Development and Testing of a Time-Resolved Personal Ozone Monitor

By

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Thesis directed by Associate Professor Shelly L. Miller and Professor Jana Milford

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Ground-level ozone is a common urban pollutant that has been linked to various health problems. Due to measurement challenges, not many experimental studies on personal ozone exposure have been conducted that provide time-resolved concentration data. In this research project, a new personal ozone monitor was built that provides increased temporal resolution. The monitor also measures temperature, relative humidity and location via GPS. Six monitors were built, calibrated and tested. Calibrations of the monitor showed a linear response to varying ozone concentration. Side-by-side comparison of the monitors showed reasonable correlations but revealed some issues with consistency across monitors. A major issue with the monitor was that it had poor or no detection at ozone levels at or below 20 ppb, which limited its usefulness.

To examine the feasibility of using the monitors in personal exposure studies, they were deployed in a small pilot study focusing on the personal ozone exposure of senior citizens. As a group, senior citizens are believed to be susceptible to health problems if they are exposed to elevated ozone concentrations. Understanding exposure patterns in older adults is important in interpreting health effects of ozone and in designing mitigation strategies.

The monitors were deployed for a pilot study conducted in Arvada, Colorado. The study was done in two five-day periods, with a six hour testing time frame between 11am and 5pm, during July and August of 2011. The volunteers were also given an activity diary, in which they recorded the amount of time they spent indoors, outside and in transit. The results from the ozone monitors were then compared to the Arvada stationary monitoring site to observe the difference between levels of personal exposure versus levels recorded at monitoring sites. The results from the study were inconclusive due to the majority of the data being below detection levels or in error. More development is needed to improve the sensor performance at lower detection limits before it can be deployed for exposure studies.

This thesis is dedicated to my mother and sister

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Table of Contents

Chapter 1: Introduction

1.1 Background

Ozone is a gas composed of three oxygen atoms. It is naturally occurring in the stratosphere where it forms the ozone layer, protecting the Earth from the sun's harmful rays (USEPA, 2011). In the troposphere, however, ozone is considered a pollutant. Ozone is a secondary pollutant because it is not directly emitted into the environment like other pollutants, such as carbon monoxide. Chemical reactions between oxides of nitrogen (NOx) and volatile organic compounds (VOCs) in the presence of sunlight are responsible for the formation of ozone in the troposphere (USEPA, 2011). Ozone is a common summertime pollutant due to increased sunlight aiding its formation.

Breathing of ozone can result in different health problems such as: coughing, throat irritation, and congestion. Ozone also worsens pre-existing conditions such as bronchitis, asthma and emphysema (USEPA, 2011). Ozone has been associated with premature mortality in a number of epidemiological studies (USEPA, 2011). Besides health effects, ozone has a negative impact on public welfare. Ozone causes damage to crops, resulting in an estimated $500 million loss due to crop reduction each year in the United States alone (USEPA, 2011). Ozone is also a component of smog and smog has been known to decrease visibility in urban areas.

Under the Clean Air Act (CAA), the U.S. Environmental Protection Agency is required to set National Ambient Air Quality Standards (NAAQS) for pollutants considered harmful to human health and to the environment (USEPA, 2011). There are two types of NAAQS, primary and secondary. Primary standards are meant to protect human health, including health of sensitive populations such as the elderly. Secondary standards are meant to protect public welfare; which includes animals, crops, vegetation and prevention of decreased visibility (USEPA, 2011). For ozone, the primary and secondary standards are the same. The NAAQS is 0.075 ppm (parts per million) for an 8-hour averaging time (USEPA, 2011). This standard became effective on May 27, 2008. The previous standard was 0.08 ppm and was set in 1997 (USEPA, 2011).

The focus of this study was to build a personal ozone monitor that incorporated GPS and relative humidity and temperature sensors, and to test it through a pilot study in Arvada, CO during the summer of 2011. The study represents a step toward the larger goal of investigating the levels of ozone to which active senior citizens are exposed during the summer months when ozone levels are at their peak. The pilot study was conducted during two five-day periods between July and August of 2011. During the pilot study, five volunteers carried personal ozone monitors between 11am and 5pm. The volunteers were also given an activity diary, in which they recorded the amount of time they spent indoors, outside and in transit. The results from some of the ozone monitors were then compared to the Arvada stationary monitoring site to see the difference between levels of personal exposure versus levels recorded at monitoring sites. Due to measurement difficulties, the results from the pilot study are inconclusive. The performance of the monitors indicates they require further development and testing before they can be deployed more widely.

1.2 Literature Review

1.2.1 Ozone and Health

As mentioned above, ozone has been associated with premature mortality (Anenberg *et al*, 2009). Other adverse health effects include impaired lung development (Bell *et al,* 2007), possible scaring of the lungs (USEPA, 2011) and reduced life expectancy (O'Neill, 2003).

Elevated ozone levels have been associated with an increase in hospital admissions (Bell *et al,* 2007), development of asthma in adult males (Weschler, 2006) and an increase of 0.87% in mortality for every 10-ppb (parts per billion) increase in daily ozone (Bell *et al,* 2005).

1.2.2 Personal Exposure Studies

Studies of personal exposure are important for understanding which groups of people are most likely to suffer harm from air pollution. For example, people of low socio-economic status may be disproportionately exposed to higher levels of air pollution. A study conducted in Tampa, Florida found that people living in poverty tend to live closer to sources of pollution and further away from monitoring sites (Stuart *et al*, 2009). The majority of these people also tend to be minorities, whereas whites were found to live further away from pollution sources and closer to monitoring sites (Stuart *et al*, 2009). Also low socio-economic status has been found to be a risk for the exacerbation of health problems caused by air pollution (Stuart *et al*, 2009). People of low socio-economic status are also believed to be more susceptible to health effects caused by air pollution because they already have compromised health due to material deprivation and psychological stress (O'Neill *et al*, 2003). In the case of ozone, it is questionable whether people of low socio-economic status are more susceptible to this pollutant because it is a secondary pollutant; and therefore, can form away from its pre-cursors' sources.

An ozone exposure study conducted in Kansas City, Missouri, focusing on comparing ozone levels in urban and suburban areas also had findings of areas with high minority populations being under represented by monitoring stations. In this study, the urban core was monitored by one station, though this area had the highest population density and also happened to be where most of the minorities from the area lived (Adegoke *et al,* 2010). Since stationary monitoring stations underrepresent certain communities it was futile, in this case, to establish differential exposures across communities by use of monitoring stations (Adegoke *et al,* 2010). Instead, passive sensing devices (PSDs) containing two nitrate-coated filter pads were used to compare ozone levels across communities. The PSDs were mounted on 2 m poles throughout the area being tested and away from sources of constant exhaust. The results from this study showed that, in this case, ozone levels were higher in urban than suburban areas (Adegoke *et al,* 2010). The topography of the area along with the city's tall buildings was believed to disrupt the airflow towards the center of the city, trapping exhaust from vehicles. This allowed ozone to form in the urban area and kept existing ozone from escaping (Adegoke *et al,* 2010).

Researchers studying the difference between ozone levels recorded by monitoring sites versus personal exposure levels usually agree that stationary monitors do not accurately represent personal exposure, but disagree as to whether these levels are higher or lower than those recorded by stationary monitors. Stationary monitors do not account for the effects of spatial variation in ozone concentrations, differences between indoor and outdoor levels, and varying activity patterns, which could affect personal exposure (Liu *et al,* 1993). A study conducted in Mexico City focused on comparing the ozone exposure of shoe-shiners working in the downtown area to ozone levels recorded by stationary monitoring sites. Shoe-shiners work outdoors, near the sources for ozone pre-cursers; therefore, their exposure was expected to be higher than people working indoors because ozone reacts with surfaces (O'Neill *et al*, 2003). Personal exposure to ozone was measured by using active ozone samplers. These samplers consisted of a small personal pump, a nitrite-coated etched-glass sampling tube, and a Teflon inlet. The samples taken were stored in a bag that the shoe-shiners were asked to wear on one arm throughout the sampling period, which on average lasted 6.5 hours. The results from this study show a large difference between personal exposure and ambient ozone concentrations recorded by stationary monitoring sites. The hourly concentrations measured by the stationary monitor tended to be higher than the concentrations measured by the active samplers. The median difference between the stationary monitor and active sampler was 46.6 ppb (O'Neill *et al,* 2003). This was attributed to the high levels of NOx from the large number of vehicles in the area reducing the levels of ozone (O'Neill *et al*, 2003). Also, shoe-shiners use various VOCs for their work that can emit chemicals that in turn can react with the ozone around them and affect the measurements by the samplers (O'Neill *et al*, 2003).

A study conducted in Baltimore, Maryland on the exposure of senior citizens to gaseous and particulate pollutants also had results indicating lower ozone exposure levels than those recorded from stationary monitoring sites. This study focused on studying a possible correlation between exposure to particulates and gaseous pollutants and employed the use of a multi-pollutant personal sampler; gaseous pollutants were measured using passive badge samplers. The sampler simultaneously took measurements for various pollutants, which were used to examine and compare for links between personal and ambient concentrations (Sarnat *et al*, 2000). The results from the study indicate gaseous pollutants, such as ozone, were extremely low during the sampling period (Sarnat *et al*, 2000). Seventy percent of the measured samples were below their respective levels of detection even when ambient concentrations were above these levels (Sarnat *et al*, 2000). As expected, the correlations between personal to ambient ozone exposure were weak.

The studies previously mentioned used methods that provided time-average ozone concentrations. A study conducted in Taipei, Taiwan, during February and March of 2007 (Wu *et al*, 2010), used the same ozone sensors used in this research study, which measure ozone concentrations with a fast time response. Wu et al.'s study focused on the effects personal exposure to particulate matter (PM) and ozone have on heart rate variability and arterial stiffness on mail carriers in Taipei. The monitors were placed in a basket in the front part of the mail carriers' motorcycles. Ambient ozone levels were collected from two stationary monitoring sites (Wu *et al,* 2010). The testing period began at 9am and ended at 4pm. The average personal ozone exposure of the mail carriers was 24.9 ppb, while the average ambient ozone concentration was 39.2 ppb (Wu *et al,* 2010).

Chapter 2: Materials and Methods

The focus of this study was to build a personal ozone monitor that incorporated GPS and relative humidity and temperature sensors, and to test the monitors in a pilot study in Arvada, CO during the summer of 2011. It was important to keep this monitor as small and light as possible and for it to be able to record data from all of its components for six hours. Once a prototype was successfully built, six more monitors were built. The monitors' response to ozone was studied by conducting individual calibrations on each monitor. From these calibrations, equations were generated to convert the data recorded by the monitor to ppb of ozone.

The pilot study consisted of two five-day sessions between July and August of 2011 and measured the personal ozone exposure of senior citizens residing in Arvada. Exposure levels were recorded twice per minute by the ozone monitors for six-hour periods. The volunteers were also asked to keep an activity diary noting the amount of time spent indoors, outdoors and in transit.

2.1 Ozone Monitor Components

2.1.1 Building GPS Shield and Coding of Arduino

The GPS shield used for the ozone monitor was purchased as a kit, as shown in Figure 2.1, from Adafruit Industries and assembled as instructed by the company. The kit includes all the necessary parts to build the GPS shield, except for the GPS antenna and the Arduino data logger; these were purchased separately and integrated into the GPS shield upon completion. The Arduino data logger and GPS shield must be connected for the shield to operate properly. These two boards are connected via male and female pin headers. The male pins from the shield attach to the female pins on the Arduino, forming a secure, tight connection between the two boards.

This connection allows the Arduino to control the GPS shield and the GPS shield to obtain power from the same power source as the Arduino. All of the data obtained from the shield is recorded into a secure digital memory card (SD card), which is located on the bottom side of the shield as shown on Figure 2.2.

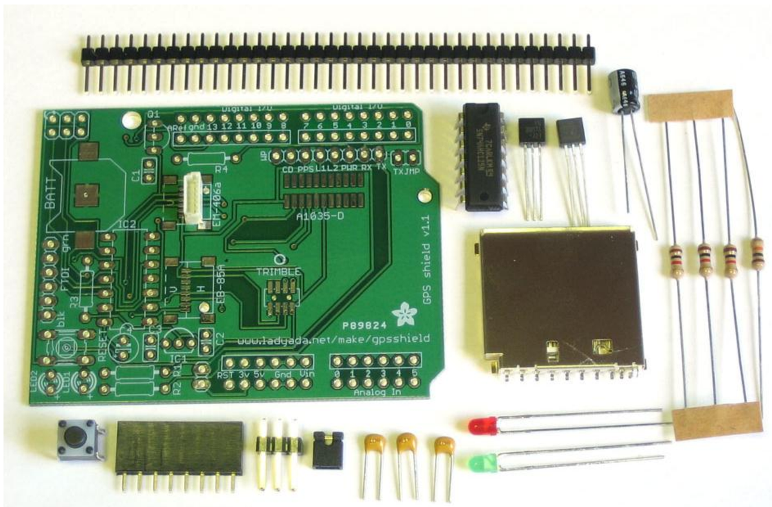


Figure 2.1: Adafruit GPS shield kit (Adafruit Industries, 2010)

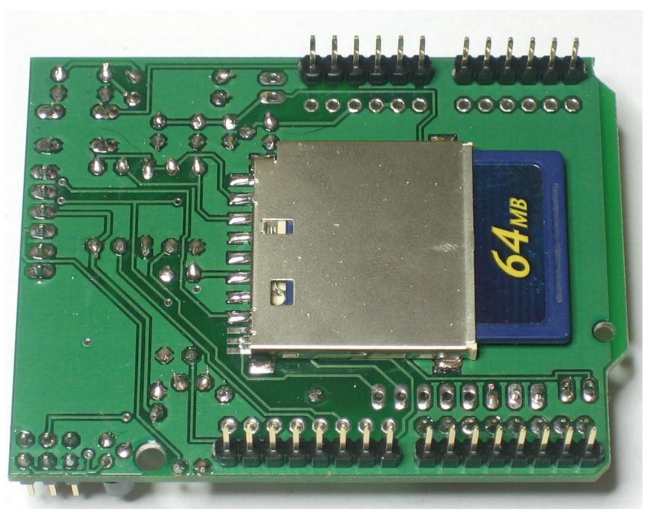


Figure 2.2: SD card holder (Adafruit Industries, 2010)

Arduino is an open source electronics prototyping platform. Various codes can be found on the Internet, which can then be altered to a specific need. A code created for the purpose of the Arduino and GPS shield combination was found on Adafruit Industries' website and then modified according to the needs of the ozone device. Darren McSweeny, an applications engineer in the Integrated Teaching & Learning Program Laboratory (ITLL) at the University of Colorado, conducted these modifications. The complete code used for the monitor can be found in Appendix A.

Once the GPS shield was completed, as shown in Figure 2.3, and properly coded; the GPS antenna was tested for accuracy. First the antenna was tested at different locations without movement. These tests consisted of placing the GPS shield outdoors, to ensure proper exposure of the antenna, and allowing the monitor to gather data. Once the GPS data was analyzed and its accuracy verified, movement was introduced. The GPS movement tests consisted of placing the device inside a vehicle to test its accuracy under driving conditions. The data collected from these tests showed the antenna's accuracy to be unaffected by driving conditions.

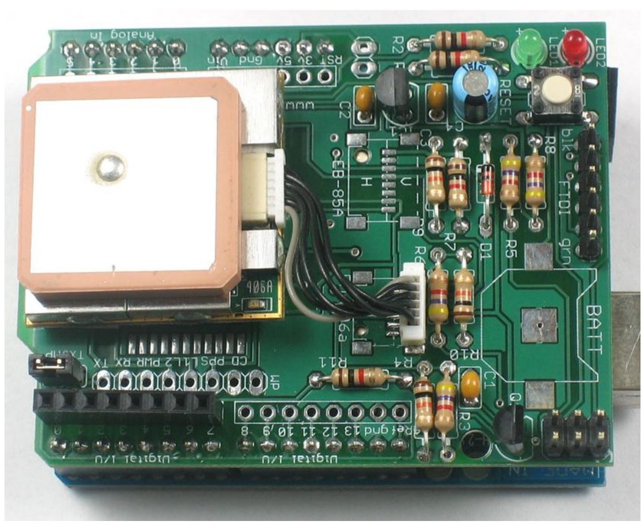


Figure 2.3: Finished version of GPS shield. Arduino data logger is below GPS shield (Adafruit Industries, 2010)

2.1.2 Ozone Sensor

Ozone sensors based on tungsten trioxide (WO_3) semiconductors have been found to exhibit outstanding sensitivity and selectivity (Utembe *et al*, 2006). The conductivity of these sensors is controlled by the conductivity of the bulk WO_3 and oxygen vacancies, which form at the gaseous interface (Williams *et al*, 2002). These vacancies are formed thermally, as shown in equation 1, and destroyed by reactions with ozone and oxygen, as shown in equations 2 and 3 respectively (Utembe *et al,* 2006). The reaction with ozone is more rapid than the oxygen reaction (Williams *et al*, 2002). In the following equations, V represents the vacancies and X represents the unperturbed WO_3 lattice.

$$X \rightarrow V + 0.5O_2 \tag{1}$$

$$V + O_3 \rightarrow X + O_2 \tag{2}$$

$$V + O_2 \rightarrow X + 0.5O_2 \tag{3}$$

The WO_3 sensor switches between two temperatures, measuring and scrubbing temperature. The scrubbing temperature of 600°C resets the sensor in preparation for the next ozone measurement, which is taken at 530°C (Utembe *et al,* 2006). When the measurements from the sensor were compared to an UV absorption spectrometer for a period of 30-days, the correlation between the two was 0.93 (Utembe *et al,* 2006). However, when eight of these sensors were compared to an UV absorption spectrometer during the same time period, the correlation decreased to 0.81 (Utembe *et al,* 2006).

2.1.3 Aeroqual SM50 Sensor

The Aeroqual SM50 sensor was designed to provide state of the art gas measurements. These sensors utilize "Gas Sensitive Semiconductor" GSS sensor technology to provide reliable, sensitive and quick response measurements for different gases. The GSS technology is exclusive to Aeroqual. The sensors exhibit an electrical resistance change when in the presence of the gas it is meant to measure; in this case, ozone (Aeroqual Ltd, 2011). These sensors are calibrated to output linear gas concentrations between 0-150 ppb and are available in diffusion, fan and pump sampling versions (Aeroqual Ltd, 2009). The fan-sampling version with an 8 bit analog signal was chosen for this study.

Figure 2.4: Aeroqual SM50 sensor (Aeroqual Ltd, 2011)

The SM50 sensor requires an input voltage range of 11-24VDC. It is connected to power through the V+ and GND (ground) slots in the screw terminal. Though this sensor is designed to operate continuously, it should be allowed to operate in a clean environment for a couple of hours on its first use or its first use after a period of no use. The sensor requires a 3-10 minute warm-up period before it is fully operational.

2.1.4 Relative Humidity and Temperature Sensors

The relative humidity (RH) sensor is a HIH-4030 Breakout board that measures %RH and outputs values as an analog output voltage. For temperature measurement, a thermistor was used. Both these sensors have linear outputs.

Figure 2.5a: RH sensor (Sparkfun Electronics, 2011)   Figure 2.5b: Thermistor (Digi-Key Corporation, 2011)

2.1.5 Power

During calibrations, the ozone sensor was powered by an AC power source with a voltage of 14.8V. A similar voltage was preferred for the finished device. The only batteries capable of providing such high voltage while maintaining size and weight at a minimum were lithium-ion batteries. Four lithium-ion cells, each with a 2800 mAh capacity and a nominal charge of 3.75V, were chosen to power the ozone sensor. The cells were connected in series to provide adequate voltage to power the ozone sensor. To prevent the Li-ion cells from over charging, which could cause them to explode; all four cells were connected to a protective circuit board (PCB). This is shown in Figure 2.6.

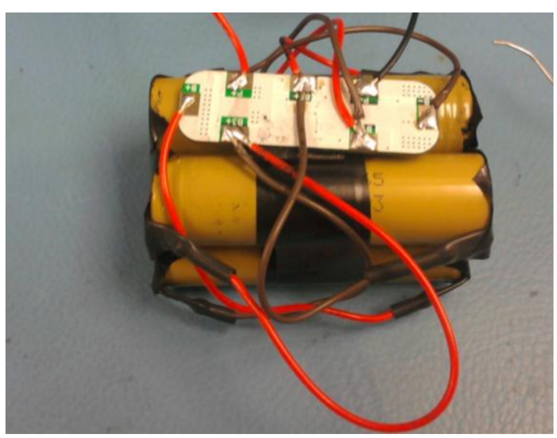


Figure 2.6: Li-ion cells connected to PCB

The GPS shield obtains its power from the Arduino; which can be powered via USB connection or battery. The Arduino was powered via USB during calibrations to allow for real-time monitoring of the monitor and by battery outside the calibration chamber. An Energizer Max alkaline 9V battery was chosen to power the Arduino since it meets the Arduino's recommended input voltage of 7-12V. The 9V battery was connected to the Arduino using a 9V Battery Holder with a 2.1 mm, center positive barrel jack, from Sparkfun Electronics, that connects to the Arduino's power jack.

2.1.6 Wiring of Ozone Monitor

The GPS shield board has six analog pins, as well as a 5V and two ground pins. These pins were used to connect the ozone sensor, RH sensor, and temperature sensor to the GPS shield. The ozone sensor was connected to the GPS shield by attaching wires from the analog and ground pins of the GPS shield to the analog terminal on the ozone sensor's screw terminal block. The RH and temperature sensors required an analog, ground and 5V pin to operate. Since only one ground and one 5V pin were available after connecting the ozone sensor, the wires from these pins were sliced into two to provide the necessary connections for the RH and temperature sensors. The analog pins on the GPS shield connect to the Arduino through the male and female pin header connections. This allows the Arduino to control and gather data from all the monitor components, which is then stored in the SD card.

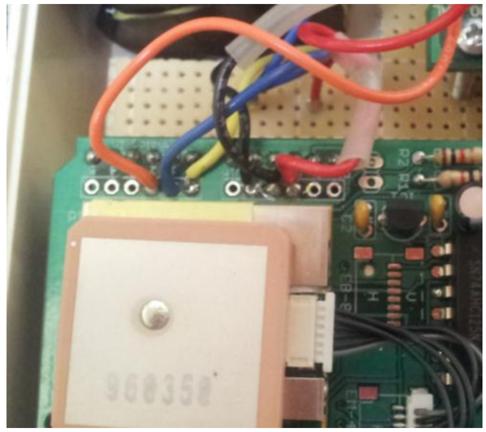


Figure 2.7: Analog connection

2.1.7 Monitor Assembly

When assembling the monitor, it was important to remember that it had to be portable, lightweight and as comfortable as possible for the study volunteers. For this reason, it was necessary to find a lightweight, yet robust, case for the ozone device. An almond color Serpac S-type box with 17.5cm x 12.4cm x 5.1cm (6.88in x 4.88in x 2.00in) dimensions and weight of 195.04 grams (6.88 oz) was chosen. A light-color was preferred for the case to keep the monitor from attracting too much heat if exposed to direct sunlight.

The arrangement of the monitor components had to be finalized to start the assembly. It was important to arrange the components in a way that would not complicate the user's ability to check the status of the monitor, wiring, and state of the batteries. The main components of the monitor, the ozone sensor and GPS shield, were mounted on a printed circuit board (PC board) first. Using a Dremel, holes were drilled on the PC board to fit the screws used to hold the ozone sensor and GPS shield in place. Plastic spacers were used to keep the Arduino from touching the PC board; this step was taken to prevent potential short-circuiting. The ozone sensor's screw terminal kept it sufficiently elevated from the PC board, making the use of the spacers unnecessary in this case.

After the GPS shield and ozone sensor were completely mounted on the PC board, the PC board was placed inside the case to ensure the parts would still fit after being raised. Once this was verified, the Li-ion cells and 9V battery holder had to be placed inside the case to ensure they would also fit. The 9V battery holder fit, but the PC board added enough height to keep the Li-ion cells from fitting inside the case. To solve this problem, the area the Li-ion cells occupied on the PC board was cut out. This gave the cells just enough space to fit inside the case and because they were in a tight space, it was not necessary to add anything to keep them in place. For the 9V battery holder, two slits were drilled on the PC board and a Velcro strip was passed through the slits and tightened around the holder to keep it in place.

The Serpac case had to be modified from its original state shown in Figure 2.8. All the cylinders protruding from the inside of the case, except the ones in each corner, were sawed or filled off using a Dremel. This step was necessary for PC board to fit inside the case once all the components were mounted. Once the PC board fit, screw holes were drilled on the PC board and the Serpac case to attach the two together. Next, holes had to be cut on the Serpac case for the ozone sensors's inlet and fan, the on/off switch, RH and temperature sensors, and the Li-ion cells charger connector. After holes were made for the on/off switch and charger connector, these parts were attached to the Serpac case using hot glue. Screws placed in the corner cylinders were used to keep the case shut when operating.

Figure 2.8: Serpac case (Digi-Key Corporations, 2011)

2.2 Calibrations and Testing

2.2.1 Calibration Set-Up

All calibrations were conducted inside a plastic box, referred to as the calibration chamber, which was lined with Teflon sheets as shown in Figure 2.9. The top of the box was not lined with Teflon to allow observation of monitor during calibrations. The ozone generator used for calibrating the ozone sensors was turned on at least an hour prior to the starting time of each calibration to allow the generator to properly warm-up. The ozone generator used was made by Thermo Electron Instruments, now known as Thermo Fisher Scientific, and it is a Model 49. The ozone generator was connected to the chamber by Teflon tubing. After the warm-up period, the SM50 ozone sensor, GPS shield and Arduino were placed inside the chamber, without any ozone flow, and allowed a ten-minute warm-up period as well. These components were placed inside the chamber without the monitor's outer case. Then, the ozone sensor was exposed to low levels of ozone for a ten-minute period before starting the calibration.

Figure 2.9: Calibration chamber

2.2.2 Calibration Method

The calibrations consisted of exposing the ozone sensors to low, medium and high levels of ozone. Each calibration was broken into two parts: starting at a low concentration and moving to a high concentration, called low-to-high (LH), and starting at a high concentration and moving to a low concentration, called high-to-low (HL). The ozone sensor's response was plotted against the ozone concentration from the generator. Regression equations and correlations were found for both LH and HL readings to note differences between the two measurement sequences as shown on Figure 2.10. Some of the sensors were slightly more responsive to low ozone levels after being exposed to high ozone levels. Three calibrations were conducted on each monitor prior to the pilot study. Calibrations were also conducted after the pilot study, but the number of calibrations conducted on each monitor, post-study, depended on whether the monitor's sensor was suspected of drifting.

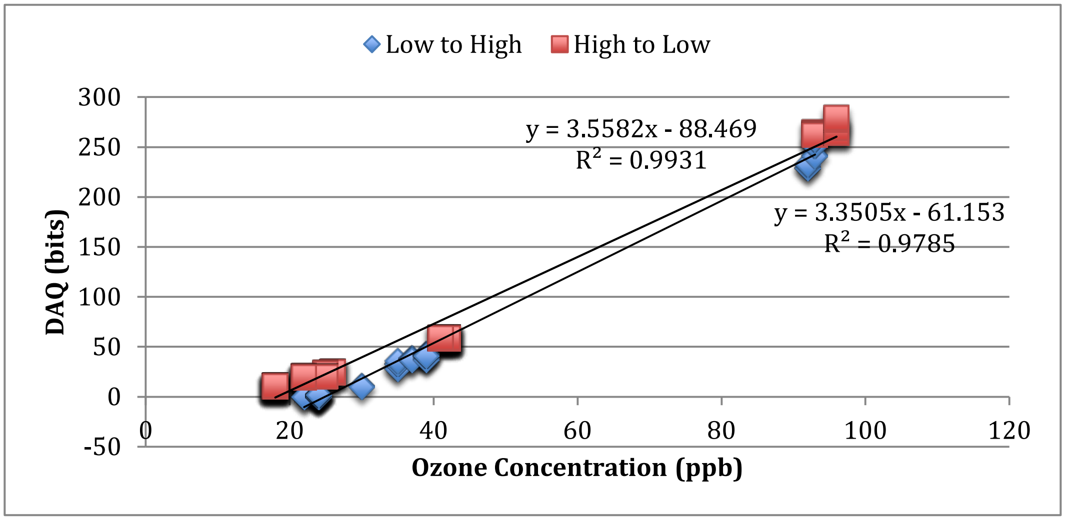


Figure 2.10: Example calibration

2.2.3 Outdoor Testing

After the ozone monitors were built, it was important to test their behavior outdoors, in a less controlled environment than the calibration chamber. During the outdoor tests, the monitors were placed on a ledge about 1.2 m (4 ft) off the ground and away from buildings and trees. The final versions of the monitors were used during these tests; therefore, only batteries powered the monitors. The monitors were placed next to each other, side-by-side, and turned on at the same time. This was done to compare the monitors' response when exposed to similar ozone concentrations during the same period of time. The readings from these tests were compared to the ozone monitor on the Skywatch Observatory in CU-Boulder's main campus or the South Boulder Creek (SBC) monitoring site. Skywatch is about 800 m from the location where the monitors were placed during outdoor tests conducted on campus. The monitors were placed about 400 m from the SBC site for the outdoor test conducted there. The latitude and longitude of Skywatch and SBC are +40° 0' 29.30", -105° 16' 5.62" and +39° 57' 26.01", -105° 14' 18.63" respectively. The SBC site is located in a rural area and its ozone monitor is 3 m above the ground while Skywatch is located in the center of the university's main campus and about 15 m above the ground. The ozone monitor used at Skywatch is also a Thermo Environmental instrument Model 49, but this one is only used to measure ozone concentrations. SBC uses a Teledyne 400E ozone monitor. Movement was added to the tests after the devices' outdoor response was analyzed.

2.2.4 Carrying Methods

The first carrying method for the ozone monitor employed the use of drawstring backpacks. This method was believed to be comfortable and less likely to interfere with the volunteers' daily activities. The front of the ozone devices was attached to the inside of the backpack using Velcro. Holes were cut out for the ozone sensors' inlet and for the RH and temperature sensors. To keep the back of the backpack from blocking the ozone sensor's fan, a piece of cardboard was placed at the bottom of the backpack to ensure sufficient room for the fan. This design is shown in Figure 2.11.

Figure 2.11: Carrying method 1

This method was used during the first portion of the pilot study but after a couple of days; the ozone monitors began noticeably malfunctioning. Initially it was believed the drawstring backpacks were causing the monitors to overheat. Holes were cut out in the back of the backpack to allow for greater airflow in an attempt to solve the problem. However, this idea did not work. The monitors were then set side-by-side on a ledge outside to test if the bags were in fact causing the problem or not. First, all the monitors were tested outside of the bags for 30 minutes and then they were placed inside of the bags. This test showed a considerable decrease in the monitors' readings after they were placed in the bag. The Skywatch Observatory's ozone readings did not show a significant decrease in ozone during that time period. During outside tests, the monitors were located about 800 m from the Skywatch Observatory. More detailed analysis on these tests can be seen in Chapter 3.

A new carrying method was then devised. This method consisted of gluing two straps across the monitor and holding the monitor as a bag or purse. Since the monitor was believed to be more susceptible to movement with this new carrying method, all of the monitors were tested to see if movement had a negative impact on the ozone sensors' function. These test were conducted by carrying each instrument for an hour or more while walking. Movement did not cause the monitors to output error data or appear to have a significant affect their function; therefore, this carrying method was chosen for the second portion of the study.

Figure 2.12: Second carrying method

2.3 Pilot Study

2.3.1 Recruitment

Volunteers for the pilot study were recruited at the Apex Community Recreation Center in Arvada, CO. Recruitment was done in compliance with the pre-approved Institutional Review Board (IRB) protocol. The Center's staff handed out information flyers regarding the study and information sessions were held. People interested in the study were given a consent form that thoroughly explained the purpose of the study and the volunteers' responsibilities. In order to participate, the volunteers had to be 65 years or older and reside in Arvada. A $200 gift card was awarded to the volunteers upon completion of the study.

2.3.2 Walk-Through Forms and Activity Diaries

To document the characteristics of the home that could affect the ozone levels indoors, a walk-through was conducted in all of the volunteers' homes. A copy of the walk through form can be found in Appendix B. The walk-through covered details about the houses' construction materials, age, number and location of windows, and types of surface materials. An activity diary was also prepared so the volunteers could keep track of their activities and surroundings during the pilot study. A copy of the activity diary can be found in Appendix C.

2.3.3 Details of Study

Each volunteer was given a device, activity diary and battery charger. Every morning during the pilot study an undergraduate student researcher, Deidre Ericson, and I drove to Arvada and met with each volunteer. Meetings were arranged either at the volunteers' homes or at the Apex Center. During the meetings, data from the previous day was transferred to my computer, the charge on the Li-ion cells, a new 9V battery was put in, and the overall performance and wiring of the monitor were checked.

The volunteers were given activity diaries for every day of the study in which we noted what monitor they were given. A copy of the activity diary can be found in Appendix C. In these diaries, the volunteers documented the amount of time they spent indoors, outdoors, in transit and whether their windows were open or closed. The volunteers were instructed to turn the devices on at 11am and to turn them off at 5pm. They were also instructed to charge them for at least a couple of hours every night. We verified they followed instructions during the morning meetings.

2.4 Data Processing and Analysis

Each of the monitor's regression equations was inspected to ensure differences between them were not statistically significant. The slopes and y-intercepts of the regression equations were analyzed by use of the t-test function in Microsoft Excel. The results of each calibration were documented in a table for easier comparison, as shown on Table 2.1a and 2.1b. Colors were added to the table to facilitate comparison between pre and post results of the ozone sensors. First the differences between the slopes and y-intercepts of the LH and HL regression equations in pre-study calibrations were analyzed. If the results of the t-test showed p-value less than or equal to 0.05, then the difference between these points was found to be statistically significant and only the HL points were used. If the p-value was above 0.05, the results were not statistically significant; therefore, all the data were used. The same analysis was done between the LH and HL regression equations for the post-study calibrations. Lastly, this same analysis was conducted between the pre and post study calibrations. This was done by comparing the slopes and y-intercepts of the pre-study calibrations to the slopes and y-intercepts of the post-study calibrations. If a statistically significant difference was not found in any of the steps, then the points from all of the calibrations of that monitor could be pooled to generate one regression equation for the device. However, if differences were found to be statistically significant in any of the steps, only HL data points were used to generate the device's regression equation. If a statistically significant difference was found between the pre and post study calibrations, then only the post-study data points were used to generate that sensor's regression equation. The regression equation, or conversion equation, of each sensor was used to convert the readings in bits from the Arduino to parts per billion (ppb) of ozone. These equations are shown below in Table 2.5; the y represents bits while the x represents ppb of ozone.

Table 2.1a: Pre and post study Low to High calibration data

	Low to High							
	Pre-Study				Post-Study			
SM 50 Sensor #	Correlation Coefficient	Regression Equation	Y-int	Slope	Correlation Coefficient	Regression Equation	Y-int	Slope
043	0.94239	y = 2.718x - 54.881	54.881	2.718	0.99559	y = 3.4333x - 80.072	80.072	3.4333
043	0.9824	y = 2.2963x - 43.008	43.008	2.2963	0.99834	y = 3.5332x - 56.772	56.772	3.5332
043	0.98529	y = 3.0328x - 59.07	59.07	3.0328				
046	0.987	y = 4.0446x-86.709	86.709	4.0446	0.98988	y = 3.6878x - 79.074	79.074	3.6878
046	0.98658	y = 3.5458x - 84.031	84.031	3.5458	0.98169	y = 3.7265x - 86.928	86.928	3.7265
046	0.97728	y = 3.3038x - 81.437	81.437	3.3038				
050	0.99351	y = 2.2623x - 40.923	40.923	2.2623	0.99256	y = 2.332x - 30.856	30.856	2.332
050	0.98378	y = 2.6258x - 52.019	52.019	2.6258	0.99638	y = 2.3951x - 22.243	22.243	2.3951
050	0.97612	y = 2.1976x - 49.319	49.319	2.1976	0.99645	y = 2.355x - 22.062	22.062	2.355
050	0.9941	y = 2.7564x - 49.15	49.15	2.7564				
051	0.9686	y = 2.7631x - 62.463	62.463	2.7631	0.99305	y = 3.5582x - 88.469	88.469	3.5582
051	0.98479	y = 3.6042x - 88.391	88.391	3.6042				
051	0.97323	y = 3.7061x - 101.43	101.43	3.7061				
056	0.9922	y = 3.2261x-67.16	67.566	3.127	0.99015	y = 2.9374x - 56.575	56.575	2.9374
056	0.955588	y = 2.8468x - 53.21	58.959	2.9799				
056	0.99502	y = 3.1343x - 76.175	76.175	3.1343				

Table 2.1b: Pre and post study High to Low calibration data

	High to Low							
	Pre-Study				Post-Study			
SM 50 Sensor #	Correlation Coefficient	Regression Equation	Y-int	Slope	Correlation Coefficient	Regression Equation	Y-int	Slope
043	0.99272	y = 3.0241x - 51.741	51.741	3.0241	0.996	y = 3.3515x - 63.772	63.772	3.3515
043	0.99589	y = 2.4605x - 39.837	39.837	2.4605	0.9986	y = 3.3836x - 40.174	40.174	3.3836
043	0.98019	y = 2.6625x - 35.683	35.683	2.6625				
046	0.9751	y = 3.6638x-65.925	65.925	3.6638	0.97388	y = 3.1695x - 51.322	51.322	3.1695
046	0.98513	y = 3.3848x - 72.517	72.517	3.3848	0.98169	y = 3.7265x - 86.928	86.928	3.7265
046	0.98326	y = 3.136x - 69.273	69.273	3.136				
050	0.99133	y = 2.1622x - 29.886	29.886	2.1622	0.99818	y = 2.1183x - 11.616	11.616	2.1183
050	0.98379	y = 2.6333x - 38.105	38.105	2.6333	0.99812	y = 2.1505x - 3.5091	3.5091	2.1505
050	0.99823	y = 2.1415x - 46.863	46.863	2.1415	0.99677	y = 2.2457x - 9.5438	9.5438	2.2457
050	0.99107	y = 2.6096x - 31.263	31.263	2.6096				
051	0.97706	y = 2.9099x - 66.61	66.61	2.9099	0.97852	y = 3.3505x - 61.153	61.153	3.3505
051	0.9862	y = 3.5743x - 79.217	79.217	3.5743				
051	0.98213	y = 3.3987x - 73.504	73.504	3.3987				
056	0.9983	y = 3.1664x-55.074	54.87	3.159	0.9912	y = 2.9188x - 42.468	42.468	2.9188
056	0.97456	y = 2.8668x - 40.2	45.153	2.9468				
056	0.99882	y = 3.1358x - 67.643	67.643	3.1358				

Table 2.2: p-values from t-test between LH and HL of pre-study calibrations

Pre-Study		
SM50 Sensor	**Y-int**	**Slope**
043	0.219	0.908
046	0.004	0.430
050	0.056	0.714
051	0.443	0.869
056	0.232	0.998

Table 2.3: p-values from t-test between LH and HL of post-study calibrations

Post-Study		
SM50 Sensor	**Y-int**	**Slope**
043	0.426	0.236
046	0.576	0.522
050	0.012	0.023
051	-	-
056	-	-

Table 2.4: p-values from t-test between pre and post study calibrations

Pre vs Post		
SM50 Sensor	**Y-int**	**Slope**
043	0.227	0.001
046	0.483	0.416
050	2.877E-05	0.0306
051	0.831	0.531
056	0.287	0.009

Table 2.5: conversion equations generated from calibration data

SM 50 Sensor	Conversion Equation
043	y= 3.3929x – 57.568
046	y= 3.5074x - 71.752
050	y= 2.2044x – 9.5535
051	y= 3.3881x – 77.359
056	y= 2.9755x – 47.47

Chapter 3: Results and Discussion

3.1 House Characteristics

The homes of Volunteers 1 through 3 were average middle class homes, ranging from 111-167 m^2 (1,200-1,800 ft^2) Volunteer 4's house was larger than the first three with an area of 195 m^2 (2,100 ft^2). Volunteer 5 had the largest house, with an estimated size of 297 m^2 (3200 ft^2). The first four houses were centrally located in Arvada, whereas the fifth house was located in the outskirts of Arvada, close to the Rocky Mountain Foothills. The location of the houses resulted in various similarities between the first four houses and differences between these four and the fifth house. The first four houses all had large trees on the property and throughout the neighborhoods; while the fifth house only had a couple of small trees on the property and very few trees throughout the neighborhood. All the houses in the study were situated on local traffic streets without painted lanes.

Table 3.1: House Characteristics

	House size (m^2)	Year Built	Brick	Wood	AC	Carpet	Tile
Volunteer 1	111.5	1970	X				X
Volunteer 2	130	1961	X			X	
Volunteer 3	111.5	1972	X			X	
Volunteer 4	196.2	1973		X	X	X	X
Volunteer 5	288	2002	X		X	X	X

3.2 Volunteer Activity

When the volunteers were recruited, active senior citizens were preferred. Even though the volunteers were active and enjoyed being outdoors, many were active outside of the time frame when data was collected. When asked why they stayed mostly indoors during this time frame, most of the volunteers answered it was too hot outside. Volunteer 4 said she usually worked on her yard during this time of year because her yard stays cool due to the large trees but since the City of Arvada had not fumigated against mosquitoes due to budget cuts, she had opted to stay inside.

Though most of the volunteers stayed inside during the testing time frame, the majority did not have AC in their homes and used open windows to keep cool. Volunteers 4 and 5 were the only volunteers with AC in their home. Volunteer 4 only used her AC for a few hours during the testing time frame, while Volunteer 5 used it constantly. Volunteer 3 did not have AC in her home but still recorded time she spent exposed to AC. It is believed she recorded the amount of time she spent in places with AC besides her home. Volunteers 1 and 2 did not have AC in their home and spend the most time outside. Volunteer 1 spent the most time outside as recreation, while Volunteer 2 spend time outside fixing portions of her house and backyard. It is believed Volunteer 1 did not record the amount of time her windows or sliding doors were open. Since she did not have AC, it is unlikely she kept them closed at all times.

Table 3.2: Total volunteer activity during the study in hours

	Indoors	**Open Window**	**Outdoors**	**In Vehicle**	**AC on**
Volunteer 1	14.83	0.00*	13.50	7.08	0.00
Volunteer 2	16.50	3.50	10.00	3.83	0.00
Volunteer 3	24.25	19.00	4.50	4.08	8.25*
Volunteer 4	21.75	0.50	0.50	1.75	7.00
Volunteer 5	16.50	0.00	2.67	2.83	24.00

(*) Volunteer 3 did not have AC in her house, she recorded "AC on" from other places and Volunteer 1 did not properly record the amount of time the windows were open

3.3 Reliability of Ozone Results

Many technical difficulties were encountered with the ozone monitors during the pilot study. We had six ozone monitors available, one for each volunteer and a back-up monitor in case one stopped working. Monitor 046 was designated as the back-up monitor and it was only used once during the pilot study. When one of the SM50 ozone sensors was suspected of malfunctioning, it was taken back and tested in the ozone chamber and outdoors. The ozone sensors generally responded well during these tests; which made technical problems difficult to diagnose.

During the Study, Monitors 050 and 051 never malfunctioned; these two monitors never recorded error data. However, Monitor 050 recorded more below detection data than expected from Volunteer 3. The other three monitors mostly recorded data below detection levels or error data. This behavior led us to analyze the reliability of the monitors; which was done by pooling all the data points from each monitor and calculating the percentage of points that fell under the following categories: below detection levels, at or above detection levels, and error output. The results of this analysis are shown below.

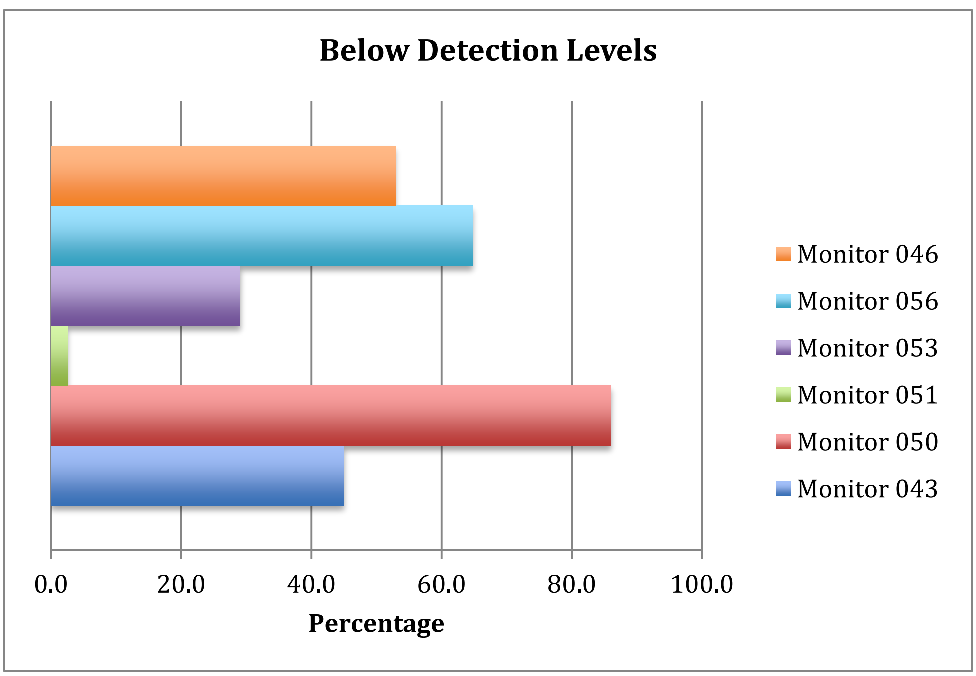


Figure 3.1: Percentage of time monitors were below detection levels

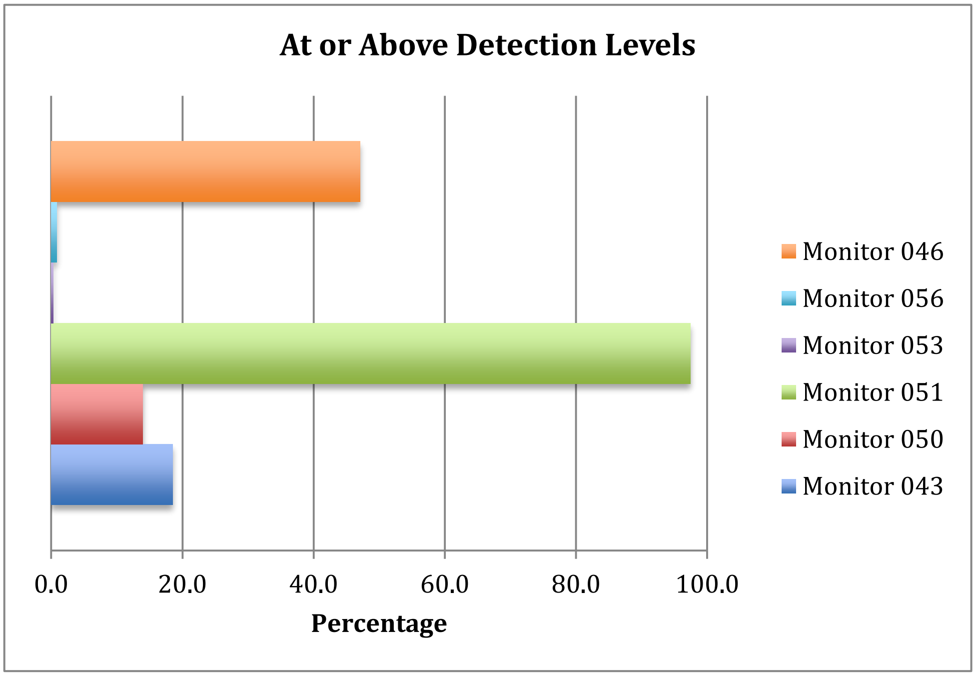


Figure 3.2: Percentage of time monitors were at or above detection levels

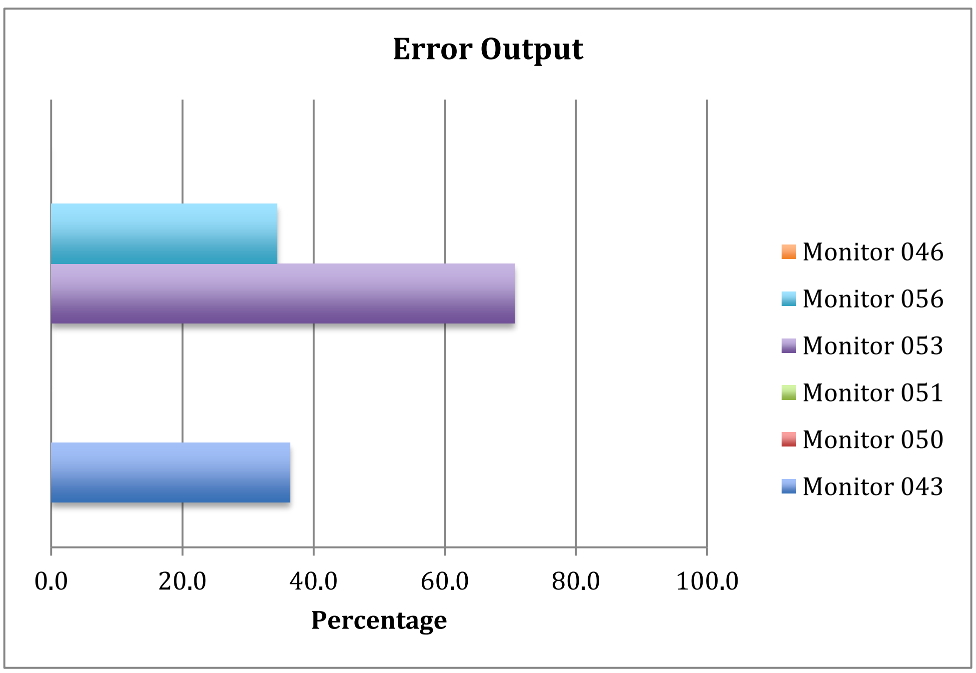


Figure 3.3: Percentage of time monitors recorded error data

As shown, the percentage of data when the monitors were measuring below detection limits is mostly high and the percentage of data at or above detection levels is mostly low. Out of all the monitors, Monitor 053 draws the most attention because approximately 75% of its data is error data. It is also noticeable in the Below Detection Levels graph and unnoticeable in the Ar or Above Detection Levels graph. Post-pilot study tests on Monitor 053 could not be conducted because its corresponding SM50 ozone sensor stopped working when the study ended. This occurrence, combined with the high percentage of error data recorded, suggests the data points from this Monitor are unreliable; therefore they were not included in the results table. Daily graphs showing the percentage of data that falls under these three categories can be seen in Appendix D.

It is important to note, though it appears that Monitor 046, the back-up monitor, was behaving better than most of the monitors on Figure 3.2, the results shown correspond to only one day of use. Monitor 046 was given to Volunteer 1 on Day 5 because the 9V battery holder's wires in Monitor 043 broke while changing batteries on Day 5. The back-up monitor was deployed due to a small technical problem, not because an SM50 ozone sensor suddenly stopped working.

3.4 Correlation of SM 50 Ozone Sensors

The SM 50 ozone sensors' simultaneous side-by-side response to outdoor ozone levels was analyzed during and after the pilot study to ensure that the monitors were responding similarly. The monitors were tested outside three times before they were deployed for the pilot study and once after the Study ended. These tests were done by placing the monitors outside close to each other and turning them on at same time. The data obtained from these tests was then tested using the Pearson Linear Correlation function on Microsoft Excel; results are shown below in Table 3.3.

Table 3.3: Correlation between monitors

Monitors	July 26	July 27	July 28	October 5 Complete data	October 5 Excluding fall	October 5 Prior to fall
043 vs 050	0.836	0.92		-0.322	0.057	-0.102
043 vs 051	0.837	0.893		0.564	0.608	0.702
043 vs 056	0.768	0.943	0.403	0.928	0.927	0.93
050 vs 051	0.8	0.861		-0.257	-0.313	-0.337
050 vs 056	0.769	0.963		-0.371	0.044	-0.176
051 vs 056	0.725	0.916		0.629	0.681	0.804

The outdoor test conducted on July 26th was the test that led us to suspect the initial carrying method using the backpacks was causing the monitors to malfunction. The points included in the correlation analysis include all of the points recorded during this test, meaning data points from when the monitors were outside of the bags and when they were placed inside of the bags. As indicated in Figure 3.4, the monitors were outside of the bags for half an hour and then were placed inside the bags for the remainder of the test. The readings for three of the four monitors show an abrupt decrease after they were placed inside the bags, in contrast to the ambient measurement from the Skywatch monitor. The July 27th test was conducted to verify the bags were in fact causing the monitors to malfunction. The test began with all the monitors inside the bags for 45 minutes and outside the bags for the remainder of the test, as shown in Figure 3.5. The results in this case show a distinct increase when the monitors were removed from the bags. All the data points collected during the testing period were included in the correlation analysis. The July 28th test only included devices that had been malfunctioning. These tests were conducted between 11am and 6 pm when ozone levels were relatively high. The results for July 26th and 27th show correlations between the devices ranging from 0.72 to 0.96. The July 28th test has the lowest correlation between Monitors 043 and 056, even though these two monitors had a high correlation the previous day.

Table 3.4: Average concentrations of ozone in ppb recorded by monitors and monitoring sites during outside test

Monitors/Site	July 26	July 27	July 28	October 5
Monitor 043	24.0	29.9	35.0	33.4
Monitor 050	10.6	26.7		32.7
Monitor 051	29.0	33.3		26.9
Monitor 056	18.5	39.4	37.4	48.4
Monitoring Site	39.3	43	48	40.5

The July 27th test had the lowest bias among the other tests conducted in July. The correlation between the monitors is the highest and the difference between the monitors' and monitoring sites' average ozone concentration is the lowest. Though the July 28th test had the lowest correlation, the average ozone concentration measured by Monitors 043 and 056 only differ by 2.4 ppb.

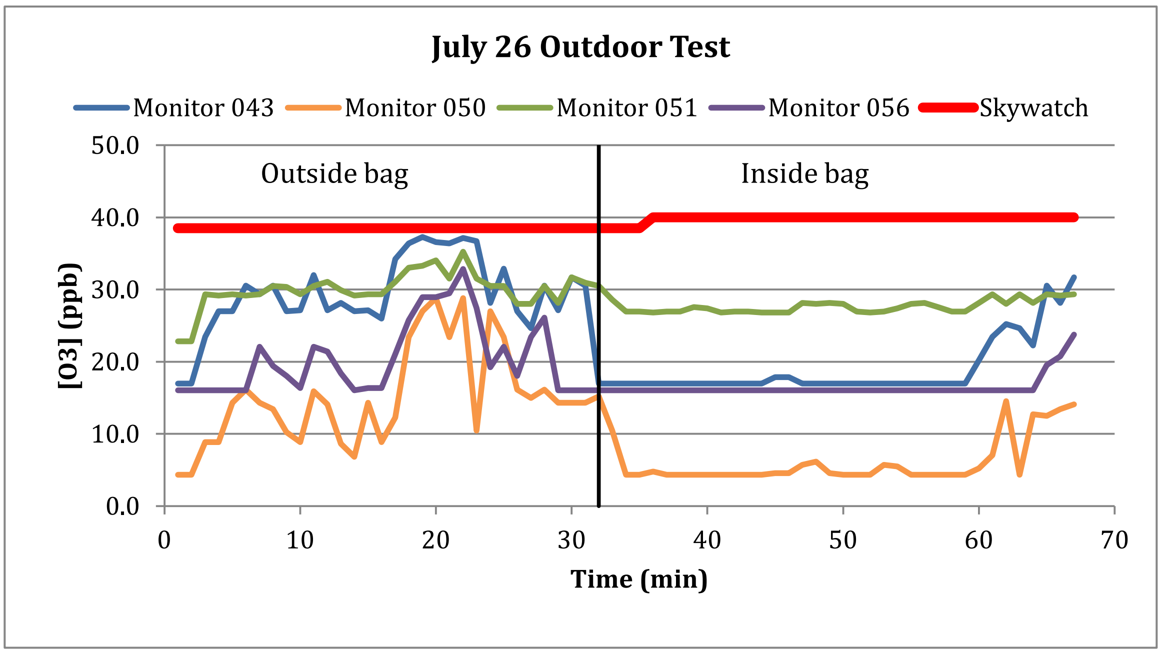


Figure 3.4: Outdoor test started at 5:13pm

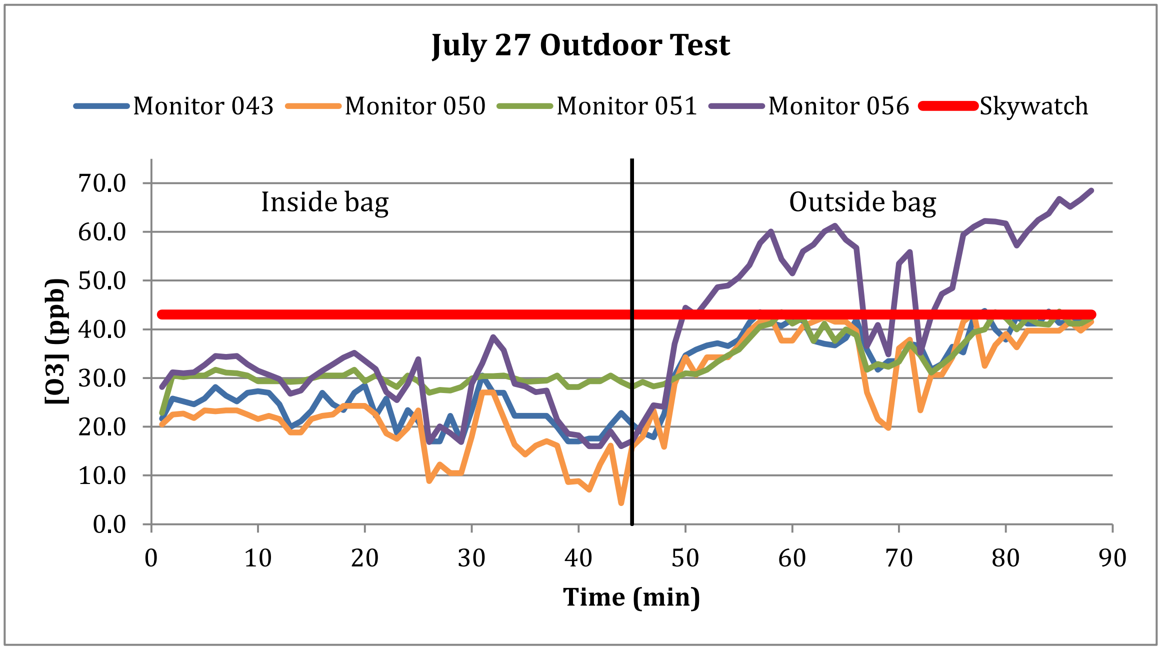


Figure 3.5: Outdoor test started at 11:28am

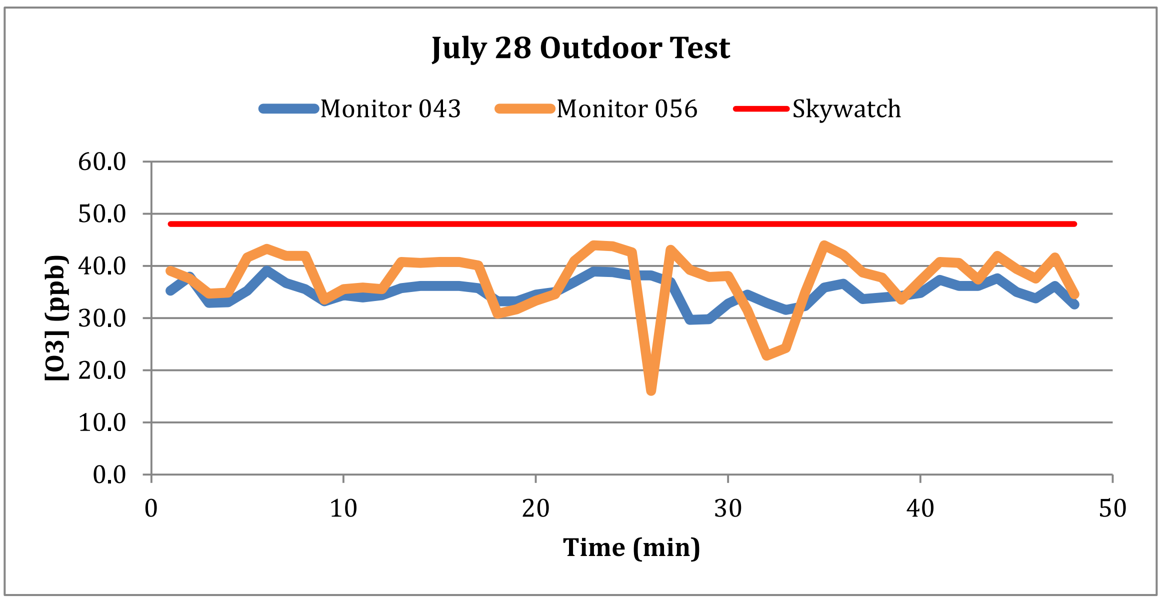


Figure 3.6: Outdoor test started at 2:50pm

The October 5th outside test was conducted at a different location from the tests in July. We wanted to compare the ozone concentrations recorded by the devices to those of a stationary monitoring station. Access to the Skywatch Observatory on campus was not allowed; therefore, the monitors were taken near the South Boulder Creek (SBC) monitoring station. During the test, the monitors were placed about 1.2 m off the ground and away from trees, as it was done during the July tests, and were placed about 400 m from the SBC site.

During the test, Monitor 050 fell off the ledge it was on twice. The first column under October 5th on Table 3.3 shows the results from the correlation analysis on all the data points recorded during the tests, including those recorded when Monitor 050 was on the ground. The second column results do not include the data points recorded while Monitor 050 was on the ground. The points from this fraction of time were discarded for all of the monitors for the second correlation analysis. The third column shows results from the correlation analysis on data points recorded before Monitor 050 fell. Data recorded after Monitor 050's first fall were excluded from the third analysis for all monitors.

The correlation between monitor pairs excluding Monitor 050 increases from the first to third analysis done for October 5th. For pairs in which this monitor is included, the correlation continues to be very low or negative throughout the analysis. This could be attributed to the monitor malfunctioning, even before it fell, or because the ozone sensor inside Monitor 050 is more sensitive to wind than the rest. The wind speed increased about halfway through the test. The ozone levels detected by the monitors were mostly about 10 ppb below the Skywatch monitor during the July tests. At the beginning of the October test, most of the monitors differed from the SBC monitor by more than 10 ppb. About halfway through the test, the monitors' response became more scattered and only Monitor 056 approached, but also surpassed, the levels recorded by the SBC Monitor. The ozone levels recorded by the SBC monitor slightly increased after the first 20 minutes of the test. A similar trend can be seen for the monitors, except for Monitor 050.

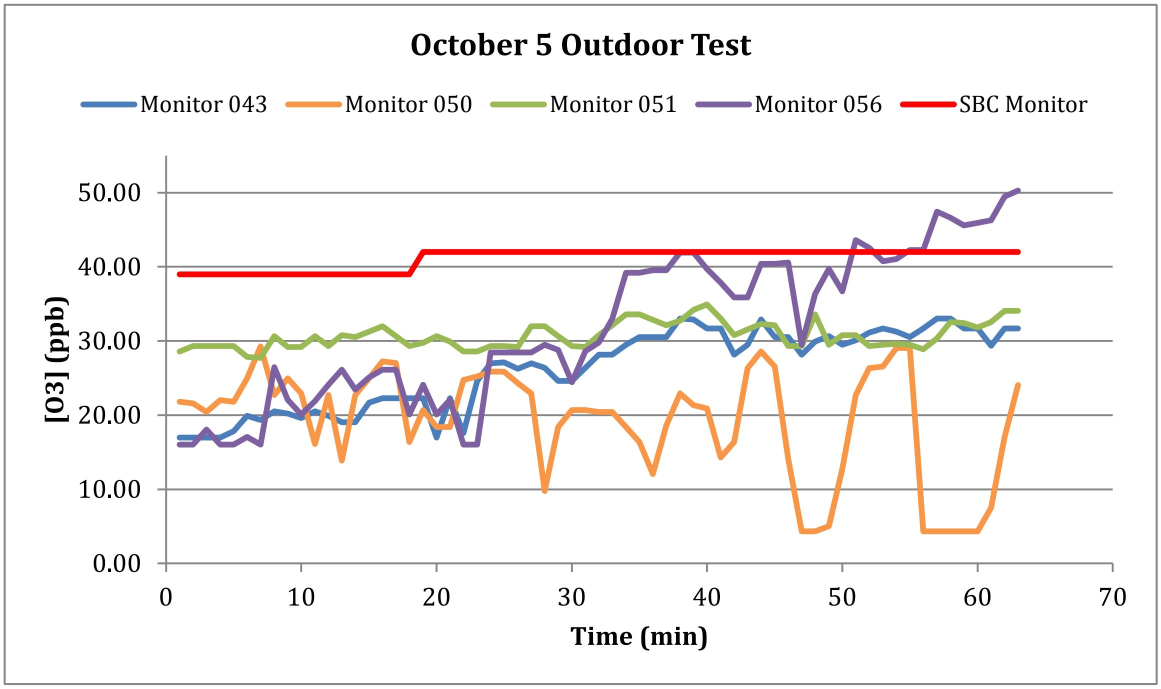


Figure 3.7: Outdoor test started at 1:42pm. Figure includes all data collected during test.

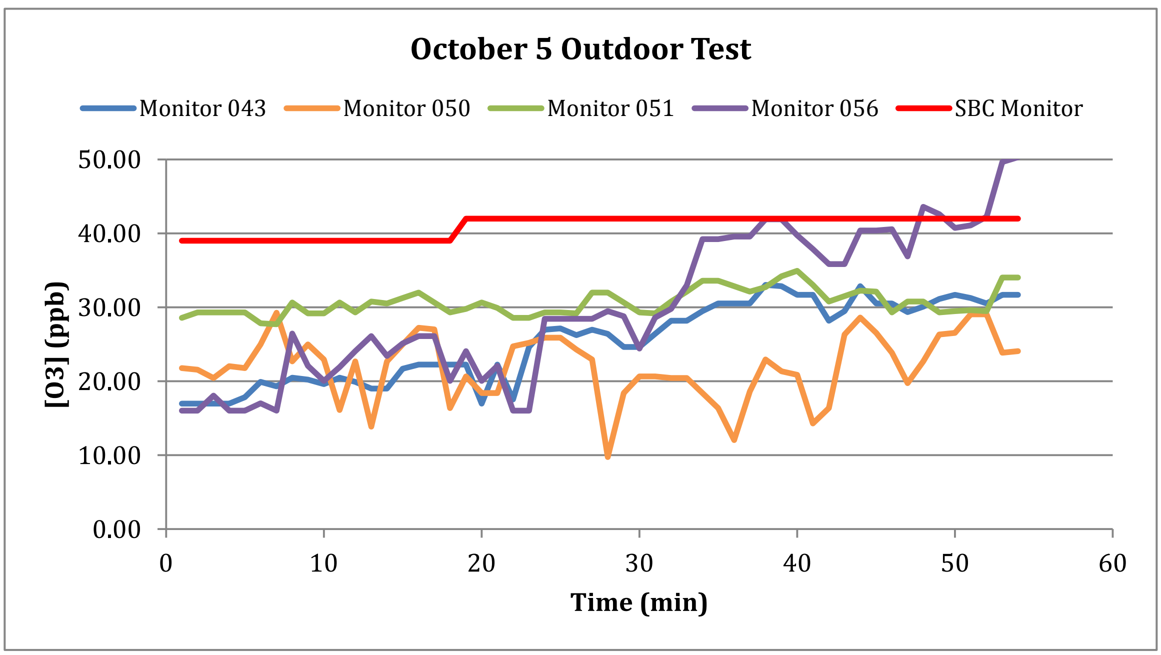


Figure 3.8: Outdoor test started at 1:42pm. Figure excludes data collected during fall of Monitor 050.

3.5 Ozone Results

The ozone exposure results for the second portion of the pilot study are shown in Table 3.4. The results from the first portion were not used due to the bags causing the monitors to malfunction. The concentrations measured by the monitors are lower than expected since ozone is at its highest levels during this time of year and Jefferson County commonly has among the highest ozone levels of all the counties in the area (CDPHE, 2011). It may also be that because most volunteers remained indoors during the monitoring periods, the indoor levels were low compared to outdoor levels measured by the stationary monitoring site. The empty slots represent days a volunteer did not have a monitor because it was malfunctioning or the data was discarded because the monitor was found to be unreliable after the pilot study. Two volunteers whose monitors continuously malfunctioned agreed to participate an extra day using monitors that did not malfunction. These results are in the "extra day" slots.

Table 3.5: Ozone exposure concentrations in ppb

Volunteer 1		Volunteer 2		Volunteer 3		Volunteer 4		Volunteer 5	
Day 1	**O3 exposure**	**Day 1**	**O3 exposure**	**Day 1**	**O3 exposure**	**Day 1**	**O3 exposure**	**Day 1**	**O3 exposure**
Min	17.0	Min	22.8	Min	4.8	Min		Min	16.0
Average	17.0	Average	26.2	Average	4.3	Average		Average	16.0
Max	17.0	Max	38.8	Max	21.6	Max		Max	16.0
Day 2	**O3 exposure**	**Day 2**	**O3 exposure**	**Day 2**	**O3 exposure**	**Day 2**	**O3 exposure**	**Day 2**	**O3 exposure**
Min	17.0	Min	22.8	Min	4.3	Min		Min	16.0
Average	17.8	Average	25.4	Average	7.0	Average		Average	16.3
Max	27.0	Max	36.4	Max	48.8	Max		Max	24.8
Day 3	**O3 exposure**	**Day 3**	**O3 exposure**	**Day 3**	**O3 exposure**	**Day 3**	**O3 exposure**	**Day 3**	**O3 exposure**
Min	17.0	Min	22.8	Min	4.3	Min		Min	16.0
Average	17.0	Average	25.6	Average	4.7	Average		Average	16.0
Max	17.0	Max	30.5	Max	12.5	Max		Max	16.0
Day 4	**O3 exposure**	**Day 4**	**O3 exposure**	**Day 4**	**O3 exposure**	**Day 4**	**O3 exposure**	**Day 4**	**O3 exposure**
Min	17.0	Min	22.8	Min	4.3	Min		Min	
Average	21.3	Average	25.3	Average	4.9	Average		Average	
Max	37.6	Max	32.9	Max	14.3	Max		Max	
Extra day	**O3 exposure**	**Day 5**	**O3 exposure**	**Day 5**	**O3 exposure**	**Extra day**	**O3 exposure**	**Day 5**	**O3 exposure**
Min	22.8	Min	22.8	Min	4.3	Min	4.3	Min	
Average	25.3	Average	28.5	Average	6.7	Average	4.3	Average	
Max	34.0	Max	38.8	Max	39.7	Max	7.1	Max	

Prior to the pilot study, Volunteers 1 through 3 were expected to have the most ozone exposure. Volunteer 4's exposure was uncertain because large trees surrounded her house and Volunteer 5's exposure was expected to be low since she used her AC frequently.

Volunteer 1's monitor malfunctioned or reported readings below detection levels frequently. She was given Monitor 043 for the first four days, Monitor 046 for the fifth day and Monitor 051 for the extra day. Due to her active lifestyle, it was expected that she would be exposed to higher levels than those recorded by Monitor 043, which is why she was asked to do an extra day with Monitor 051; this monitor had not malfunctioned during the study. Her activity diary also supports this expectation; Table 3.2 shows Volunteer 1 to have spent the most time outdoors out of all the volunteers in the pilot study. Even though Monitor 043 had a higher percentage of points at detection levels during day 4 than on previous days, the error percentage was still higher than preferred; therefore, a monitor with zero error was used. As shown in the extra day slot for Volunteer 1, she was exposed to higher ozone levels than what Monitor 043 recorded during the first three days it was used. Also, it was possible to analyze more hours of data with Monitor 051 than with Monitor 043. The results from her extra day are shown below. A very high percentage of the recorded points were at or above detection levels and error points were not recorded.

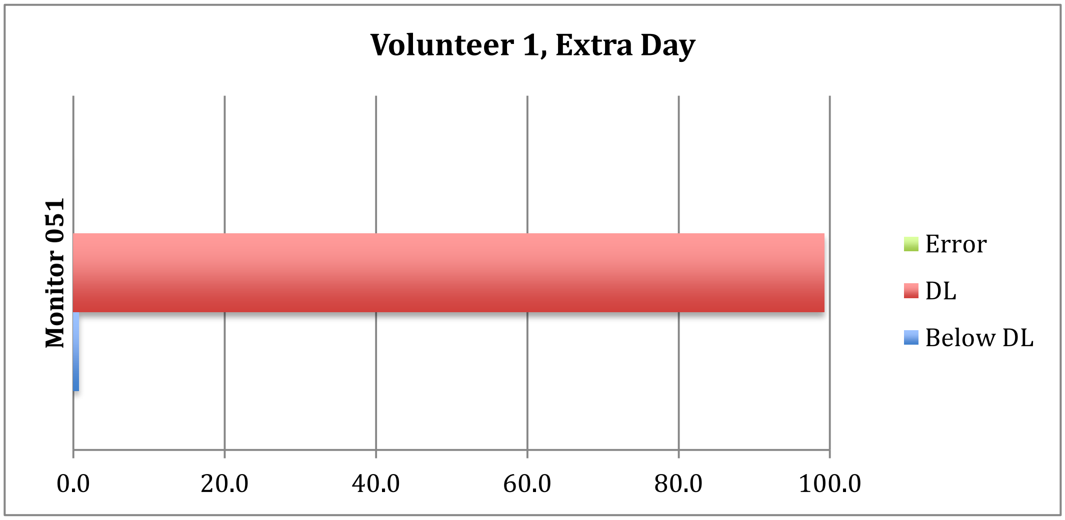


Figure 3.9: Reliability of results for Volunteer 1, Extra Day

Volunteer 2 was given Monitor 051, which never malfunctioned during the pilot study. This volunteer was expected to have the highest exposure because she spent many hours outside, including hours within the testing time frame, fixing her home and backyard. She did not have any large trees in her backyard, which could protect her from ozone exposure by reacting with ozone and in turn depleting it. Overall, Volunteer 2 had the highest average levels of ozone out of all the volunteers; however, these levels are lower than expected.

Volunteer 3 spent the most time indoors but also had her windows open the longest during the testing time frame. This Volunteer exercised mostly indoors at the Apex Center and during the morning hours. She also spent some time in her front yard but she also had a large tree in her front yard which could have caused the ozone levels around her to decrease.

The percentage of time Volunteers 2 and 3 were exposed to different detectable ozone levels is shown below. The results for Volunteer 2 correspond with our expectation that she would have the highest ozone exposure, but her exposure range is very limited; her monitor only shows exposure between 20 to 40 ppb. Over 80% of the data recorded for Volunteer 2 is between

20 to 30 ppb. Volunteer 3 has a larger exposure range, between 5 and 60 ppb, though the percentage of time she was exposed to ozone levels above 40 ppb is very low.

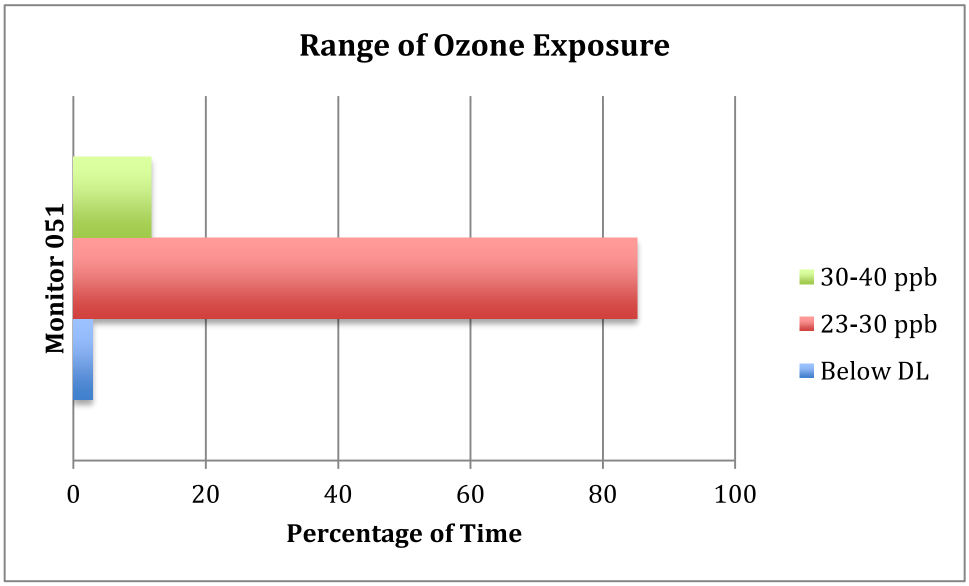


Figure 3.10: Range of ozone exposure for Volunteer 2

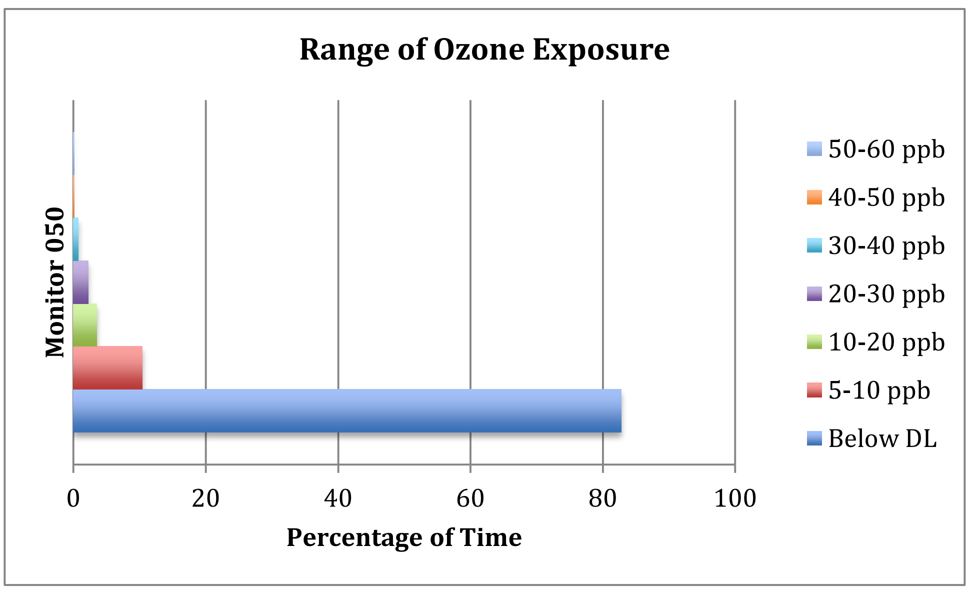


Figure 3.11: Range of ozone exposure for Volunteer 3

Volunteers 4 and 5 had the lowest overall ozone exposure. Both of these volunteers were active during the morning hours. Volunteer 4 exercised indoors at the Apex Center while Volunteer 5 usually exercised outdoors, but in the early hours of the morning, before monitoring started. During the testing time frame, these two Volunteers were usually indoors with the AC on. Volunteer 4 agreed to do an extra day with Monitor 050 to ensure her exposure levels were indeed low. The results from the extra day in Figure 3.12 show a high percentage of below detection levels and a very low percentage of points at detection levels.

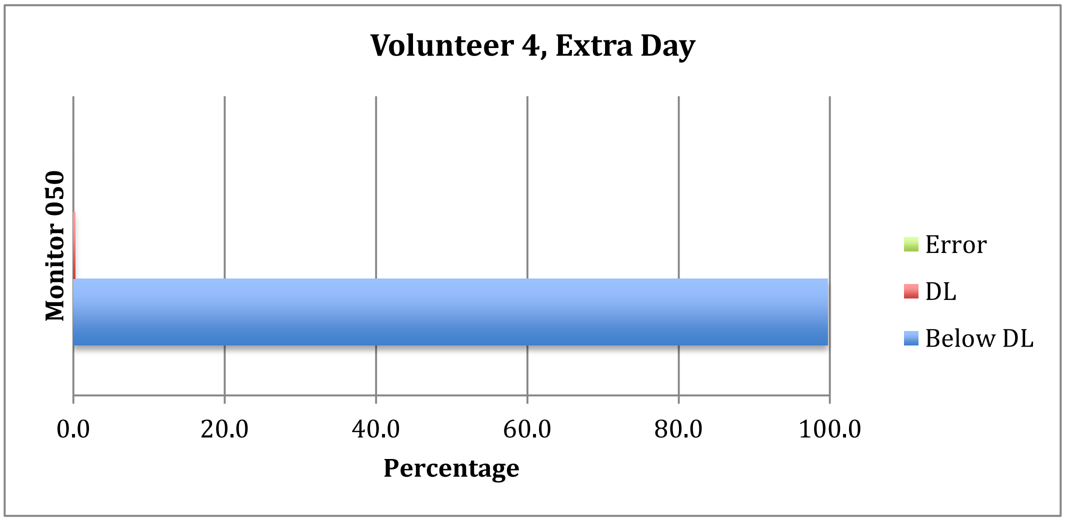


Figure 3.12: Reliability of results for Volunteer 4, Extra Day

3.5.1 Comparison to Stationary Monitoring Site

Days 1 and 2 were the days with the highest ozone concentrations during the pilot study's testing time frame. Hourly averages from the Arvada and Rocky Flats monitoring stations were obtained for comparison between the monitors and monitoring stations. The Arvada monitor's latitude and longitude are 39°48'0.62" and -105° 5'57.35". The Rocky Flats monitor's latitude and longitude are 39°52'20.94" and -105° 9'55.79". The distance of these monitors to the volunteers' houses ranges from 3 to 10 km. The Arvada monitor is located in a residential area while the Rocky Flats monitor is located in a rural area. Both of these sites use Teledyne 400E ozone monitors and the monitors are 3 m above the ground. As shown below, Monitor 051's readings, which had the highest averages, were well below the levels recorded by the monitoring stations.

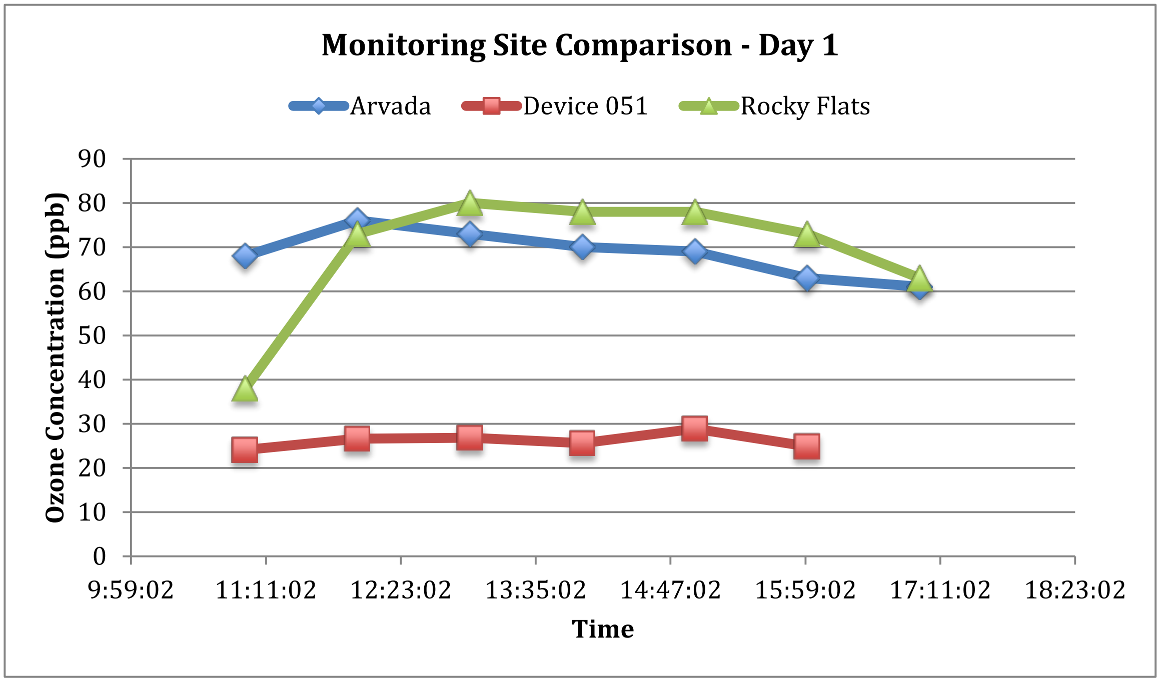


Figure 3.13: Comparison of hourly averages between Monitor 051 and monitoring stations for Day 1

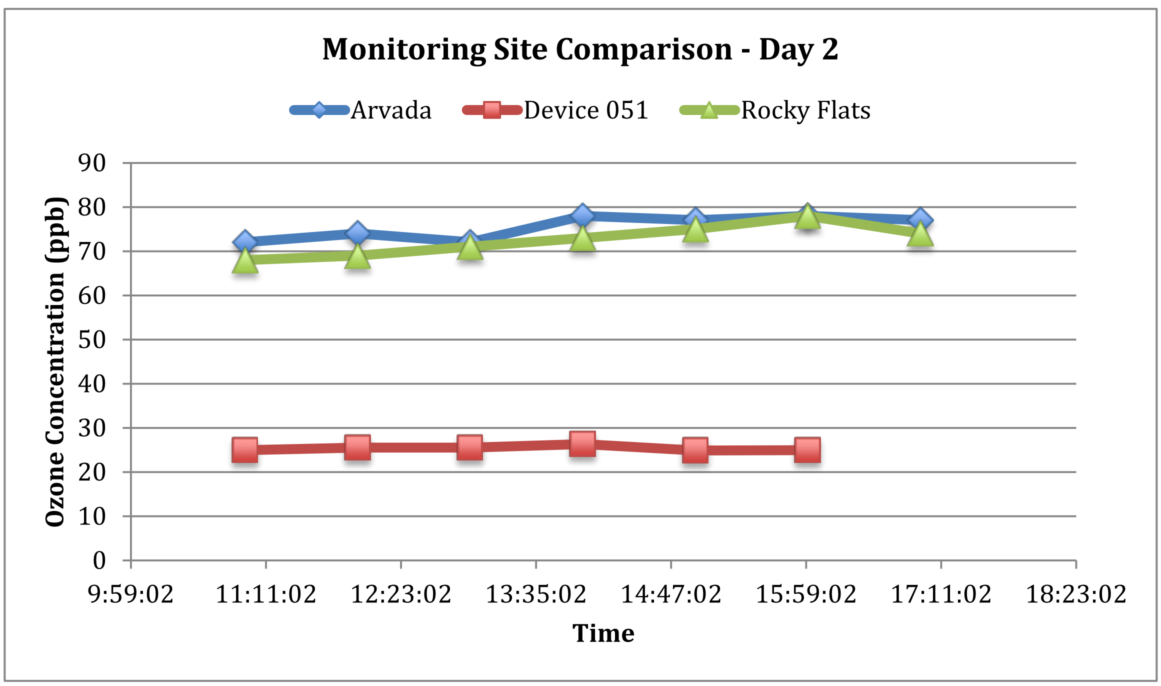


Figure 3.14: Comparison of hourly averages between Monitor 051 and monitoring stations for Day 2

As shown in Figures 3.13 and 3.14, Monitor 051 was recording ozone concentrations around 50 ppb lower than those recorded by the stationary monitors. Monitors recording ozone concentrations below what stationary monitors recorded was common during the outdoor tests conducted in July and October. However, Monitor 051 usually recorded concentrations around 10ppb lower than the concentrations recorded by the stationary monitors, as shown in Figures 3.4, 3.7 and 3.8. In Figure 3.5, Monitor 051 is around 10ppb lower than the Skywatch monitor while inside the bag but approaches the Skywatch monitor's concentrations once it is out of the bag. Most of the monitors had similar behavior during this test, except for Monitor 056; which exceeded the concentrations from the Skywatch monitor once out of the bag. During the July outdoor tests, the monitors were located around 800 m from the Skywatch location. The distance between the volunteers' homes and the Arvada and Rocky Flats sites ranged from 3 to 10 km. During the October test, the monitors were placed around 400 m from the SBC site.

Though the monitors did not consistently match the concentrations from stationary monitors, the difference between Monitor 051 and the stations was never as great as the difference seen during the pilot study. This difference may be due to the outdoor tests being conducted while leaving the monitors still on a ledge, whereas the volunteer was probably carrying the monitor causing movement. Also, during the outdoor tests, the monitors were kept away from trees and walls; the only surface they were near was the ledge itself. The volunteer probably had the monitor near different kinds surfaces, with which the ozone could have reacted, reducing the ozone concentrations detected by the monitor. Lastly, though the volunteer with Monitor 051 was one of the volunteers who spent the most time outdoors, she also spend time indoors or in a vehicle, where ozone levels are expected to be low.

3.6 Relative Humidity, Temperature and GPS Results

The results for %RH and temperature are shown in Figures 3.15 and 3.17. Portions of time when ozone levels dropped below detection levels are represented by gaps in the ozone series. According to Volunteer 2's activity diary, more time was spent indoors and in transit on Day 1 than on Day 2.

For the Day 1, as shown in Figure 3.15, Volunteer 2 was outside her house during the first 60 minutes of the testing time frame and in and out of her house between minutes 60 and 90. Then between minutes 90 and 150, the GPS data shows the volunteer to be in transit. During this period of time, %RH steadily decreased, spiked during minute 126 and then continued decreasing. Ozone slightly increased, also spiked during minute 126 and decreased again. Temperature remained constant. When Volunteer 2 reached her destination, she was indoors between minutes 150 and 210. The %RH increased and temperature and ozone levels decreased during this time. The volunteer was again in transit between minutes 210 and 225. Temperature increased, %RH decreased, but ozone levels spiked during minute 214, dropped below detection levels as shown by the gap in the series, and then decreased to levels similar to those recorded indoors. As the volunteer arrived at her second destination, a commercial greenhouse, %RH increased to the highest levels recorded for the day, ozone also increased and temperature decreased. The volunteer was at this location between minutes 225 and 270. Her movement at the commercial greenhouse is shown in Figure 3.16. The volunteer was in transit again between minutes 270 and 300. During this time, the temperature increased and ozone levels and %RH decreased. When the volunteer arrived at her house, she remained outdoors for the last hour of the testing time frame, between minutes 300 and 360. During this time, the ozone levels, temperature and %RH remained constant.

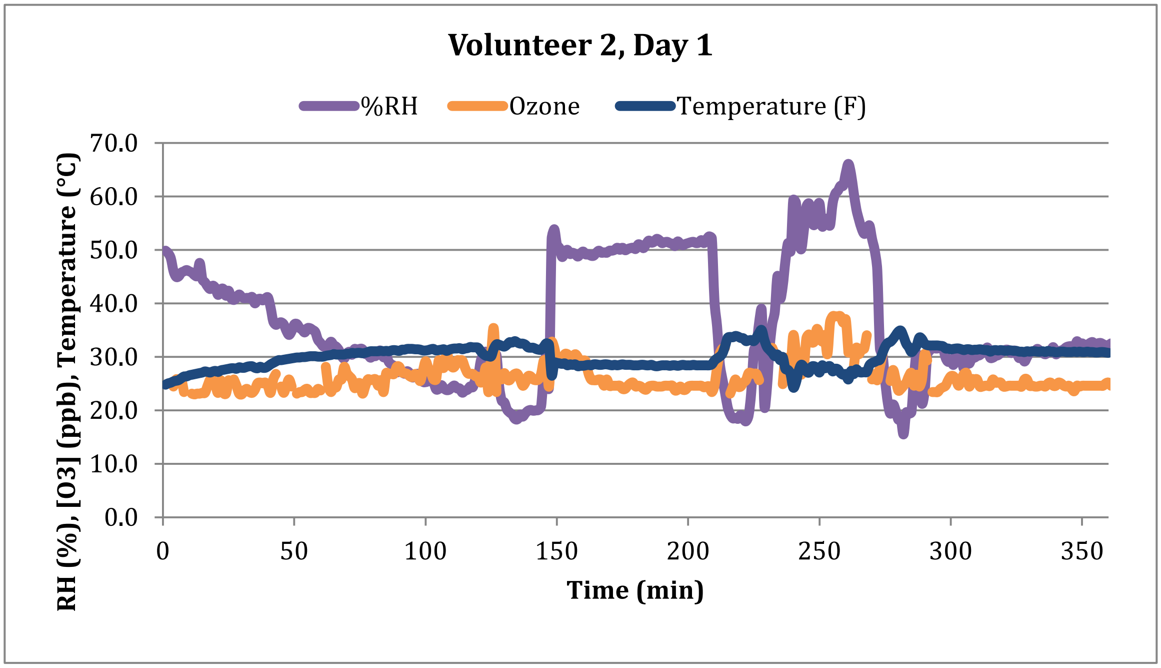


Figure 3.15: comparison of %RH, Temperature and ozone levels for Volunteer 2, day 1

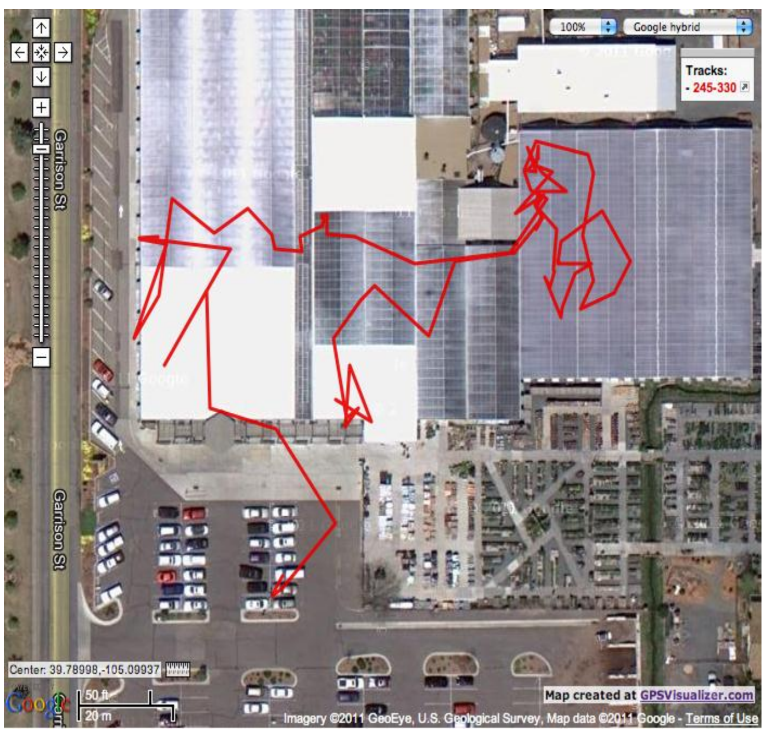


Figure 3.16: Example of GPS data

For Day 2, Volunteer 2 spent the first 34 minutes of the testing time frame in her front yard. At this time, temperature increased, %RH decreased and ozone levels fluctuated between 23 and 30 ppb. Between minutes 34 and 139, the volunteer was either in her front yard or inside her home. During this time, gaps are not seen in the ozone series; therefore, the ozone levels did not drop below detection levels when she was indoors. Also, %RH and temperature are consistent except for a drop in %RH during minutes 113 and 114. The volunteer was in transit between minutes 139 and 154. During this time %RH and ozone levels decreased and temperature increased. The volunteer was at her destination, a store, between minutes 154 and 244. While at the store, the %RH increased, decreased and increased again, temperature decreased, and ozone levels remained constant at first but then spiked, decreased to below detection levels and then remained constant at 25 ppb. As the volunteer was leaving the store, an increase in temperature and ozone levels and a drop in %RH can be seen. The volunteer was again in transit between minutes 244 and 259. During the transit period, %RH dropped to the lowest levels recorded for Day 2, temperature increased and ozone levels remained constant at 23 ppb. Volunteer 2 remained in her front yard or backyard for the remainder of the testing time frame for Day 2. When she arrived at her house, the ozone levels increased to 29 ppb for two minutes but then decreased 25 and remained constant for the remainder of the testing time frame. The %RH also remained constant and the temperature had a slight decrease during that time.

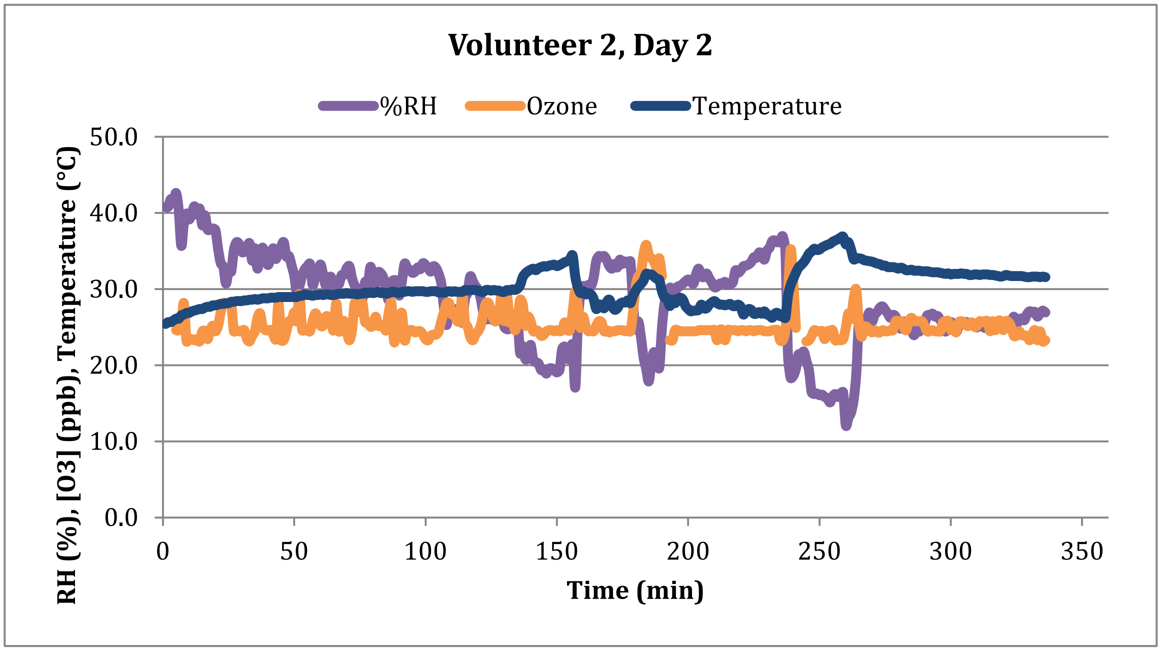


Figure 3.17: comparison of %RH, Temperature and ozone levels for Volunteer 2, day 2

Chapter 4: Conclusion and Future Research

4.1 Conclusion

The reliability of the ozone sensors was questionable throughout the study. When their reliability was analyzed, the majority of the sensors had poor results; Monitors 053 and 056 had a 71% and 35% error output respectively. Also, as shown in Figure 3.2, all of the monitors except for Monitor 051 and the back-up monitor, were at or above detection levels less than 20% of the time they were on. The manufacturer suggested steps to take when the sensors malfunctioned but these steps did not solve the issue. When one ozone sensor malfunctioned while under warranty, the manufacturer took back the sensor, fixed it and returned it; however, information on why the sensor had malfunctioned and what was fixed was not disclosed. Although we deduced that the first carrying design contributed to reliability problems, some of the monitors continued to malfunction with the second carrying design. It is still unknown what caused these problems.

Out of all the monitors used, only Monitors 050 and 051 performed without any apparent malfunction and provided the most hours of useful data. From the period of six hours during which data was collected, only Monitors 050 and 051 provide data for the entirety or majority of the testing period. It is important to note that the sensor of Monitor 051 was the sensor returned to the manufacturer. Though Monitor 050 appeared to have performed well during the pilot study, it did not work during the post-study outside test, even before it fell off the ledge on which it had been placed.

Overall, the results from this study are inconclusive. The ozone sensors ability to detect ozone at concentrations below 20 ppb is questionable. The detection limits of the sensors were calculated using calibration data and varied between ozone sensors. During chamber calibrations, the sensors did not respond to concentrations below 20ppb during the LH portion of the calibration, but usually had better response to low concentrations after being exposed to high concentrations.

The low levels recorded by the monitors could mean the volunteers are not exposed to high levels of ozone as it was hypothesized; however, their true exposure remains unknown because the monitors' ability to detect levels below 20 ppb is uncertain. Four out of the five volunteers did say they purposely tried to stay indoors during the testing time frame because of the high temperatures of the summer days. By doing this, the volunteers are unknowingly protecting themselves from ozone exposure.

Volunteer 2 also preferred to stay indoors during this period of time, but due to her obligations to fix her home and backyard, she spent time outdoors during the testing time frame and if indoors, she kept her windows open. However, the GPS data for this volunteer showed she was exposed to ozone levels at or above detection levels inside her house and when she was indoors at other places, such as stores. Volunteer 2 had the highest daily averages of all the volunteers, but the averages were much lower than the levels recorded by the stationary monitoring sites. It is possible Volunteer 2's exposure levels are in fact much lower than those from the monitoring sites due to ozone reacting with the various types of surfaces surrounding her while she is in her backyard, house or stores. Exposure studies similar to this study, O'Neill *et al* and Sarnat *et al,* also found personal exposure results much lower than the concentrations recorded by stationary monitoring sites. However, as shown in Figure 3.2, almost all of the data collected from Monitor 051 was at or above detection levels, which suggests Volunteer 2 was constantly exposed to ozone levels above 20 ppb. The GPS data corroborates this theory by showing that the volunteer was exposed to ozone levels at or above detection levels when indoors. In the case of the other volunteers, as shown in Figure 3.1, the majority of the data points were below detection levels, especially for Monitor 050; which indicates Volunteers 3 to 5 were mostly exposed to levels below 20 ppb. It is possible Volunteer 1 was exposed to ozone levels above 20 ppb, but only one day of data with Monitor 051 is available to assess her exposure.

4.2 Future Research

The use of calibration data obtained inside the calibration chamber caused ambiguity on how the ozone sensors respond to ozone outdoors and what their detection limits were. To avoid this, the ozone sensors should be tested outside and compared to stationary monitoring stations at least the same amount of times chamber calibrations are conducted. This step could lead to better understanding of the ozone sensors' response to ozone outside and at what concentrations the sensors detect ozone. A study conducted in Taipei, Taiwan used the same ozone sensors used in this study, but the sensors were calibrated against stationary monitoring sites. Correlation between the sensors' readings and the stationary monitor ranged between 0.89 and 0.93 for one-minute intervals (Wu *et al,* 2010).

Outside, side-by-side tests, away from a monitoring site should also be conducted more frequently to test how the monitors' response to similar levels of ozone differs between them. These tests should also be conducted during high wind and low wind days to test the effects of wind on the ozone sensor. Lastly, the effects of movement should be more thoroughly tested before deployment and by people un-familiar with the study, since people familiar with the study cause bias in how the monitor is carried and how carefully it is treated.

REFERENCES

Aeroqual Ltd, "Our Technology," http://www.aeroqual.com/about/technology, accessed November 2011

Aeroqual Ltd, SM50 Sensor Module Guide, November 2009

Adegoke Jimmy, Steurer Joan, Green Christopher. "The Kansas City, Missouri, Ground-Level Ozone (GLO) Project: A Community-Based Air Pollution Field Experiment," Environmental Health, 2010, 73: 8-13

Anenberg Susan, West Jason, Fiore Arlene. "Intercontinental Impact of Ozone Pollution on Human Mortality," Environmental Science and Technology, 2009, 43: 6482-6487.

Bell Michelle, Dominici Francesca, Samet Jonathan. "A Meta-Analysis of Time-Series Studies of Ozone and Mortality With Comparison to the National Morbidity, Mortality, and Air Pollution Study," 2005, 16: 436-445.

Bell Michelle, Goldberg Richard, Hogrefe Christian. "Climate Change, Ambient Ozone, and Health in 50 US Cities," Springer Science, 2007, 82: 61-76.

Liu Sally, Koutrakis Petros, Suh Helen, Mulik James. "Use of Personal Measurements for Ozone Exposure Assessment: A Pilot Study," Environmental Health Perspectives, 1993, 101:318-324.

O'Neill Marie, Ramirez-Aguilar Matiana, Meneses-Gonzales Fernando. "Ozone Exposure Among City Outdoor Workers," Air and Waste Management Association, 2003, 53:339-346.

O'Neill Marie, Jerrett Michael, Kawachi Ichiro. "Health, Wealth and Air Pollution: Advancing Theory and Methods," Environmental Health Perspectives, 2003, 111: 1861- 1870.

Sarnat Jeremy, Koutrakis Petros, Suh Helen. "Assessing the Relationship between Personal Particulate and Gaseous Exposures of Senior Citizens Living in Baltimore, MD," Air and Water Management, 50:1184-1198.

Stuart L Amy, Mudhasakul Sarntharm, Sriwatanapongse Watanee. "The Social Distribution of Neighborhood-Scare Air Pollution and Monitoring Protection," Air and Waste Management Association, 2009, 59:591-602.

U.S. Environmental Protection Agency (USEPA 2011). "Ground Level Ozone", http://www.epa.gov/glo/, accessed November 2011.

U.S. Environmental Protection Agency (USEPA 2011). "Health", http://www.epa.gov/glo/health.html, accessed November 2011.

U.S. Environmental Protection Agency (USEPA 2011). "National Air Quality Standards (NAAQS)", http://www.epa.gov/air/criteria.html, accessed November 2011.

Utembe S. R., Hansford G.M., Sanderson M.G. "An Ozone Monitoring Instrument Based on the Tungsten Trioxide (WO3) Semiconductor," Elsevier, 2006, 114:507-512.

Weschler, Charles. “Ozone’s Impact on Public Health: Contributions from Indoor Exposures to Ozone and Products of Ozone-Initiated Chemistry,” Environmental Health Perspectives, 2006, 114:1489-1496.

Williams David E, Aliwell Simon R, Pratt Keith F. “Modeling the Response of a Tungsten Oxide Semiconductor as a Gas Sensor for the Measurement of Ozone,” Measurement Science and Technology, 2002, 13:923-931

Wu Chang-fu, Kuo I-Chun, Su Ta-Chen. “Effects of Personal Exposure to Particulate Matter and Ozone on Arterial Stiffness and Heart Rate Variability in Healthy Adults,” American Journal of Epidemiology, 2010, 171:1299-1309.

APPENDIX A: Code for Arduino

```
/* Code starts here - call it GPSLogger_v2.1 :) */

// this is a generic logger that does checksum testing so the data written should be always good
// Assumes a sirf III chipset logger attached to pin 0 and 1

#include "AF_SDLog.h"
#include "util.h"
#include <avr/pgmspace.h>
#include <avr/sleep.h>
#include <stdlib.h>
#include <string.h>

// power saving modes
#define SLEEPDELAY 30
#define TURNOFFGPS 0
#define LOG_RMC_FIXONLY 0

AF_SDLog card;
File f;

#define led1Pin 4
#define led2Pin 3
#define powerPin 2

#define BUFFSIZE 75
#define BUFFSIZE2 17
char buffer[BUFFSIZE];
char buffer1[BUFFSIZE2];
char buffer2[BUFFSIZE2];
char buffer3[BUFFSIZE2];
char comma[] = ",";
char ret[] = "\n";
uint8_t bufferidx = 0;
uint8_t fix = 0; // current fix data
uint8_t i;

int sensorPin0 = 0;
int sensorPin1 = 1;
int sensorPin2 = 2;
int sensorValue0 = 0;
int sensorValue1 = 0;
int sensorValue2 = 0;

/* EXAMPLE
```

```
$PSRF103,<msg>,<mode>,<rate>,<cksumEnable>*CKSUM<CR><LF>

<msg> 00=GGA,01=GLL,02=GSA,03=GSV,04=RMC,05=VTG
<mode> 00=SetRate,01=Query
<rate> Output every <rate>seconds, off=00,max=255
<cksumEnable> 00=disable Checksum,01=Enable checksum for specified message
Note: checksum is required

Example 1: Query the GGA message with checksum enabled
$PSRF103,00,01,00,01*25

Example 2: Enable VTG message for a 1Hz constant output with checksum enabled
$PSRF103,05,00,01,01*20

Example 3: Disable VTG message
$PSRF103,05,00,00,01*21

*/

#define SERIAL_SET   "$PSRF100,01,4800,08,01,00*0E\r\n"

// GGA-Global Positioning System Fixed Data, message 103,00
#define LOG_GGA 0
#define GGA_ON   "$PSRF103,00,00,01,01*25\r\n"
#define GGA_OFF  "$PSRF103,00,00,00,01*24\r\n"

// GLL-Geographic Position-Latitude/Longitude, message 103,01
#define LOG_GLL 0
#define GLL_ON   "$PSRF103,01,00,01,01*26\r\n"
#define GLL_OFF  "$PSRF103,01,00,00,01*27\r\n"

// GSA-GNSS DOP and Active Satellites, message 103,02
#define LOG_GSA 0
#define GSA_ON   "$PSRF103,02,00,01,01*27\r\n"
#define GSA_OFF  "$PSRF103,02,00,00,01*26\r\n"

// GSV-GNSS Satellites in View, message 103,03
#define LOG_GSV 0
#define GSV_ON   "$PSRF103,03,00,01,01*26\r\n"
#define GSV_OFF  "$PSRF103,03,00,00,01*27\r\n"

// RMC-Recommended Minimum Specific GNSS Data, message 103,04
#define LOG_RMC 1
#define RMC_ON   "$PSRF103,04,00,01,01*21\r\n"
#define RMC_OFF  "$PSRF103,04,00,00,01*20\r\n"
```

```
// VTG-Course Over Ground and Ground Speed, message 103,05
#define LOG_VTG 0
#define VTG_ON   "$PSRF103,05,00,01,01*20\r\n"
#define VTG_OFF  "$PSRF103,05,00,00,01*21\r\n"

// Switch Development Data Messages On/Off, message 105
#define LOG_DDM 1
#define DDM_ON   "$PSRF105,01*3E\r\n"
#define DDM_OFF  "$PSRF105,00*3F\r\n"

#define USE_WAAS   0     // useful in US, but slower fix
#define WAAS_ON    "$PSRF151,01*3F\r\n"       // the command for turning on WAAS
#define WAAS_OFF   "$PSRF151,00*3E\r\n"       // the command for turning off WAAS


// read a Hex value and return the decimal equivalent
uint8_t parseHex(char c) {
  if (c < '0')
    return 0;
  if (c <= '9')
    return c - '0';
  if (c < 'A')
    return 0;
  if (c <= 'F')
    return (c - 'A')+10;
}

// blink out an error code
void error(uint8_t errno) {
  while(1) {
    for (i=0; i<errno; i++) {
      digitalWrite(led1Pin, HIGH);
      digitalWrite(led2Pin, HIGH);
      delay(100);
      digitalWrite(led1Pin, LOW);
      digitalWrite(led2Pin, LOW);
      delay(100);
    }
    for (; i<10; i++) {
      delay(200);
    }
  }
}

void setup()
{
```

```
WDTCSR |= (1 << WDCE) | (1 << WDE);
WDTCSR = 0;
Serial.begin(4800);
putstring_nl("\r\nGPSlogger");
pinMode(led1Pin, OUTPUT);
pinMode(led2Pin, OUTPUT);
pinMode(powerPin, OUTPUT);
digitalWrite(powerPin, LOW);

if (!card.init_card()) {
  putstring_nl("Card init. failed!");
  error(1);
}
if (!card.open_partition()) {
  putstring_nl("No partition!");
  error(2);
}
if (!card.open_filesys()) {
  putstring_nl("Can't open filesys");
  error(3);
}
if (!card.open_dir("/")) {
  putstring_nl("Can't open /");
  error(4);
}

strcpy(buffer, "GPSLOG00.TXT");
for (buffer[6] = '0'; buffer[6] <= '9'; buffer[6]++) {
  for (buffer[7] = '0'; buffer[7] <= '9'; buffer[7]++) {
    //putstring("\ntrying to open ");Serial.println(buffer);
    f = card.open_file(buffer);
    if (!f)
      break;
    card.close_file(f);
  }
  if (!f)
    break;
}

if(!card.create_file(buffer)) {
  putstring("could not create ");
  Serial.println(buffer);
  error(5);
}
f = card.open_file(buffer);
if (!f) {
```

```
  putstring("error opening ");
  Serial.println(buffer);
  card.close_file(f);
  error(6);
}
putstring("writing to ");
Serial.println(buffer);
putstring_nl("ready!");

putstring(SERIAL_SET);
delay(250);

if (LOG_DDM)
  putstring(DDM_ON);
else
  putstring(DDM_OFF);
delay(250);

if (LOG_GGA)
  putstring(GGA_ON);
else
  putstring(GGA_OFF);
delay(250);

if (LOG_GLL)
  putstring(GLL_ON);
else
  putstring(GLL_OFF);
delay(250);

if (LOG_GSA)
  putstring(GSA_ON);
else
  putstring(GSA_OFF);
delay(250);

if (LOG_GSV)
  putstring(GSV_ON);
else
  putstring(GSV_OFF);
delay(250);

if (LOG_RMC)
  putstring(RMC_ON);
else
  putstring(RMC_OFF);
```

```
  delay(250);

  if (LOG_VTG)
    putstring(VTG_ON);
  else
    putstring(VTG_OFF);
  delay(250);

  if (USE_WAAS)
    putstring(WAAS_ON);
  else
    putstring(WAAS_OFF);
}

void loop()
{
  //Serial.println(Serial.available(), DEC);
  char c;
  uint8_t sum;

  // read one 'line'
  if (Serial.available()) {
    c = Serial.read();
    //Serial.print(c, BYTE);
    if (bufferidx == 0) {
      while (c != '$')
        c = Serial.read(); // wait till we get a $
    }
    buffer[bufferidx] = c;

    //Serial.print(c, BYTE);
    if (c == '\n') {
      //putstring_nl("EOL");
      //Serial.print(buffer);
      buffer[bufferidx+1] = 0; // terminate it

      if (buffer[bufferidx-4] != '*') {
        // no checksum?
        Serial.print('*', BYTE);
        bufferidx = 0;
        return;
      }
      // get checksum
      sum = parseHex(buffer[bufferidx-3]) * 16;
      sum += parseHex(buffer[bufferidx-2]);
```

```
// check checksum
for (i=1; i < (bufferidx-4); i++) {
  sum ^= buffer[i];
}
if (sum != 0) {
  //putstring_nl("Cxsum mismatch");
  Serial.print('~', BYTE);
  bufferidx = 0;
  return;
}
// got good data!

if (strstr(buffer, "GPRMC")) {
  // find out if we got a fix
  char *p = buffer;
  p = strchr(p, ',')+1;
  p = strchr(p, ',')+1;       // skip to 3rd item

  if (p[0] == 'V') {
    digitalWrite(led1Pin, LOW);
    fix = 0;
  } else {
    digitalWrite(led1Pin, HIGH);
    fix = 1;
  }
}
if (LOG_RMC_FIXONLY) {
  if (!fix) {
    Serial.print('_', BYTE);
    bufferidx = 0;
    return;
  }
}
// rad. lets log it!

sensorValue0 = analogRead(sensorPin0);
sensorValue1 = analogRead(sensorPin1);
sensorValue2 = analogRead(sensorPin2);
itoa(sensorValue0, buffer1, 10);
itoa(sensorValue1, buffer2, 10);
itoa(sensorValue2, buffer3, 10);
buffer[bufferidx-1] = ',';
buffer[bufferidx] = 0;
strcat(buffer, buffer1);
strcat(buffer, comma);
strcat(buffer, buffer2);
```

```
      strcat(buffer, comma);
      strcat(buffer, buffer3);
      strcat(buffer, ret);
      Serial.print(buffer);
      bufferidx = strlen(buffer);
      //Serial.print(bufferidx, DEC);
      //Serial.print('#', BYTE);
      digitalWrite(led2Pin, HIGH);      // sets the digital pin as output

      if(card.write_file(f, (uint8_t *) buffer, bufferidx) != bufferidx) {
        putstring_nl("can't write!");
    return;
      }

      digitalWrite(led2Pin, LOW);

      bufferidx = 0;

      // turn off GPS module?
      if (TURNOFFGPS) {
        digitalWrite(powerPin, HIGH);
      }

      sleep_sec(SLEEPDELAY);
      digitalWrite(powerPin, LOW);
      return;
    }
    bufferidx++;
    if (bufferidx == BUFFSIZE-1) {
       Serial.print('!', BYTE);
       bufferidx = 0;
    }
  } else {

  }
}

void sleep_sec(uint8_t x) {
  while (x--) {
     // set the WDT to wake us up!
    WDTCSR |= (1 << WDCE) | (1 << WDE); // enable watchdog & enable changing it
    WDTCSR = (1<< WDE) | (1 <<WDP2) | (1 << WDP1);
    WDTCSR |= (1<< WDIE);
    set_sleep_mode(SLEEP_MODE_PWR_DOWN);
    sleep_enable();
    sleep_mode();
```

```
    sleep_disable();
  }
}

SIGNAL(WDT_vect) {
  WDTCSR |= (1 << WDCE) | (1 << WDE);
  WDTCSR = 0;
}

/* End code */
```

APPENDIX B: Walk-through Form

Investigator: ___________________ Subject ID # __________________ Date: _________________

Walk Through Cover Sheet

Number of bedrooms: ________________ Size of Residence: ___________________

Year residence was built: _____________

I. Type of Residence

[ ] Single Family Home

[ ] Duplex House

[ ] Townhouse

[ ] Condo

[ ] Apartment

[ ] Studio Apartment

[ ] Other _______________________________________

If apartment or condo: which floor is the apartment/condo located on? ________

II. Type of Garage

[ ] Attached

[ ] Detached

III. Construction of residence

[ ] Brick

[ ] Wood

Investigator: ___________________ Subject ID # __________________ Date: _________________

[ ] Siding

[ ] Combination (describe) ____

[ ] Other (describe) ____

IV. Road Category the property is situated upon?

[ ] Major Arterial (double yellow line, 4 lanes)

[ ] Primary or Secondary Arterial (double yellow line, 2 lanes)

[ ] Collector Road (single yellow or dashed yellow)

[ ] Local Traffic Street or Lesser (dashed white line or nothing)

V. Home appliances

1. Air conditioning? yes [ ] no [ ]

   If "yes", what type Central AC [ ] Central Swamp Cooler [ ]

   Window AC Unit [ ] Window Swamp [ ]

2. Type of stove: ____

3. Exhaust fan over stove? yes [ ] no [ ]

4. Type of oven: ____

5. Any other gas appliances? (For example: hot water heater, clothes dryer)

   If so, indicate type and location:

   ____

   ____

Investigator: __________________ Subject ID # _________________ Date: ________________

Occupied Room Details

(complete 1 sheet for each normally occupied room)

Layout of room (indicate location of windows and doorways):

Room (Living room, kitchen, bedroom, office or den): _______________

Level: _________ Dimensions: ____

Windows (total size and opening): _______________________________________

Indicate type of window covering (drapes) if any: ____________________________

Type of ceiling: ____

Type of walls: ____

Investigator: ____________________ Subject ID # ___________________ Date: __________________

Type of flooring: ____

Screened windows: ____

Number of upholstered furniture: ____

Number of mattresses: ____

Ceiling fan: yes [ ] no [ ]

Area fan: yes [ ] no [ ]

Air humidifier: yes [ ] no [ ]

Ash trays: yes [ ] no [ ]

Number of plants: ___

Number of candles: ___

APPENDIX C: Activity Diary

Diary of Activities

Thank you for participating in our ozone exposure study. To assist us in interpreting the monitoring data we collect, please answer the following questions regarding your activity while carrying the ozone sensor. Please complete a separate form for each day you carry the sensor.

Tell us about your locations while you were carrying the ozone sensor today:

- How much time did you spend indoors at home?
  _____ Hours

- How much time did you spend indoors at another location besides your home?
  _____ Hours/minutes (**circle one**)

- How much time did you spend outdoors?
  _____ Hours/minutes (**circle one**)

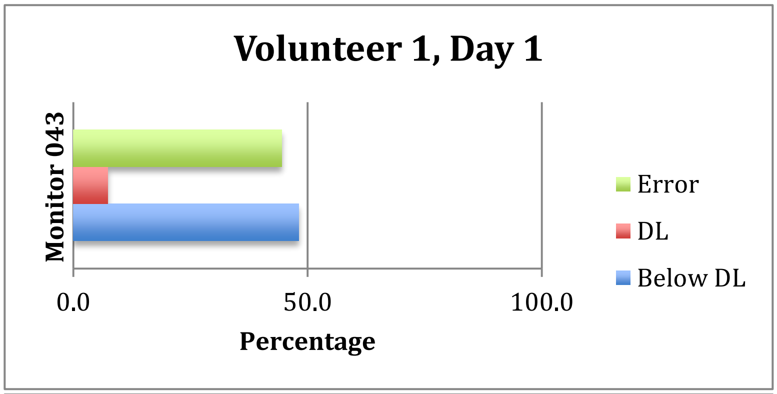
- How much time did you spend in a motor vehicle (in a car or bus)?
  _____ Hours/minutes (**circle one**)

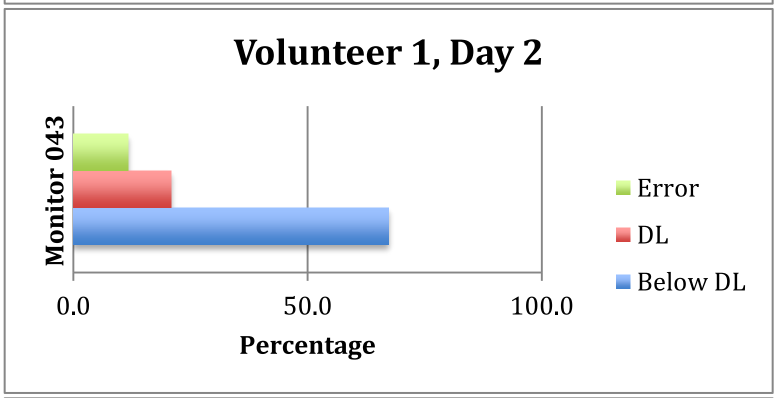
While the ozone sensor was on and you were at home:

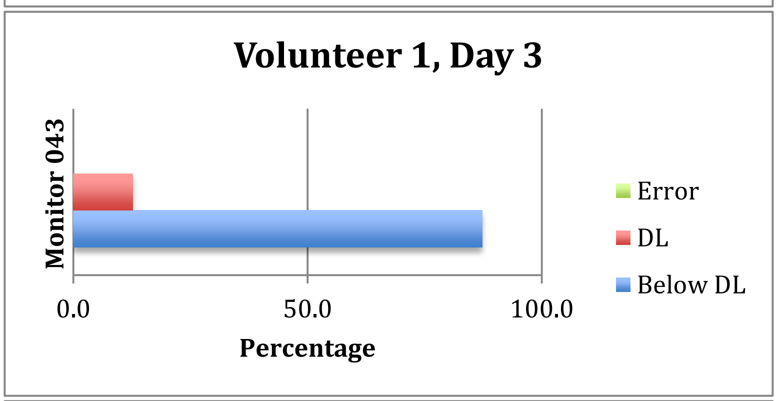
- How long was the Air Conditioner on? _____ Hours
- How long were the windows open?_____ Hours
- How long was your stove on?_____ Minutes
- What kind of stove do you use? Gas **or** Electric (**circle one**)
- Did anyone in the household smoke? _____ Yes _____No
- Where do you spend most of your time at home?

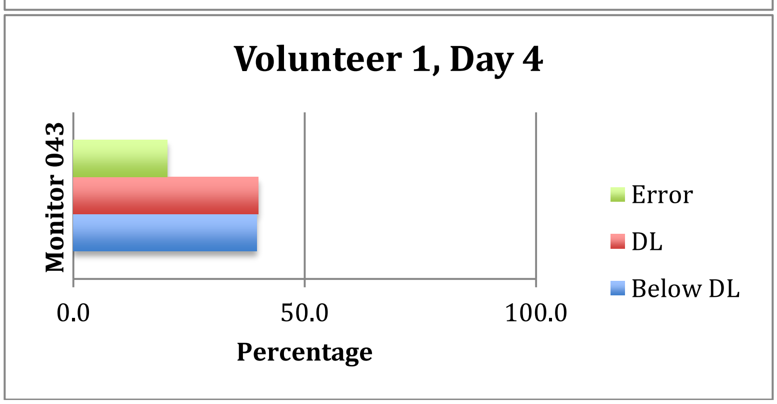
  ____

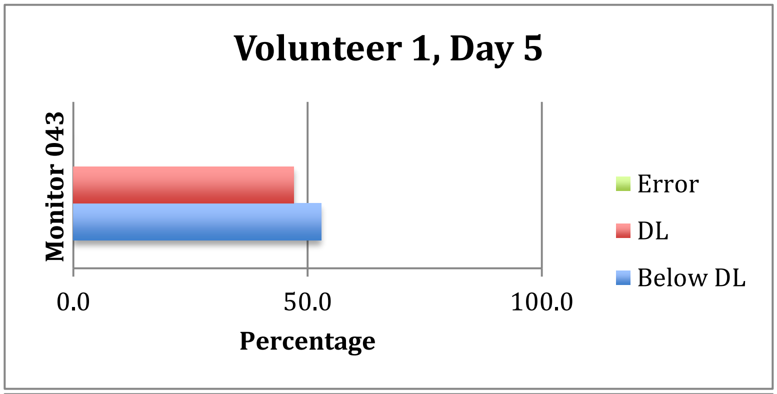
APPENDIX D: Daily Reliability of Graphs










Volunteer 1, Day 5
Monitor 043
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50.0
100.0
Percentage
Error
DL
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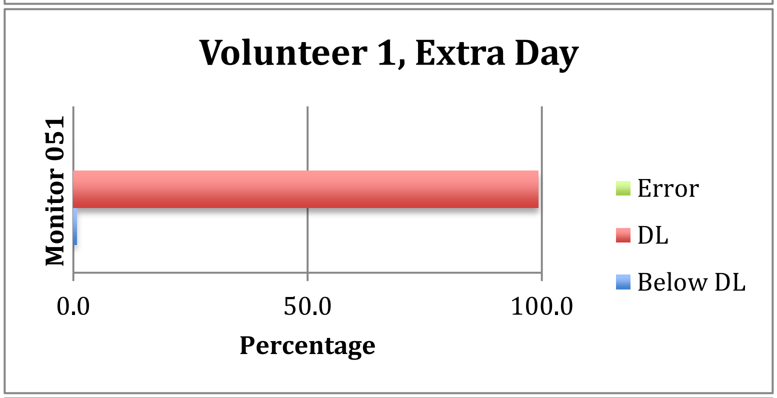
Volunteer 1, Extra Day
Monitor 051
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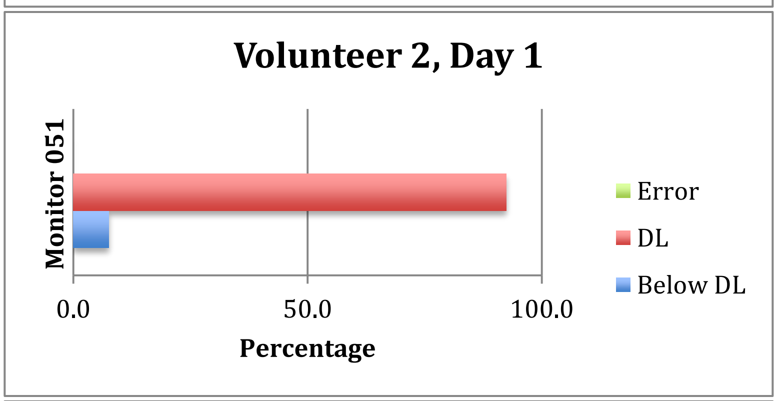
50.0
100.0
Percentage
Error
DL
Below DL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Monitor 051
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Percentage
Error
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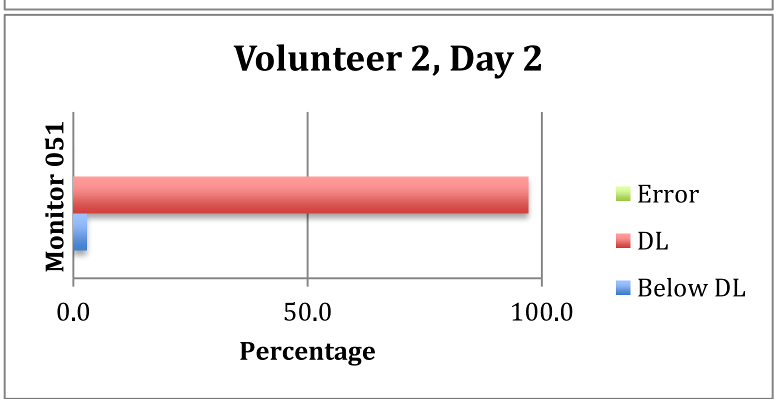
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Monitor 051
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Percentage
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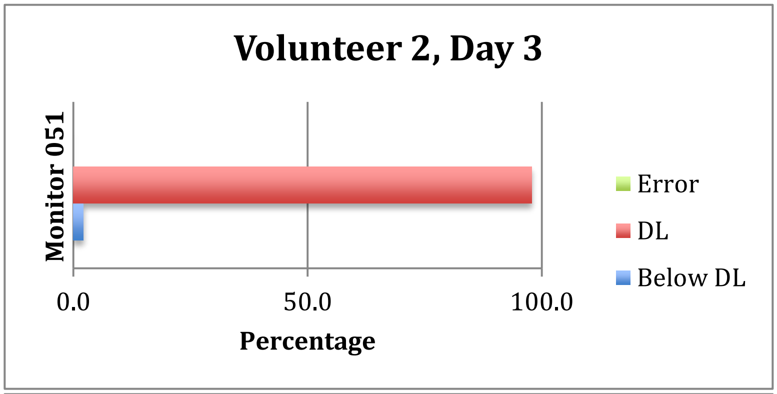
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Error
DL
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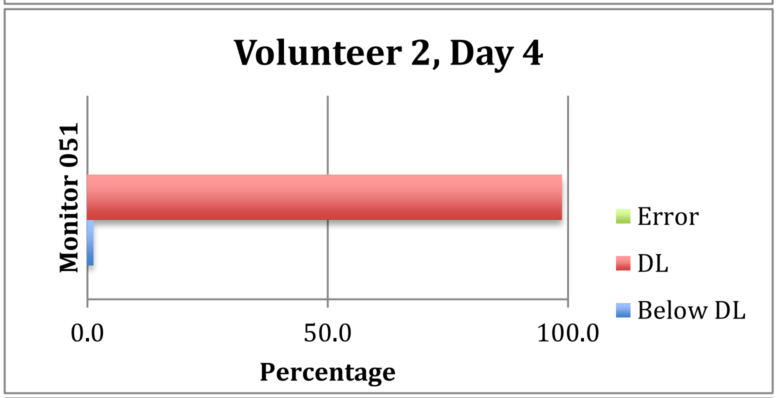
0.0
50.0
100.0
Percentage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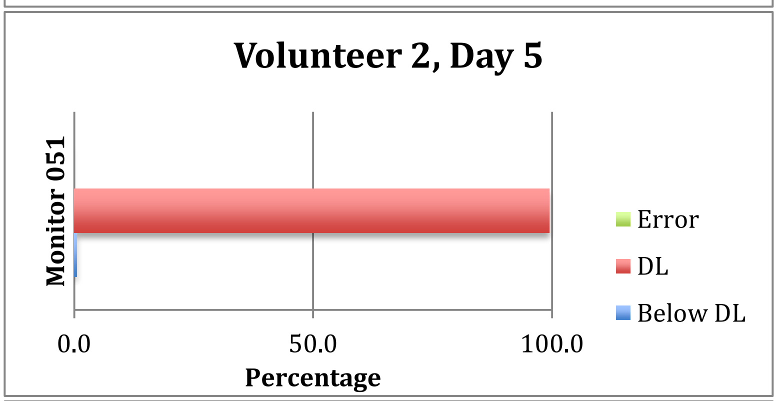
Percentage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DL
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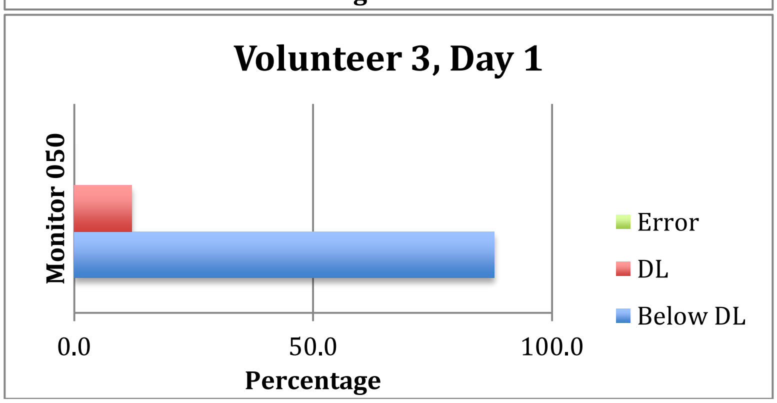
50.0
100.0
Percentage


Volunteer 3, Day 1
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Error
DL
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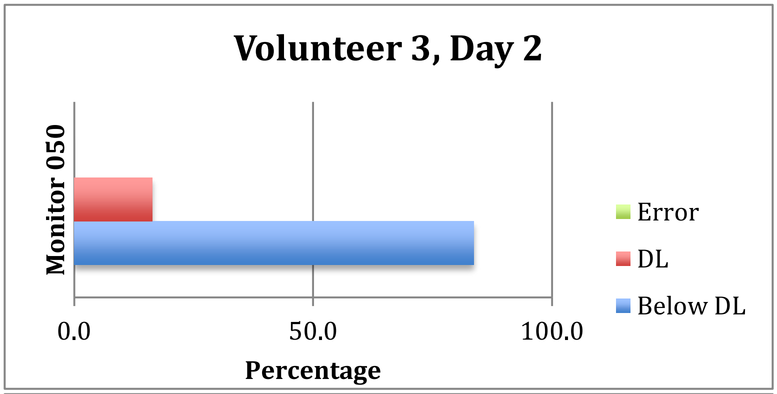
0.0
50.0
100.0
Percentage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Percentage
Error
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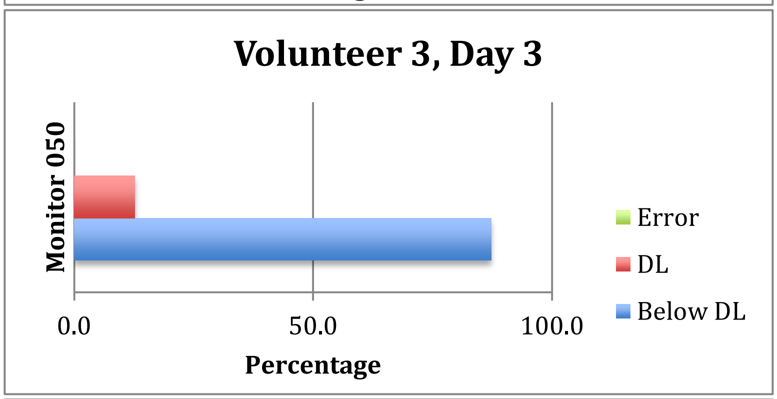
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Percentage
Error
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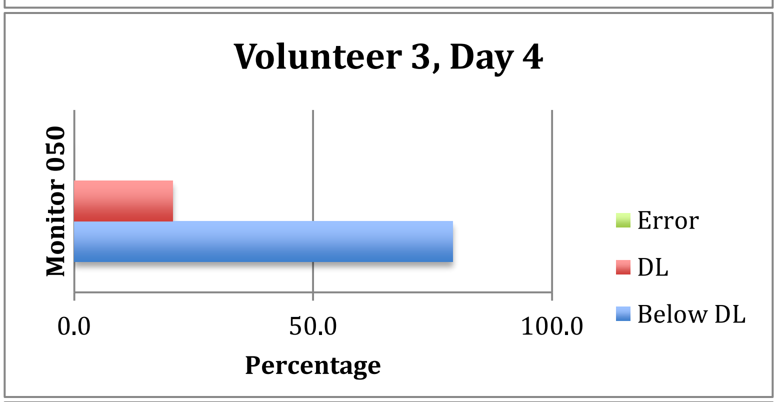
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Percentage
Error
DL
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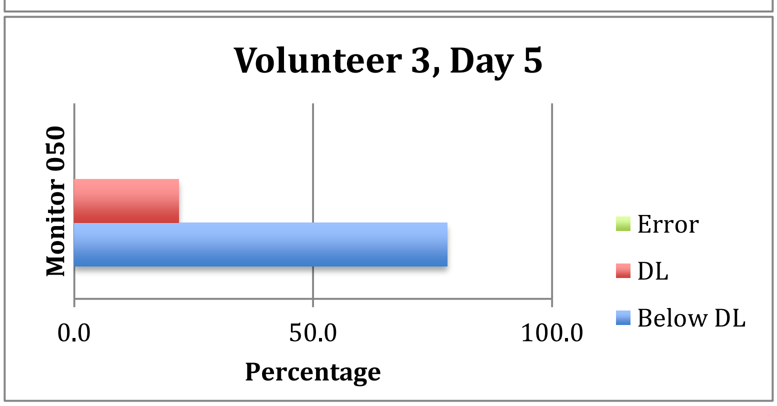
Volunteer 3, Day 5
Monitor 050
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50.0
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Percentage
Error
DL
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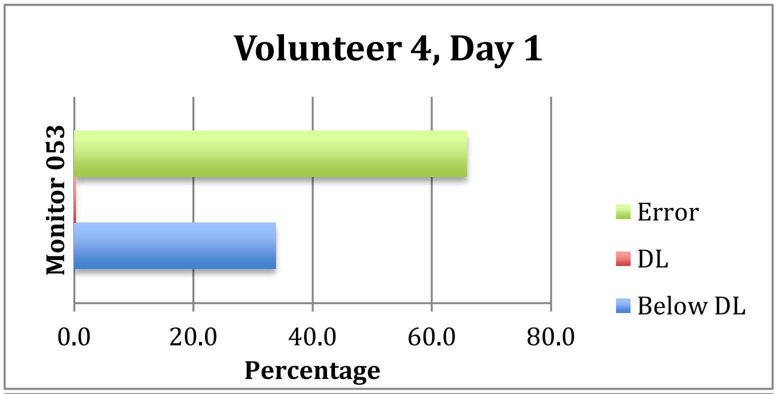
Volunteer 4, Day 1
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40.0
60.0
80.0
Percentage
Error
DL
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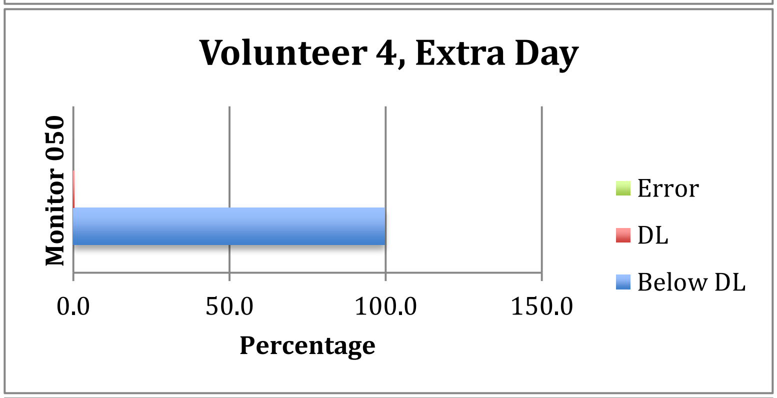
Volunteer 4, Extra Day
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100.0
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Percentage
Error
DL
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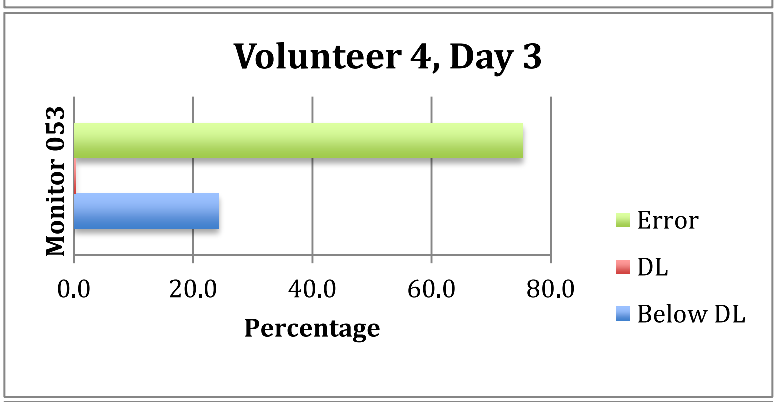
Volunteer 4, Day 3
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40.0
60.0
80.0
Percentage
Error
DL
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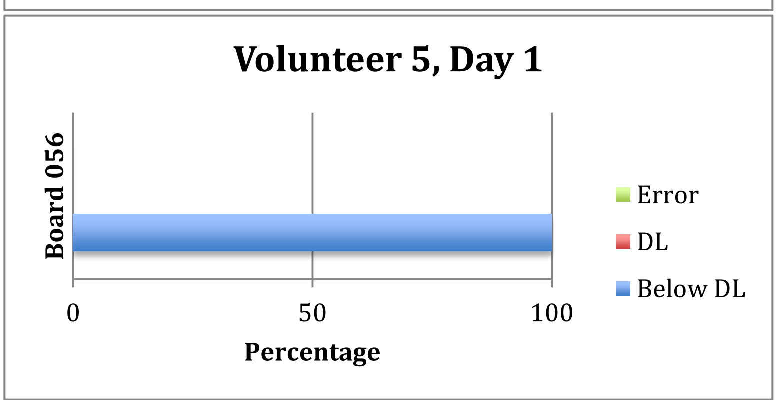
Volunteer 5, Day 1
Board 056
0
50
100
Percentage
Error
DL
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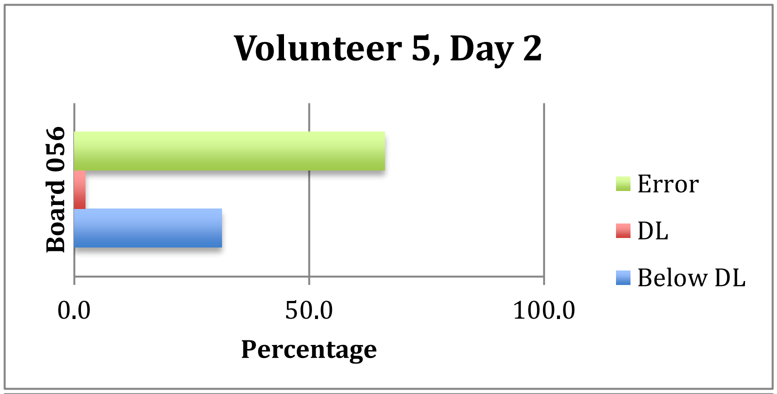
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Percentage
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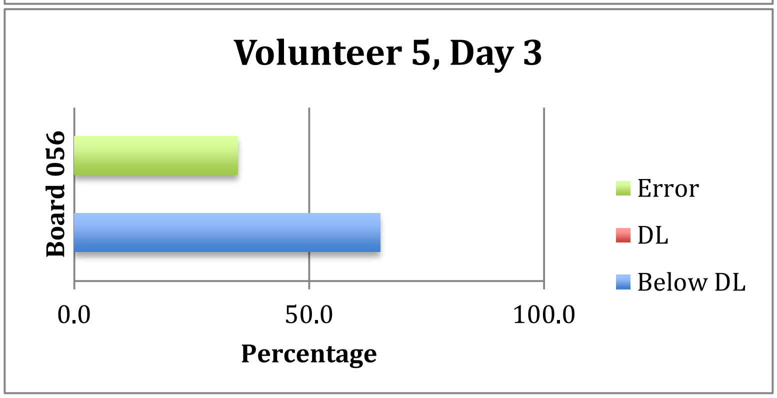
Volunteer 5, Day 3
Board 056
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50.0
100.0
Percentage
Error
DL
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