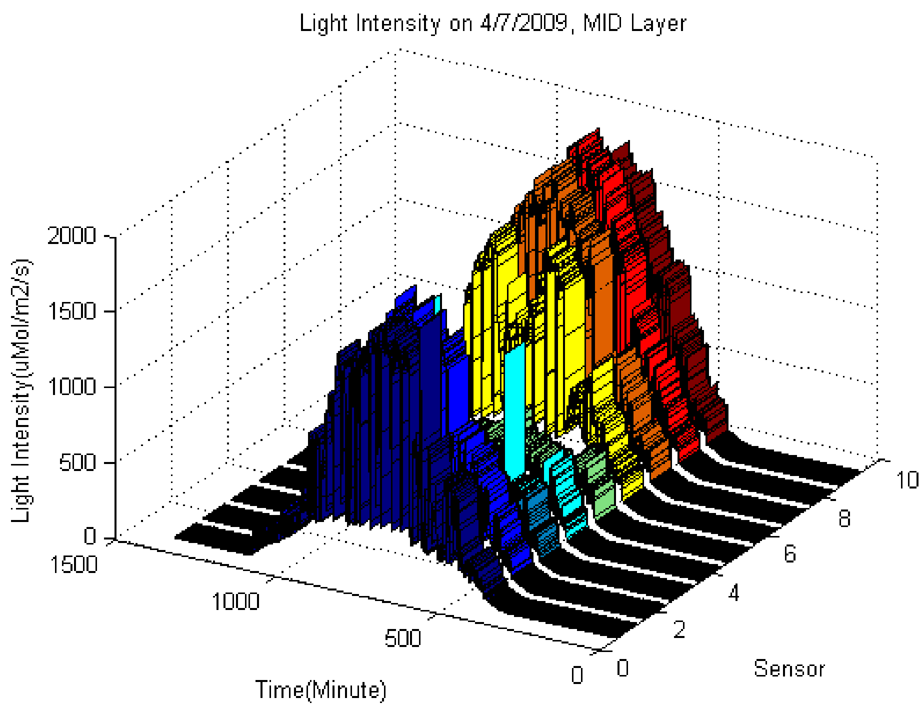

Figure 71. Middle Layer of Light Intensities on 4/7/2009

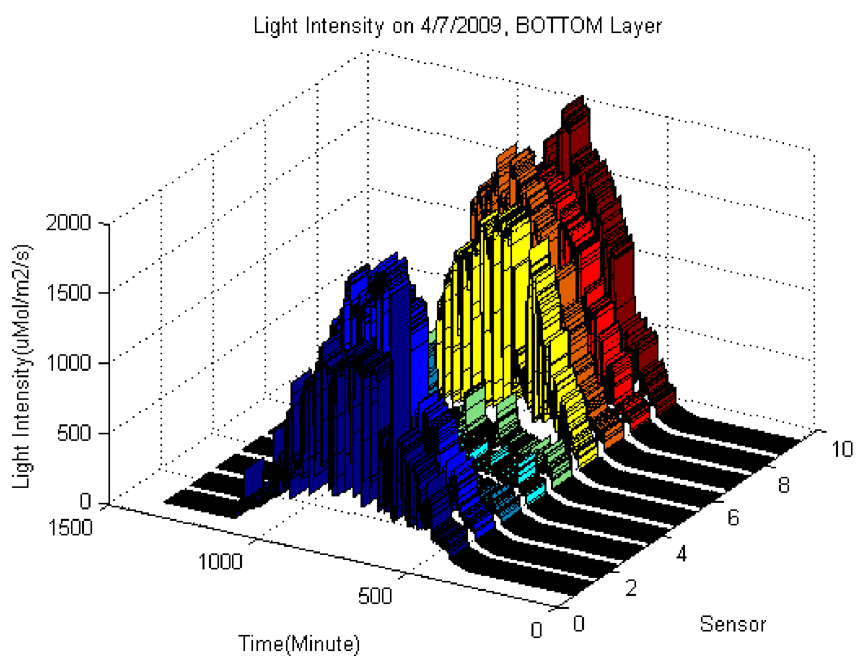

Figure 72. Bottom Layer of Light Intensities on 4/7/2009