Calibration and Characterization of Low-Cost Fine Particulate Monitors and their Effect on Individual Empowerment

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For my parents, John and Jennifer Taylor.

Abstract

Air quality has long been a major health concern for citizens around the world, and increased levels of exposure to fine particulate matter ($PM_{2.5}$) has been definitively linked to serious health effects such as cardiovascular disease, respiratory illness, and increased mortality. $PM_{2.5}$ is one of six attainment criteria pollutants used by the EPA, and is similarly regulated by many other governments worldwide. Unfortunately, the high cost and complexity of most current $PM_{2.5}$ monitors results in a lack of detailed spatial and temporal resolution, which means that concerned individuals have little insight into their personal exposure levels. This is especially true regarding hyper-local variations and short-term pollution events associated with industrial activity, heavy fossil fuel use, or indoor activity such as cooking.

Advances in sensor miniaturization, decreased fabrication costs, and rapidly expanding data connectivity have encouraged the development of small, inexpensive devices capable of estimating $PM_{2.5}$ concentrations. This new class of sensors opens up new possibilities for personal exposure monitoring. It also creates new challenges related to calibrating and characterizing inexpensively manufactured sensors to provide the level of precision and accuracy needed to yield actionable information without significantly increasing device cost.

This thesis addresses the following two primary questions:

1. Can an inexpensive air quality monitor based on mass-manufactured dust sensors be calibrated efficiently in order to achieve inter-device agreement in addition to agreement with professional and federally-endorsed particle monitors?
2. Can an inexpensive air quality monitor increase the confidence and capacity of individuals to understand and control their indoor air quality?

In the following thesis, we describe the development of the Speck fine particulate monitor. The Speck processes data from a low-cost dust sensor using a Kalman filter with a piecewise sensing model. We have optimized the parameters for the algorithm through short-term co-location tests with professional HHPC-6 particle counters, and verified typical correlations between the Speck and HHPC-6 units of $r^2 > 0.90$. To account for variations in sensitivity, we have developed a calibration procedure whereby fine particles are aerosolized within an open room or closed calibration chamber. This allows us to produce Specks for commercial distribution as well as the experiments presented herein.

Drawing from previous pilot studies, we have distributed low-cost monitors through local library systems and community groups. Pre-deployment and post-deployment surveys characterize user perception of personal exposure and the effect of a low-cost fine particulate monitor on empowerment.

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Chapter 1

Introduction

This thesis is about the design, calibration, and deployment of low-cost fine particulate monitors and their effect on user perception of risk and empowerment with respect to personal exposure. We submit that fine particulate monitors that are affordable, precise, and designed for ease of use can empower individuals and communities to better understand and control their personal exposure to airborne fine particulate matter.

We begin by defining fine particulate matter and its importance as an overall air quality metric. We then offer our definition of low-cost fine particulate monitors, and the questions we will address in the thesis. Subsequently, we describe the contributions of this research and conclude by outlining the organization of this thesis.

1.1 Definition and Relevance of $PM_{2.5}$

Fine airborne particles that are smaller than 2.5 microns, collectively designated as $PM_{2.5}$, pose a serious health risk to the public. These airborne particulates have been linked to significantly increased risk of cardiopulmonary and respiratory illnesses, particularly in the elderly and other sensitive populations [24][26][31].

$PM_{2.5}$ can be composed of any number of airborne particulate substances, and is a particularly useful metric in predicting adverse health effects [10]. Outdoor fine particulates commonly include products from combustion such as diesel exhaust and coal particulates [27] but not larger particles such as pollen. $PM_{2.5}$ is often present indoors as well, and includes fine dust and particulates created from certain kinds of cooking, such as frying.

Inside the home, $PM_{2.5}$ is composed of particles both from indoor sources as well as outdoor sources. Open windows and doors as well as insulation can affect how much particle interchange occurs. Because air quality dynamics are complex, there are times when it is beneficial to open a window if the outside air is cleaner than the indoor air, and vice versa. Different cooking oils have varying smoke points, which can affect the number of particulates generated. Kitchen smoke hoods should ideally vent outside, but it is common for these hoods to simply pass cooking emissions through a coarse filter and then exhaust back into the kitchen. A HEPA air purifier can dramatically lower indoor particle counts if located in an appropriately sized room. Unfortunately, air quality is largely an unknown until adverse symptoms present themselves and prompt the need for personal indoor air quality monitoring.

Because $PM_{2.5}$ is a measurement that can indicate the presence of a diverse range of pollutants, [23] it is an ideal single metric for personal air quality monitors. Existing particle counters are almost solely available in the scientific and industrial markets, and as such are much more expensive than is practical for a home budget. As a result, $PM_{2.5}$ measurements are sparse and information on personal exposure is often unavailable or difficult to understand.

1.2 Definition of Low-Cost Monitors

As federally regulated air quality monitors frequently cost tens of thousands of dollars, research often defines low cost at many different levels. In the context of this thesis, we define low-cost monitors as those devices which are generally affordable by an individual or small organization. These devices marketed to individual non-professional users typically cost under $500.

We also define a low-cost monitor as an integrated system containing at least one sensor which must, at minimum, either display real-time measurement or store data for later review. These monitors may or may not achieve this through the use of an external device such as a smartphone or other computing platform. The intent is that these systems are usable by non-experts and experts alike, requiring a level of technology literacy comparable with other contemporary consumer electronics. Bare sensors are excluded from this definition if they require any hardware engineering, mathematical operation, or data manipulation to use, or if these sensors are designed exclusively for integration into other sensors.

1.3 Thesis Statement

Air quality measurement and analysis with high temporal and spatial resolution has yet to be achieved due to prior limitations on instrument cost, size, and technical complexity. Rather than precision optics and complex control of temperature, flow, and humidity of incoming air, low cost air quality monitors may utilize an inexpensive mass-manufactured dust sensor and on-board signal processing to estimate particle count and $PM_{2.5}$.

Calibration of inexpensive sensors is generally challenging because of the low precision of manufacturing, large numbers of sensors to be calibrated, and the goal to keep the calibration inexpensive relative to the cost of the monitor. This challenge is made more difficult for air quality, where it can be hard to generate repeatable levels of air pollution.

While prior research efforts have deployed personal air quality monitors in the home and workplace, these works are typically concerned with monitoring the air quality and its effects on health and productivity for the occupants in these spaces. (See the following chapter for specific examples and references.) Relatively few studies have explored the effect of the monitors themselves on the users' perception of risk and sense of empowerment with respect to air quality.

Accordingly, this thesis is concerned with answering the following two questions:

1. Can an inexpensive air quality monitor based on mass-manufactured sensors be calibrated efficiently in order to achieve inter-device agreement in addition to agreement with professional and federally-endorsed particle monitors?
2. Can an inexpensive air quality monitor increase the confidence and capacity of individuals to understand and control their indoor air quality?

1.4 Contributions

This thesis outlines the development of the Speck air quality monitor, which meets the aforementioned definitions of a low-cost fine particulate monitor for personal use. We describe our initial prototyping efforts, design iterations, pilot deployments, and eventual manufacturing and distribution for general use.

We have explored a method using low-frequency speakers to aerosolize fine dust and spread it across a batch of sensors to be calibrated. In this thesis, we describe our intial efforts at calibration in an open room and the subsequent development of a calibration enclosure, controlled distribution of source particle sizes, and additional instrumentation using an optical $PM_{2.5}$ federal equivalence monitor. We outline the general application of the enclosure design to other low-cost monitors as well as the importance of calibrating the monitor as an assembled unit rather than as isolated sensors.

We have deployed low-cost monitors through local pilots in the Pittsburgh region in order to study the effect of these monitors on individual empowerment. One vector for distribution is through the public library system. Through surveys conducted at the time of check-out and at check-in, we evaluate changes in user confidence and understanding of their indoor air quality while in possession of the monitor. We have also used the surveys to gauge whether people were able to use their collected and observed data to make in-home changes to improve their air quality. Additional in-person interviews gathered anecdotal evidence to support the results of the surveys.

1.5 Organization of the Work

Chapter two describes related work, including brief descriptions of different detection techniques used by high-end federal equivalence monitors as well as some contemporary low-cost monitor designs. We also describe several commonly-cited studies linking $PM_{2.5}$ and poor air quality to deleterious effects on cardiovascular and respiratory health as well as reductions in productivity in the workplace. These related works establish the importance of air quality monitoring, especially for $PM_{2.5}$.

Chapter three describes the design of the Speck fine particulate monitor, including initial prototype development, pilot deployment, refinement, and mass-manufacturing. The end of this chapter demonstrates the need for an efficient, precise and replicable calibration process.

Chapter four explains the calibration process and its development from a manual process involving cooking tests to the largely automated and enclosed process we use today. We demonstrate the benefits of group calibration and the statistical analysis it affords, as well as our observations on the effect of a changing calibration process on the Speck monitors we have deployed.

Chapter five contains the procedures and results from several tests intended to characterize the performance, capabilities and limitations of the Speck fine particulate monitor. These tests are a combination of internal experiments and external evaluations. This chapter also describes the results of comparative testing we performed using several common low-cost fine particulate monitors and the strengths and weaknesses we observed in each.

Chapter six focuses on the effect of low-cost fine particulate monitors on community and individual empowerment and risk perception. We describe our initial pilot study in which Specks were deployed through the local library system over three week periods to library patrons, and the results of the surveys and interviews we conducted before, during, and after their use. The survey and interview questions used in this study are included in the appendix at the end of this thesis. This chapter also briefly describes other efforts by community groups and organizations in which the Speck played a key role in exploring air quality.

Chapter seven summarizes our results from chapters three through six, and chapter eight asserts the contributions of these findings toward the development, calibration, and deployment of low-cost air quality monitors for community and individual empowerment.

Chapter 2

Related Work

2.1 Health Effects of $PM_{2.5}$

Exposure to elevated levels of particulate matter has been linked to numerous health impacts, including but not limited to respiratory illness, cardiovascular problems, low birth weight, and reduced productivity. Particulate matter is one of the EPA's six criteria air pollutants, alongside ozone, carbon monoxide, nitrogen oxides, sulfur dioxide, and lead. While particles less than 10 microns are recognized to pose a significant threat to human health, the EPA is especially concerned with particles smaller than 2.5 microns, collectively referred to as fine particulate matter or $PM_{2.5}$. Particles within this size range are small enough to enter the lungs, and the smallest of these can additionally enter the bloodstream. Populations at increased risk of negative health effects include children and older adults, and premature death can result in people with heart or lung disease.

$PM_{2.5}$ is also of concern to employers and workers whose jobs regularly place them in environments with higher exposure to fine particulate matter. Increased levels of pollution, including fine particulate matter, have been linked with lower productivity in the workplace. This in turn results in higher employment costs, which often constitute the greatest fraction of operational expenses for many businesses.

2.1.1 Harvard Study

The Harvard Six Cities Study [17] followed 8111 participants in six cities around the United States in order to determine the effects of air pollution on mortality and cause of death over a period of 14 to 16 years. The study found that fine inhalable particulate matter and sulfate particles had the greatest effect on mortality rates, moreso than total particulate pollution, aerosol acidity, sulfur dioxide, or nitrogen dioxide. Fine particulates were especially significant in association with cardiopulmonary illness, lung cancer, and other respiratory illnesses. The study acknowledges potential confounding factors including cumulative lifetime exposure to particulate matter, though controlling for as many factors as possible yields similar results. Smoking was also shown to have an extreme effect on mortality due to lung cancer, as additionally supported by most other relevant studies.

2.1.2 American Thoracic Society and Marron Institute Report

A recent American Thoracic Society (ATS) report attributes an estimated 9,320 premature deaths in the United States due to exposure to excess ozone (69%) and fine particulate matter (31%) [14]. The study also estimates 21,400 incidents of excess morbidity, defined in the study as including "acute myocardial infarction, chronic bronchitis, cardiovascular and respiratory hospital admissions, and emergency department visits." Ozone and $PM_{2.5}$ are responsible for 74% and 26% of these cases, respectively. Approximately 37% of the total estimated health impacts are associated with California alone, with Pennsylvania, Texas, and Ohio as the next largest contributors. The study also notes the high spatial variability of air pollution, which is supported by the discrepancy in the health burdens present in each state due to ozone and fine particulates.

The exposure data from this study was generated using measurements from nationwide monitors used to determine county-level attainment of EPA standards. Similarly, the EPA's BenMAP CE-1.1 tool was used for estimation of health and economic impacts of changes in air pollution [7].

2.1.3 Low-Concentration $PM_{2.5}$ and Mortality

As one of six EPA-specified criteria pollutants, $PM_{2.5}$ levels must be maintained below a national standard in order for counties to avoid losing some forms of federal financial assistance. In accordance with the Clean Air Act, these standards are reveiwed by the EPA every five years and revised as deemed necessary to protect public health.

One recent study [32] examines the health effects of fine particulates on the Medicare population at concentrations below National Ambient Air Quality Standards (NAAQS). Results show that the dose-response relationship between chronic exposure and mortality remains linear down to $6\mu g/m^3$. In contrast, the EPA standards at the time of this study's publication (2014) specify a maxumum of $12\mu g/m^3$ averaged annually and $35\mu g/m^3$ daily.

The discrepancy between these standards and the lower concentrations at which there is a demonstrated effect on mortality is important for several reasons. This study can be used as evidence that current standards are not effective in truly minimizing the risk posed by fine particulates. It also reveals that these current standards can be misleading to the general public, who may assume that their air is safe as long as their region is in attainment with federal levels.

This also highlights the need for better education on air pollution and fine particulates on an individual citizen and community level. A key element in further education (and, subsequently, empowerment) is access to local and personal exposure measurements. We demonstrate in this thesis that it is possible to achieve these measurements using smaller, lower-cost, and more user-friendly air quality monitors.

2.1.4 Traffic-Related Health Effects in Bronx Schoolchildren

Spira-Cohen et al ([35]) measured personal exposure to fine particulates in asthmatic schoolchildren in their oft-cited South Bronx backpack study. This study found a significant correlation between respiratory symptoms and fine particulate matter, especially diesel exhaust. These symptoms included increased coughing, wheezing, allergic inflammation, decreased lung function, and other asthma symptoms. The data for this study were obtained through qualitative and quantitative self-assessment of symptom presence and severity along with quantitative data from mobile and stationary air quality monitors.

Stationary monitors included a TEOM 1400a $PM_{2.5}$ sampler, AE-21 black carbon aethalometer, and an ACCU filter sampler as well as monitors for O_3, CO, SO_2, and NO_x, all located at the school. Additionally, background $PM_{2.5}$ data was available from a rooftop monitor operated by the New York State Department of Environmental Conservation. The personal monitors carried by the children were placed in rolling backpacks, which the children were instructed to keep with them 24/7. The backpacks contained filter-based 24-hour integrated weekday $PM_{2.5}$ samples as well as motion sensors to determine if the backpacks were being carried at all times.

The wide assortment of sensor data gathered in this study allowed the research team to investigate many independent correlations, and represented a significant amount of research effort as each of the 40 students required regular intervention to change, collect, and analyze filter samples in addition to gathering symptom data. One shortcoming of this study is that because of the 24-hour integrated samples, the lag effect between exposure and the presentation of symptoms could only be resolved as same-day or in one-day increments. Continuous sampling as is made possible by optical nephelometer-based devices could provide significant time resolution in similar experiments. These devices also do not require changing filters or regular maintenance over a period of only a few months, and with automatic wireless data uploads, the interventions of the research team could be decreased to symptom collection. Additionally, smaller and more lightweight optical monitors could reduce the impact and intrusion of the equipment on the participants' behavior. With new technology, these monitors may become wearable, thus increasing the accuracy of personal exposure monitoring. The scope of the experiments can also be extended to a larger population if the cost of the equipment is reduced along with the personnel expense associated with tending to filter-based samplers.

2.1.5 Clarkson HEPAiRx Study

In a study conducted by Xu et al. [43], air quality monitors were placed in the homes of 30 asthmatic children for 18 weeks along with a HEPAiRx air cleaning and ventilation unit. The unit was kept on for 12 of the 18 weeks for each household, with half of the group turning the unit on during the first 12 weeks and the other half turning it on for the last 12 weeks. During this period, the AirAdvice air quality monitor was used to track the effects of the HEPAiRx operating status on PM_{10}, CO, CO_2, TVOC, temperature and humidity. Every sixth day, measurements would be taken from participants of their exhaled breath concentrate (EBC), pH, and peak expiratory flow (PEF). The study found that the air purifier reduced PM_{10} by 72%, VOC by 59%, CO_2 by 19%, and CO by 30%. Additionally, these reductions were shown to have a statistically significant effect in improving EBC nitrate concentrations, pH, and PEF. These results were made possible by the relatively small and unobtrusive AirAdvice unit, which can rest on a table or countertop and requires only one household power outlet. Data is relayed wirelessly on a minute by minute basis, thus simplifying measurement collection. The typical business model of AirAdvice is for contractors to place the monitor in the home for a short time, typically less than one hour. This data is automatically transmitted and analyzed by the AirAdvice servers. The monitor itself is not available to consumers, potentially because of cost and usability constraints. A lower-cost monitor with greater ease of use could potentially expand the scope of similar experiments to a greater number of houses. The AirAdvice platform solves many of the shortcomings associated with using other technology, such as the difficulty of manually collecting data or the requirement for multiple and/or large monitoring devices in the home. Clarkson University was able to confirm the value of the HEPAiRx unit by utilizing the AirAdvice monitor over a long period of time. With a commercially available and affordable air quality monitor, individuals can verify the effectiveness of their own air purifier, including whether it has sufficient airflow to properly clean any specific room or floor.

2.1.6 Indoor Air Quality and Productivity

Elevated levels of fine particulate matter have been linked to reduced worker productivity [12]. Because lower productivity leads to higher employment costs, and given that employment costs constitute the largest fraction of operating expenses for many businesses, building managers should be greatly concerned with monitoring and controlling particulate matter levels in the workplace. With the increased ability of building management systems to track comfort factors like temperature and humidity, building managers are now able to optimize thermal comfort and energy expenditures. This is in large part due to the quantification of the impact of discomfort on employee productivity and the resulting increase in personnel costs. As particulate matter sensors are only now becoming miniaturized and affordable, however, these systems have yet to implement spatially-distributed $PM_{2.5}$ monitoring, which would provide another variable for assessing employee comfort. Some recently launched products such as the Airassure $PM_{2.5}$ monitor from TSI are designed to connect to networked building management systems, though at this time the Airassure $PM_{2.5}$ monitor is not yet available in the USA or Europe.

2.2 Survey of Existing Fine Particulate Monitoring Technologies

2.2.1 Federal Reference Method

The federal reference methods (FRM) for measuring $PM_{2.5}$ and PM_{10} involve circulating air through carefully pre-weighed filters over a period of time [30]. The change in mass over time, given a constant and known flow rate, can be used to determine the particulate concentration of a volume of air. This method is very labor intensive, however, and outdated by more recent methods. It has the advantage of being the only widely-accepted means of measuring mass directly (rather than through resonance, beta attenuation, etc.).

Its downsides include non-continuous sampling over large intervals, and the large potential for human error. Additionally, volatile substances may be initially captured as fine particulates, but they have the ability to sublimate off of the filters, and are thus only intermittently recorded.

2.2.2 GRIMM Laser Aerosol Spectrometer (LAS)

The GRIMM EDM 180 is a federal equivalence monitor that calculates mass at multiple size cutoffs by counting and sizing particles optically [33]. The GRIMM is capable of discriminating between 32 distinct size ranges of particles. Because the measured particles are categorized by size, no cyclones or impactors are required; only very coarse filtering to prevent bugs and singly-visible particles from entering. Because the instrument is based on optical measurement, however, the device must account for or reduce hydroscopic growth due to humidity. The GRIMM accomplishes this by transporting newly sampled air down through a long nafion tube. Dry, non-sample air flows upward in a concentric pipe around the nafion tube, extracting moisture from the intake air in the process. An additional concentric pipe recirculates the air back into the base unit for expulsion. The pressure needed to circulate this air necessitates a large and relatively noisy pump. The pump only receives power at an observed humidity of around 70%.

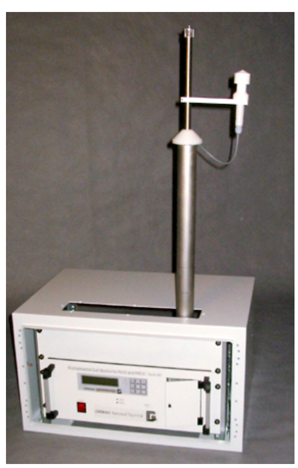

Figure 2.1: Rack-mount GRIMM EDM 180 and sampling tube [3]

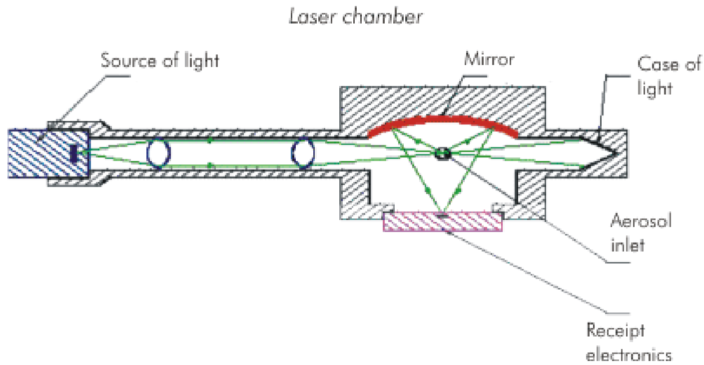

Figure 2.2: Schematic of the laser chamber in the GRIMM Model 1.109 LAS [3]

2.2.3 Beta Attenuation Monitor (BAM)

Beta attenuation monitors (BAMs) operate on the principle that beta radiation from any particular source is attenuated by obstructing solid matter. Typically, a continuous ribbon cycles past a window of controlled airflow. The ribbon is made of fine filter paper capable of capturing $PM_{2.5}$ matter. Two detectors on either side of the window measure the beta attenuation level before and after that section of ribbon is exposed to the airflow, and the difference in attenuation can be used to calculate the increase in mass of the ribbon [19]. Given a known flow rate and a known exposure time, airborne particle concentration is easily determined.

Some shortcomings of this method include the necessity to pre-filter the air to the appropriate size particle distribution (usually $PM_{2.5}$ or PM_{10}) using a cyclone assembly. The minimum sampling rate is typically once per hour, whereas optical or resonant methods can report samples every minute (though shorter sampling times lead to greater error, especially at low concentrations). Additionally, while the GRIMM is capable of delivering estimates for $PM_{2.5}$ and PM_{10} simultaneously, this is not possible with the BAM. The BAM also suffers from the volatile sublimation issue present in the FRM.

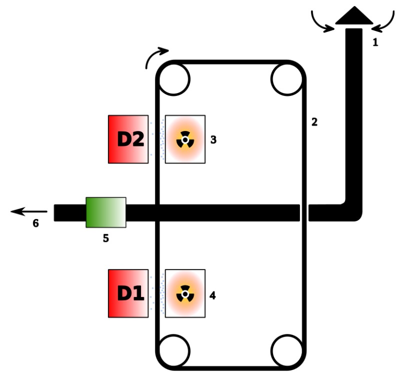

Figure 2.3: Diagram of BAM operation [41]

2.2.4 Tapered-Element Oscillating Microbalance (TEOM)

TEOMs operate by directing particles from an airstream onto or through a small filter or plate attached to a thin oscillating beam. The total mass on the plate can be determined by calculating the resonant frequency of the beam and plate [8]. Like the BAM, particle concentration is calculated using the difference in accumulated mass across the sample interval. These intervals can be short (e.g. one minute) but shorter intervals can sometimes result in imprecise readings. This is especially true if a large number of the particles are volatile and evaporate from the plate or filter, as this can cause a net loss of mass across a small time interval, which is then used to calculate an impossible negative particle concentration. Also, similar to the BAM, cyclones and impactors must be used to separate out particles that are larger than the cutoff size of interest.

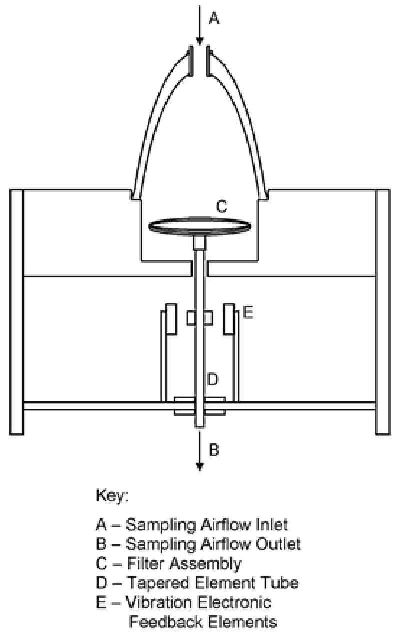

Figure 2.4: Diagram of TEOM operation [38]

2.2.5 Handheld Optical Particle Counter (OPC)

Handheld optical particle counters such as the Hach Met One HHPC-6+ are significantly less expensive and more portable than the previous devices, but are not considered federal reference methods. The principle of operation behind these devices is similar to that of the GRIMM, where a laser is used to count and size particles drawn through the sensing chamber using a small pump. Typically, the sample volume is smaller and little or no preconditioning is performed on the sample air. Temperature and relative humidity are frequently measured in these units at the point of particle detection. Devices like the HHPC-6+ frequently incorporate a basic user interface, on-board storage of varying capacities, and a rechargeable battery. These devices can be very useful for point sampling, but are not designed for continuous operation. Additionally, while some devices like the TSI DustTrak will estimate mass, the HHPC-6+ delivers only particle counts across different size bins, making comparison with mass-only methods like the BAM difficult. If the particle source is well characterized, it is possible to estimate mass with an OPC that possesses at least micron-level size resolution [9].

2.3 Existing Low Cost Air Quality Monitors

Related works [21] have established that inexpensive sensors designed to detect larger dust particles can also be used to detect particles in the $2\mu m$ range. Typically, these experiments use a moving average of raw sensor readings, with a linear scale factor used to match these values to particle counts or $2\mu m$ values from a professional monitor.

There are a growing number of personal air quality monitors available on the market. The Air Quality Egg [13], available from Wicked Device, uses a similar dust sensor to those in [21] in its particulate sensor add-on. The Egg and daughterboard, at a combined cost of $243, upload data to a publicly-available map currently populated with 1094 units. The Dylos [2], priced from $199 to $425, is widely used in experiments and publications where inexpensive and often mobile particulate monitoring is desired. The basic Dylos units use custom laser optics and report particle counts larger than $2.5\mu m$ and larger than $.5\mu m$ on two separate channels. Advanced models feature additional functions such as additional size channels, datalogging capability, and battery power. In China, where air quality is a major concern within cities, several low-cost particulate monitors are available, though these have not been as extensively characterized or used in air quality studies in comparison with the Dylos. These include the BPEER [20] and Air.Air! [5] devices, both of which rely on ambient airflow through a central passage.

We have tested several of these devices using a particle generation system and a calibrated Grimm EDM 180 federal equivalence particle monitor, the results of which are discussed in Chapter 5. We have observed that poor manufacturing tolerances, a lack of calibration, and a lack of sensitivity can cause these sensors to deliver varying qualities of information. We believe that the quality control, calibration, and more sophisticated algorithmic implementation can produce much higher data quality.

A few qualitative methods are sometimes used by civilians and citizen scientists to determine relative amounts of pollution. These often include either basic grab-samples (capturing air in a non-reactive jar or bag) or sticky traps made of white paper and double-sided tape. The sticky traps can be investigated with a microscope to identify the source of larger particles. Higher powered microscopes are needed to examine fine particles.

Although personal air quality monitors are becoming more available and affordable right now, it is also important to develop appropriate knowledge and support infrastructure for users. This type of scaffolding can help guide everyday citizens as they explore ways to improve their air quality and overall home health. A goal for this thesis is to gain a better understanding of what this type of holistic air quality tool kit could look like.

2.4 Documented Calibration Procedures

2.4.1 Laboratory Evaluation and Calibration of Thee Low-Cost Particle Sensors

Wang et al. [39] have characterized and calibrated three low-cost particle sensors, namely the Shinyei PPD42NS (PPD), Samyoung DSM501A (DSM), and Sharp GP2Y1010AU0F (GP2Y). All three of these sensors operate using an infrared emitter/detector pair. The PPD and DSM sensors are similar in both appearance and operation, and both contain a resistive heating element to convectively move air through the sensing chamber. The GP2Y device requires a high-frequency square wave to operate its infrared LED, so the researchers used a dedicated Arduino Uno board to supply the required signal.

A SidePak Personal Aerosol Monitor (TSI model AM510) scanning mobility particle sizer (TSI SMPS) and a TSI Air-Assure $PM_{2.5}$ Indoor Air Quality Monitor served as reference instruments for the characterization and calibration. These devices are stand-alone monitors rather than bare sensing elements, and are carefully calibrated after manufacture.

A sealed 58 x 58 x 28 cm acrylic enclosure served as the test chamber for characterization and calibration. The reference instruments were located outside the chamber and sampled air from inside the enclosure through tubes. One of each of the three types of low-cost sensors were attached next to each other along the wall of the chamber, with care taken that the orientation of the sensors was conducive to natural airflow through their optical chambers. Incense particles were introduced through a stainless steel pipe into the center of the enclosure. Data was collected as the particles were allowed to settle and precipitate, resulting in the gradual decrease in particulate levels inside the chamber. Data was collected simultaneously from all instruments starting at the point at which the concentration dropped below $1mg/m^3$.

The general findings of the experiments included that the GP2Y sensor appeared to exhibit the strongest linearity, and the PPD and DSM sensors had lower limits of detection than the GP2Y, suggesting that these sensors may provide imprecise and/or inaccurate readings at low particle concentrations. Calibration using linear regression achieved r^2 correlation values of 0.9452, 0.8914, and 0.9838 for the PPD, DSM, and GP2Y sensors respectively. At the time of development, the DSM module was selected as the sensing unit for the Speck air quality monitor described in Chapter 3. In Chapter 3, we also describe the rationale for choosing this sensor over other low-cost sensors with evidently better performance.

2.4.2 Field Calibration of a Cluster of Low-Cost Available Sensors for Air Quality Monitoring

Spinelle et al. [34] noted the challenges in using low-cost ozone (O_3) and nitrogen dioxide (NO_2) sensors to produce accurate and precise measurements, which arise primarily from the manufacturing variability and degeneration over time of many sensor compositions. Selecting several different types of sensors for both ozone and nitrogen dioxide, the researchers explored linear regression (LR), multivariate linear regression (MLR), and artificial neural networks (ANNs) as candidate methods for calibration. Two weeks of calibration and five weeks of evaluation were completed at a semi-rural location equipped with reference instruments.

The results showed that, in general, linear regression underperformed compared to MLR and ANN methods which utilized additional variables. The MLR equations predict sensor response based on reference measurements of NO_2, NO, and O_3 in addition to relative humidity, absolute humidity, and temperature. Similarly, the ANNs for O_3 and NO_2 use multiple variables in a multilayered perceptron. The MLR and ANN methods both take advantage of the co-location and prior characterization of different sensorrs to overcome and compensate for the strong cross-sensitivity of these low-cost sensors.

The ANN calibration methods were shown to have the lowest measurement uncertainty compared to LR and MLR. The researchers claim that while the sensors are affected by temperature and humidity, a cluster of one O_3 chemical sensor, one NO_2 resistive sensor, and one CO electrochemical sensor were sufficient to overcome most of the uncertainty arising from cross-sensitivity. It appears that the ANN is able to compensate for the effects of temperature and humidity without directly measuring these variables based solely on the behavioral differences of the three sensor types. Additionally, measurement error due to sensor drift over time seems to be improved by the dependence of these measurements on multiple sensor types.

While this thesis primarily deals with low-cost particulate matter sensors, the aforementioned research is relevant in that it demonstrates the potential gains to be realized from more sophisticated modeling of sensor behavior as opposed to simple linear regression. Furthermore, while it is widely accepted that many compound-specific sensor technologies such as metal oxide suffer from strong cross-sensitivities and measurement variability, multiple sensors performing together can overcome some of these disadvantages.

There are nevertheless some barriers to implementing these methods in mass-produced low-cost particulate matter sensors. Artificial neural networks often require significantly large training datasets which must span the multidimensional space of possible inputs, which requires either significant calibration time in a natural operating environment or a very well controlled environment where each of these inputs can be tightly modulated. ANNs, depending on their complexity, can also be too computationally expensive for small microprocessors. At the very least, training would likely need to be performed off of the internal microprocessor, and the resulting weighted function would then be uploaded to the device. With the miniaturization of processing power, however, this is likely feasible now or in the near future.

Chapter 3

Low-Cost Monitor Design

3.1 Prototype History

The development of the Speck air quality monitor began in 2011 as part of a more general project called Bodytrack. Bodytrack (now called Fluxtream) is a data collection and visualization platform designed to aggregate and present explorable personal health data. This data is self-reported through time-stamped notes, photos, and event triggers, and collected through wearable or environmental sensor data [42]. Data is also collected from externally curated sources such as air pollution databases and weather reports.

Air quality is one environmental variable that significantly affects personal health. As previously discussed in earlier chapters, elevated levels of airborne fine particulate matter negatively affects cardiovascular and respiratory health, leads to decreased cognitive function, and can aggravate existing diseases such as asthma. Professional fine particulate monitors are too expensive for most individuals to own, with handheld particle counters such as the HHPC-2+ costing $2000 or more, and stationary FEM units costing tens of thousands of dollars based on the underlying technology. Furthermore, these devices are intended for professional use, and lack features that could improve usability by non-professionals.

The Dylos [2] was one of the only air quality monitors designed for non-professional use capable of measuring fine particulates in 2011. The Dylos remains a widely used and affordable monitor among citizen scientists, with a price of $200 for the most basic unit. Models featuring serial output, internal batteries, and higher sensitivity cost up to $425. We chose to develop a new fine particulate monitor based on the difficulty in storing and exporting data generated by the Dylos along with its size and cost for the more fully-featured models. Our primary goals were to develop a monitor capable of measuring fine particulates at a retail price of under $200. Additionally, we determined that features such as data storage and review, wireless communication, and real-time feedback were essential usability features for a non-professional monitor.

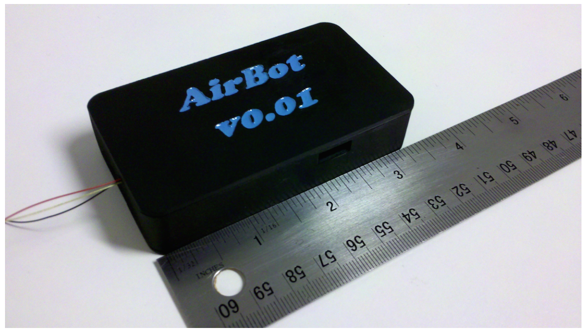

Figure 3.1: The first prototype of the Airbot, the predecessor to the Speck fine particulate monitor.

Our initial prototypes were based on a custom optical assembly. The prototypes were 3D-printed and included a board-mounted photodiode and a focused orthogonal laser similar to those found in small laser pointers. Particles at the intersection of the axes of the laser and photodiode reflect a portion of the light from the laser onto the sensing surface. The 3D-printed enclosure shields the detection region from light and provides a tortuous inlet that further limits external light infiltration. A small blower fan pulls air through the chamber to maximize the sampling volume. The increased sampling volume causes more particles to pass through the optical interrogation region per sampling interval, thus increasing the signal to noise ratio in low concentration environments.

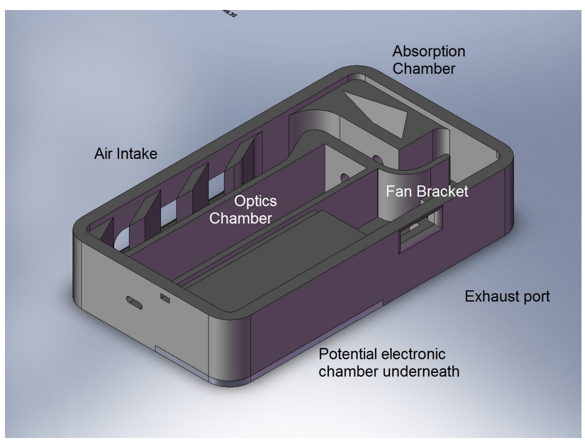

Figure 3.2: Inside the first prototype Airbot. Note the cavity for the laser, fan location, and tortuous path for incoming air.

The bill of materials (BOM) for the prototype shown in fig. 3.3 is given in table 3.1. The estimated costs have been updated for items such as calibration and assembly based on the corresponding costs for the mass-produced monitors described in the next section.

Table 3.1: AirBot Bill of Materials

Part Name	**Cost**
Bluetooth Radio	$11.50
Small DC Blower Fan	$9.20
Assembly	$8.50
Li-Po Battery	$6.50
Xmega Microcontroller	$6.50
Laser Module	$5.50
Calibration and Packaging	$5.00
PC Board	$4.00
Injection-molded Case	$3.50
Packaging material	$2.30
SD Card and Holder	$1.90
USB Cable and Power Supply	$1.55
Testing	$1.00
Other components	$9.24
Total	**$76.19**

The total production cost of $76.19 met the requirement of a device that could be sold at a retail price of under $200, however the measurements were prone to interference. We tested regular photodiodes as well as photodiodes with integrated pre-amplification. Unfortunately the electrical signal to noise ratio was high in the first prototypes, and light contamination also obscured most particle detection in well-lit environments. Passing shadows often registered as false positives, thus rendering the measurements unreliable in the presence of any significant motion. Making the inlet longer or introducing additional bends to reduce light contamination also increased the number of particles that collided with and adhered to the inlet wall, and thus we were unable to find an optimal configuration that significantly reduced light interference without also interfering with the particle flow.

The next set of prototypes replaced the custom optical sensor with a Shinyei PPD42NS dust sensor. These prototypes focused only on the sensing capabilities of the device, though we also introduced a bluetooth connection for wireless connectivity. Eventually we included a micro-SD persistent data storage solution and an inexpensive monochrome LCD screen. Early testing and feedback of the device demonstrated that internal storage and real-time feedback on the display would greatly improve the device's usability by non-expert individuals.

Figure 3.3: Compact keyring Airbot prototype with bluetooth but no display

Figure 3.4: Later Airbot prototype with black and white LCD screen.

Subsequently, we began designing the first air quality monitor to be mass-produced in quantities greater than 12. It became more economical to design and fabricate an injection mold rather than continuing to have the enclosures 3D-printed, and selected the contoured design still used in present Speck models. We replaced the Shinyei PPD42NS with the Syhitech DSM501A, which is nearly identical in operation but less expensive (approximately \$2 compared to \$15 at the time of the decision in 2014). Additionally, we incorporated a resistive color touchscreen for the inclusion of a user interface. These original prototypes were made in black, while later retail versions (described below) use white injection-molded cases to distinguish them from older models. These newer models also included WiFi connectivity, and eventually temperature and humidity sensors.

Figure 3.5: Pre-retail prototypes, prior to the incorporation of WiFi.

The Speck interface allows users to view a scaled estimate of $PM_{2.5}$ levels in micrograms per cubic meter ($\mu g/m^3$). In addition, the screen presents the level of air quality from a scale of Good to Hazardous, to facilitate data interpretation. Historical data is also available on the Speck screen. Users are able to toggle between the instantaneous fine particulate measurement and graphs of readings from the past hour and past 12 hours. Initially, the color coding and scale used for the Speck interface were aligned with the U.S. Air Quality Index [6] for comparison between indoor Speck readings and outdoor federal monitor data. The current version displays real-time estimates of $2\mu m$ particle concentration as well as a scaled estimate of $PM_{2.5}$ levels in $\mu g/m^3$, and uses a different color palette and scale. As we will describe in Chapter 6, this is to prevent confusion because the U.S. AQI numbers are calculated using 24-hour averages rather than near-real-time measurement.

3.2 Speck Sensor Hardware

The Speck utilizes an inexpensive DSM501a dust sensor [1] rather than custom optics, and also employs a small fan to maximize the signal to noise ratio by increasing airflow. The Speck contains on-board signal processing and storage in addition to a color LCD touch-screen for the user interface. Power is supplied via USB, and data can be downloaded directly to any computer or uploaded via WiFi to the Environmental Sensor Data Repository. The interface allows users to view the current estimate of $2\mu m$ particle concentration as well as a scaled estimate of $PM_{2.5}$ in $\mu g/m^3$. The interface also graphs the past hour or past 12 hours of data on-screen, allowing for quick access to historical data.

Table 3.2: Speck Bill of Materials

Part Name	**Cost**
WiFi Radio	$19.59
Color Touchscreen Display	$15.70
Labor: Assembly	$8.50
DSM501a Particle Sensor	$6.50
Small DC Fan	$5.96
Humidity/Temp Sensor	$5.11
Labor: Calibration/Packaging	$5.00
Injection-molded Case	$3.68
Xmega Microcontroller	$3.40
Packaging material	$2.30
Flash Memory	$2.16
PC Board	$1.75
USB Cable and Power Supply	$1.55
Real-time Clock (RTC)	$1.54
Labor: Testing	$1.00
Other Components	$22.46
Total	**$106.20**

Figure 3.6: The Speck air quality monitor

The production cost of the current Speck fine particulate monitor is given in table 3.2. While the final version is more expensive to produce than the initial Airbot prototypes

($106.20 versus $76.19), the Speck design includes additional usability features including WiFi, temperature and humidity sensors, and a color touchscreen for an integrated user interface. Most importantly, as discussed in the next section, additonal processing of the dust sensor output allows this monitor to achieve our performance requirements.

3.3 Disadvantages of Low-Cost Sensors

The output of the DSM501a dust sensor is a digital pin which is pulled low when particles are detected in the optical chamber. The duty cycle is approximately proportional to the number of detected particles. The period of the sensor varies greatly, however, especially at low particle concentrations. While the duration of a low pulse (indicating detected particles) rarely exceeds 100ms, the time between pulses can last from under one second to more than one minute. The DSM501a datasheet [1] does not specify a recommended sampling interval, though a figure demonstrating a single reading depicts a sampling interval of 30 seconds. We determined that this sampling rate is insufficient to provide real-time feedback on particle concentration dynamics, as this requires the user to observe the interface for up to 30 seconds to determine if particle concentration is increasing or decreasing. Users must be able to glance quickly at the interface and determine ambient particle concentration and any immediate trends due to acute air quality events.

Figure 3.7 depicts six hours of measurement using one-second sampling intervals, along with moving averages of 30 seconds and 5 minutes. Note that the unfiltered samples (herein referred to as raw measurements) have a very low signal to noise ratio. A 30 second moving average improves the signal to noise ratio, but the variability creates user difficulty in establishing particle concentration from a single glance. By contrast, single values from the 5 minute moving average are sufficient to convey ambient particle concentration, but responsiveness is decreased and several minutes of delay are present between when the particle concentration reaches a local maxima and when this is reflected in the presented values, as demonstrated across the ten minute period in figure 3.8.

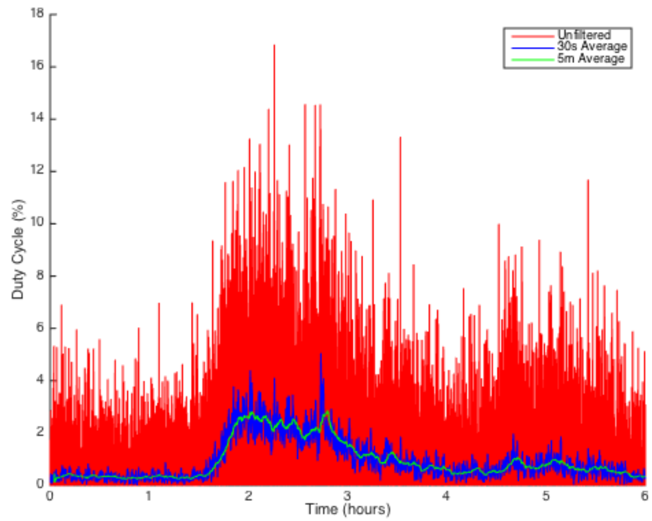

Figure 3.7: Dust sensor duty cycle at 1 second, 30 second, and 5 minute intervals over 6 hours.

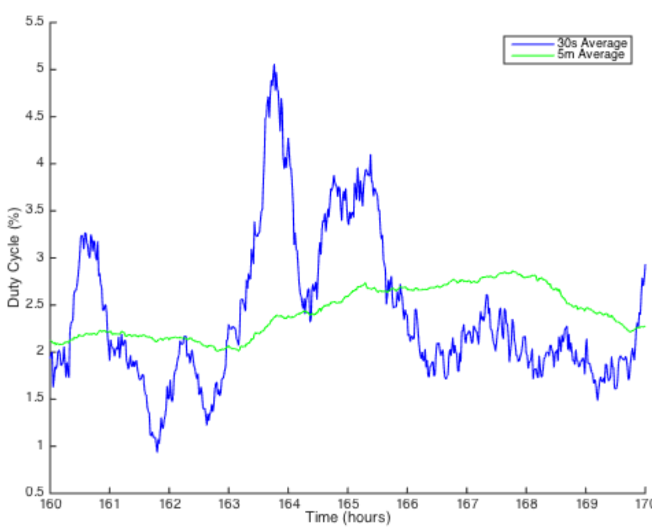

Figure 3.8: Dust sensor duty cycle at 30 second and 5 minute intervals over 10 minutes.

3.4 Algorithms for Low-Tolerance Sensors

3.4.1 Piecewise Form

A low-pass filter such as the 5 minute moving average in the previous section is sufficient to provide single-sample estimates of ambient particle concentration, but also introduces significant delay. In this section, we present a piecewise filter to improve the signal to noise ratio while preserving responsiveness to rapidly changing environments. The piecewise function given in eqn 3.1 describes the second-by-second processing of the raw sensor values, where est_t is the Speck's $2\mu m$ particle count estimate at time t, raw_t is the raw sensor value at time t, and A, B, and D are constants. We observe that the individual raw sensor values are frequently zero in all but visibly smoky environments, though the non-zero values tend to increase linearly with particle concentration. Thus, we design our filtering algorithm to give more weight to non-zero raw values. Each second, if the raw value is non-zero, the algorithm increments or decrements our current estimate at a rate proportional to the difference between the prior estimate and the current raw value scaled by a constant. If the raw value is zero, the estimate exponentially decays toward zero at a lower rate. The resulting behavior is that the estimate quickly responds to non-zero raw values, but decays toward zero slowly due to the potential for long pauses between pulses.

$$est_{t+1} = \begin{cases} (A * raw_t - est_t)/B + est_t & : raw_t > 0 \\ (1 - D) * est_t & : raw_t = 0 \end{cases} \tag{3.1}$$

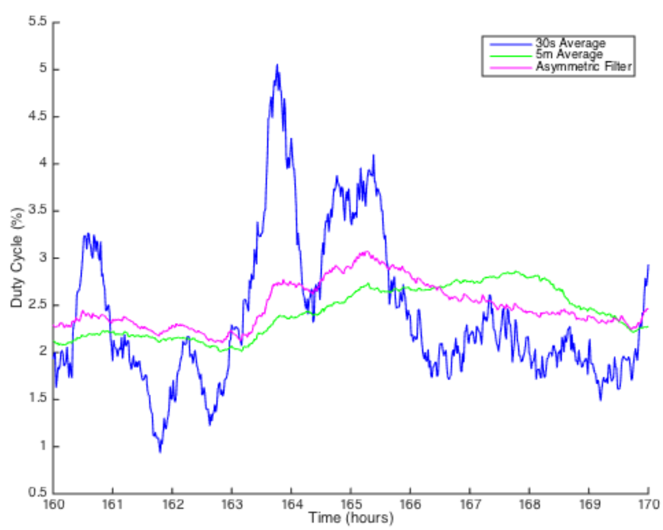

Figure 3.9: Output of 3.1 scaled to moving averages at 30 second and 5 minute intervals over 10 minutes.

As shown in figure 3.9, the asymmetric filter output exhibits the stability of the 5 minute moving average while preserving the sign of the general trend shown by the 30 second moving average.

3.4.2 Kalman Filter Form

The algorithm in 3.1 was formulated because it corresponds to the behavior of particulate matter in enclosed spaces. More specifically, we expect particle concentrations to quickly increase during an event and then slowly decrease due to gradual dissipation. This is functionally equivalent to a simplified Kalman filter with a piecewise sensor model. The general Kalman filter algorithm is given in equations 3.2 through 3.6.

$$\overline{\mu}_t = A_t \mu_{t-1} + B_t u_t \tag{3.2}$$

$$\overline{\Sigma}_t = A_t \Sigma_{t-1} A_t^T + R_t \tag{3.3}$$

$$K_t = \overline{\Sigma}_t C_t^T (C_t \overline{\Sigma}_t C_t^T + Q_t)^{-1} \tag{3.4}$$

$$\mu_t = \overline{\mu}_t + K_t(z_t - C_t \overline{\mu}_t) \tag{3.5}$$

$$\Sigma_t = (I - K_t C_t)\overline{\Sigma}_t \tag{3.6}$$

where μ_t is the estimated mean, Σ_t is the estimate covariance, and K_t is the Kalman gain. Other parameters A, B, and C represent the motion model, control model, and sensor model respectively. R_t and Q_t are the state and sensor covariances, respectively.

Many of these parameters and covariances do not change as a function of time in this case, so we simplify the algorithm by writing these as constants. Additionally, there is no control term since this is a sensing device, so we remove the control portion of the first equation. Lastly, since our state estimate is one-dimensional for a single sensor and because we do not add additional state variables (e.g. first and second derivatives of the estimate), we eliminate the vector math. The simplified algorithm is given in equations 3.7 through 3.11.

$$\overline{\mu}_t = A\mu_{t-1} \tag{3.7}$$

$$\overline{\Sigma}_t = A^2 \Sigma_{t-1} + R \tag{3.8}$$

$$K_t = \overline{\Sigma}_t C (C^2 \overline{\Sigma}_t + Q)^{-1} = \overline{\Sigma}_t (C\overline{\Sigma}_t + \frac{Q}{C})^{-1} \tag{3.9}$$

$$\mu_t = \overline{\mu}_t + K_t(z_t - C\overline{\mu}_t) \tag{3.10}$$

$$\Sigma_t = (I - K_t C)\overline{\Sigma}_t \tag{3.11}$$

Examining equations 3.8, 3.9, and 3.11 reveals that the Kalman gain K_t and estimate covariance Σ_t do not depend in any way on the state estimate μ_t or any other variables aside from one another. We may choose to treat K as a constant by initializing it to its stable final value. Thus, for the purpose of state estimation, we can focus on equations 3.12 and 3.13.

$$\overline{\mu}_t = A\mu_{t-1} \tag{3.12}$$

$$\mu_t = \overline{\mu}_t + K(z_t - C\overline{\mu}_t) \tag{3.13}$$

Specifically regarding air quality and particle concentration, we make the assumption that the air quality is likely to remain approximately constant between one iteration of the algorithm to the next if the sample rate is high (one sample per second in the case of the Speck). Thus, we can assign $A = 1$ and simplify the Kalman filter to the single equation 3.14 to be implemented on the device.

$$\mu_t = \mu_{t-1} + K(z_t - C\mu_{t-1}) \tag{3.14}$$

The piecewise nature of the algorithm as originally expressed in 3.2 through 3.6 (where the rate of change for a sensor reading of zero is much lower than for other readings) is encoded here in the sensor model C, as seen in equation 3.16.

$$c_t = x = \begin{cases} C_1 & z_t > 0 \\ C_2 & z_t = 0 \end{cases} \mid C_1 > C_2 \tag{3.15}$$

$$\mu_t = \mu_{t-1} + K(z_t - c_t\mu_{t-1}) \tag{3.16}$$

All constants described in this section were empirically determined through post-processing optimization of raw data from a single prototype Speck to minimize its RMS error with respect to the $2\mu m$ channel of a handheld particle counter, the HHPC-6+. As shown in figure 3.10 however, multiple Speck monitors exposed to the same environment are prone to disagreement. This is a consequence of mechanical and electrical variability in these mass-produced and inexpensive devices. We observe that the dust sensor elements exhibit a variable response to identical stimuli. Additionally, the fans are driven at reduced voltage for quieter operation, which causes different fans to produce varying levels of airflow. Assembly differences due to warped injection-molded components also affect the flow of particles through the optical chamber. While the algorithm in this chapter maximizes the agreement between the $2\mu m$ particle channel of the HHPC-6+ and Specks of median sensitivity, we will describe calibration and quality control methods to reduce the remaining error for individual Specks in the next chapter.

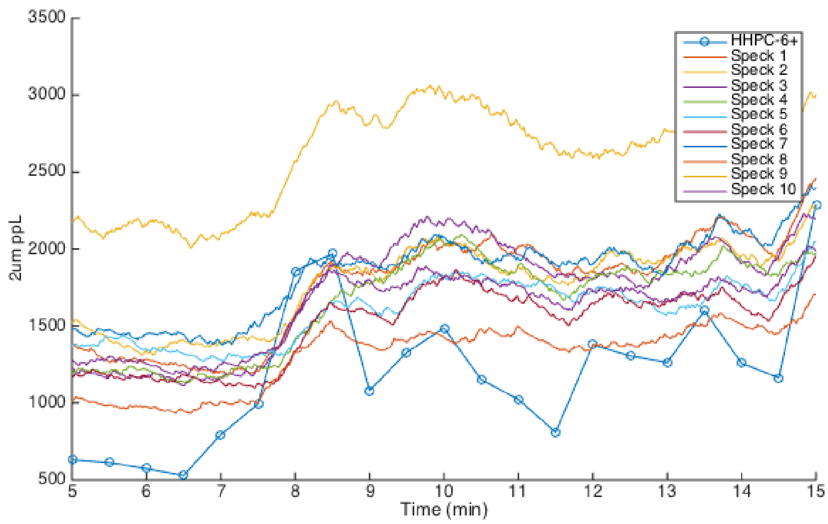

Figure 3.10: Test showing uncalibrated Specks with disagreement relative to each other and the $2\mu m$ HHPC-6+ channel.

3.5 Conversion of Particle Counts to Mass Concentration

The Kalman filter described in this chapter estimates $2\mu m$ particles per liter from the raw values from the dust sensor. Federal reference and equivalence methods report $PM_{2.5}$ mass concentration rather than particle counts. While the sensitivity of the Speck is not strictly limited to particles smaller than $2.5\mu m$, (see Chapter 5, Section 3 for sensitivity characterization), comparison between these monitors and mass-based FEMs is important to individual users and community groups.

One prototype Speck monitor encased in a weatherproof enclosure was co-located with an outdoor TEOM maintained by the Allegheny County Health Department (ACHD). The Speck data was averaged over one hour to match the hourly sample rate of the TEOM. The ratio of medians between the Speck $2\mu m$ particle count averages and the TEOM $PM_{2.5}$ values over the one month period is 25.44 particles per microgram. Scaling the Speck particle count by this ratio produces the agreement shown in figure 3.11.

The TEOM is unsuitable for calibration as the hourly sample rate prohibits rapid calibration. The HHPC-6+ is used as the calibration reference instrument due to its lower cost, compact size, and faster sample rate. Thus, the Specks are calibrated to $2\mu m$ particle counts, and the scaling factor generated from the ratio of medians in the previous experiment is used in all Specks to estimate $PM_{2.5}$. Chapters 4 descriptes the calibration procedure, and comparison of calibrated Speck $PM_{2.5}$ values is demonstrated in Chapter 5.

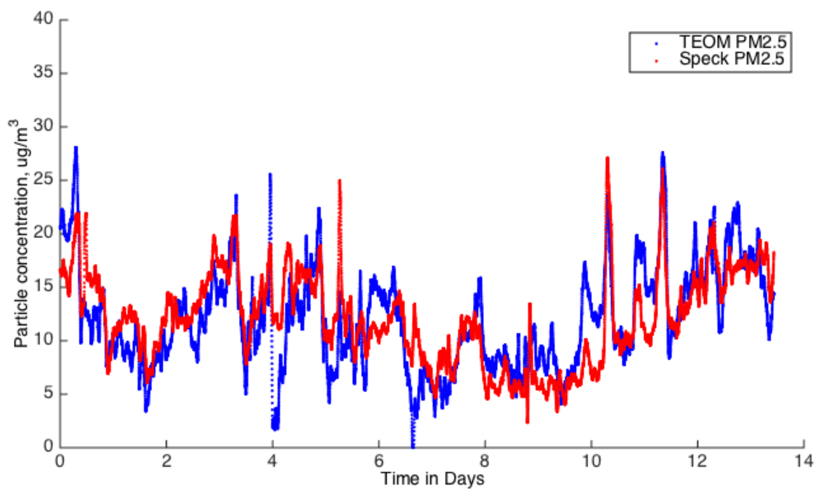

Figure 3.11: Two weeks of TEOM and Speck $PM_{2.5}$ measurements. Speck values are averaged over one hour to match TEOM hourly sample rate.

Chapter 4

Group Calibration and Quality Control

4.1 Explanation of the Calibration Constant

Figure 3.10 establishes the need for individual correction of monitors that are slightly more or less responsive than the median monitor behavior. The Speck algorithm described in the previous chapter compensates for the nonlinear behavior of the sensing element. A linear scaling factor serves as a calibration value while preserving sufficient linearity as long as that scaling factor is close to 1. We refer to this scaling factor as the calibration value in this paper.

A personal home monitor is likely to experience low to moderate particle concentrations, punctuated by brief highly elevated events caused by cooking, cleaning, etc. Minimizing the sum of squared differences between the Speck and reference outputs will decrease the error at highly elevated concentrations, but will result in increased relative error at concentrations that are an order of magnitude lower than these events. Minimizing the percent difference, by contrast, allows for a margin of error that is proportional to the magnitude of the particle concentration. Thus, our calibration procedure involves scaling each of the Speck instrument outputs in order to minimize the mean percent error between the Speck signals and the $2\mu m$ channel of the HHPC-6+. This minimization is given in eqn 4.1, where C is the calibration constant and H_t is the HHPC-6+ $2\mu m$ measurement at time t.

$$\min_C \frac{|C * est_t - H_t|}{H_t} \tag{4.1}$$

4.2 Comparison with Handheld Particle Counters

4.2.1 Calibration Pre-Test

Development of an automated calibration and quality control process began with a basic calibration test of three Specks in a home kitchen [37]. Five Speck units were co-located

Figure 4.1: Cooking test with five Specks, the HHPC-6+ (top left), and the HHPC-6 (top right).

Table 4.1: Table of scalar calibration values

	Calibration Constant
Speck 1	4.09
Speck 2	1.19
Speck 3	2.92
Speck 4	2.78
Speck 5	3.21

with one HHPC-6+ particle counter and one HHPC-6 particle counter. The older HHPC-6 model was calibrated roughly ten months prior to the HHPC-6+. The HHPC units log particle counts within six size ranges. The HHPC-6 unit measures $.3\mu m$, $.5\mu m$, $.7\mu m$, $1\mu m$, $2\mu m$, and $5\mu m$ sizes, while the newer HHPC-6+ unit measures $.3\mu m$, $.5\mu m$, $1\mu m$, $2\mu m$, $5\mu m$, and $10\mu m$ sizes. We exposed these seven instruments to one half-hour cooking event in order to gather an appropriate calibration dataset with high dynamic range. The cooking event involved frying papadum (Indian lentil crackers) in a medium-sized kitchen with windows closed and the stove hood off. After approximately 15 minutes, we ceased cooking and allowed the air to clear naturally. Scalar calibration values given in table 4.1 were generated using the minimization in 4.1. Pairwise r^2 correlation values are presented in 4.2.

Table 4.2: Table of pairwise r^2 values for all Specks for the calibration test

	Speck 1	Speck 2	Speck 3	Speck 4	Speck 5
Speck 1	1	0.935	0.991	0.991	0.993
Speck 2	0.935	1	0.902	0.955	0.922
Speck 3	0.991	0.902	1	0.979	0.985
Speck 4	0.991	0.955	0.979	1	0.985
Speck 5	0.993	0.922	0.985	0.985	1

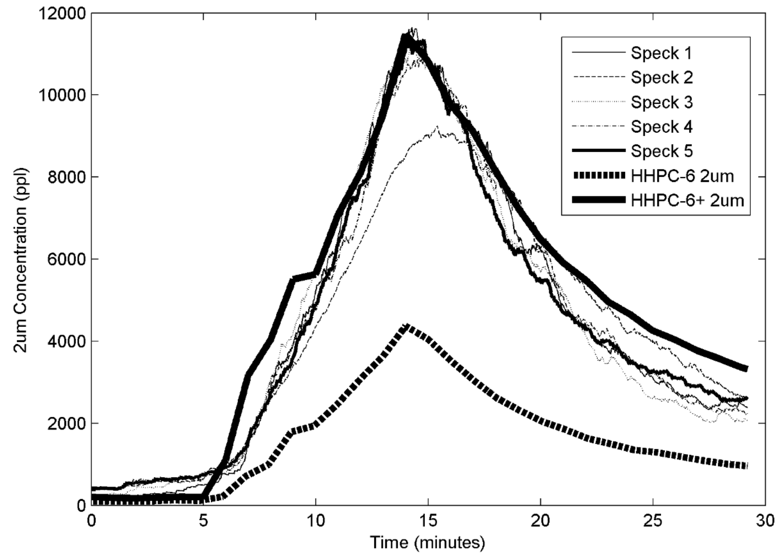

Figure 4.2: Plot of calibration data over time. Note the large discrepancy between the HHPC-6 channels.

4.2.2 Cooking Test

In the cooking test, the three most internally consistent Specks (1, 4, and 5, those with the highest pairwise r^2 values) and the two HHPC particle counters were exposed to a second cooking test, with environmental conditions similar to those used in the calibration pre-test. The outputs of the Specks were scaled by the calibration values calculated in the pre-test. Figure 4.3 demonstrates consistency in magnitude and shape in the response of the calibrated Specks relative to the HHPC-6+ $2\mu m$ channel. Additionally, table 4.5 demonstrates that the Speck units correlate with the $2\mu m$ channels for both HHPC instruments. While the channels of the two HHPC units correlate well, there is a discrepancy between the magnitudes of the HHPC-6 and the HHPC-6+ measurements, shown in figure 4.4.

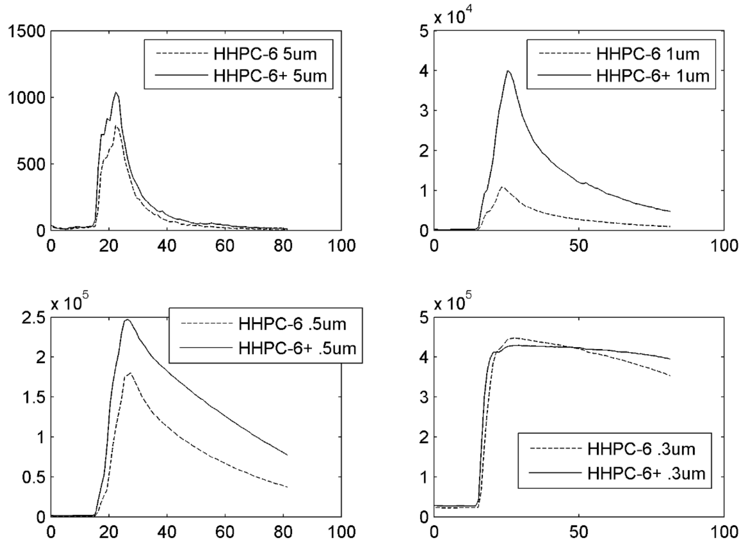

Figure 4.4: Comparison of additional HHPC size channels for the cooking test, showing ppl vs time (minutes)

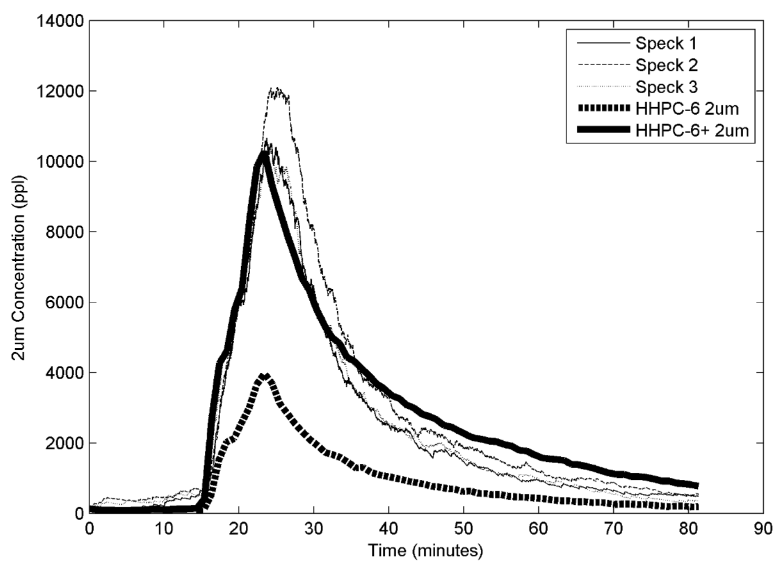

Figure 4.3: Plot of cooking data over time

		Specks			HHPC-6					HHPC-6+				
		Speck 1	Speck 2	Speck 3	.3um	.5um	1um	2um	5um	.3um	.5um	1um	2um	5um
	Speck 1	1.000	0.987	0.994	0.193	0.567	0.955	0.966	0.796	0.156	0.498	0.863	0.956	0.726
	Speck 2	0.987	1.000	0.981	0.200	0.626	0.950	0.926	0.715	0.155	0.536	0.900	0.928	0.639
Specks	Speck 3	0.994	0.981	1.000	0.175	0.547	0.950	0.972	0.816	0.142	0.478	0.850	0.960	0.752
	.3um	0.193	0.200	0.175	1.000	0.648	0.349	0.207	0.050	0.974	0.799	0.446	0.288	0.041
	.5um	0.567	0.626	0.547	0.648	1.000	0.723	0.509	0.186	0.534	0.965	0.886	0.612	0.148
	1um	0.955	0.950	0.950	0.349	0.723	1.000	0.950	0.702	0.296	0.679	0.945	0.980	0.640
	2um	0.966	0.926	0.972	0.207	0.509	0.950	1.000	0.879	0.181	0.473	0.807	0.984	0.828
HHPC-6	5um	0.796	0.715	0.816	0.050	0.186	0.702	0.879	1.000	0.053	0.173	0.485	0.804	0.983
	.3um	0.156	0.155	0.142	0.974	0.534	0.296	0.181	0.053	1.000	0.693	0.367	0.254	0.049
	.5um	0.498	0.536	0.478	0.799	0.965	0.679	0.473	0.173	0.693	1.000	0.820	0.580	0.141
	1um	0.863	0.900	0.850	0.446	0.886	0.945	0.807	0.485	0.367	0.820	1.000	0.875	0.425
	2um	0.956	0.928	0.960	0.288	0.612	0.980	0.984	0.804	0.254	0.580	0.875	1.000	0.761
HHPC-6+	5um	0.726	0.639	0.752	0.041	0.148	0.640	0.828	0.983	0.049	0.141	0.425	0.761	1.000

Figure 4.5: Table of cooking r^2 values. Shaded cells indicate $r^2 > .9$

Figure 4.6: Incense setup. Notice the close spacing of the instruments, which may have disrupted readings (see Results and Discussion).

4.2.3 Incense Test

The three Specks and two HHPC particle counters were then placed in a small, closed room, where incense was burned for approximately five minutes, followed by a 45 minute rest period, and another five minute burning period. Ten minutes after the second burning, a HEPA air purifier was turned on until particle counts approached the initial baseline. In this experiment, the Specks underestimated the $2\mu m$ particle concentration with respect to the HHPC-6+, as shown in 4.7. The correlation values between all five instruments in table 4.9 were notably less than those from the cooking experiment. Despite the weaker correlation between HHPC instruments, the magnitude of the errors between these instruments is similar to those in the cooking experiment.

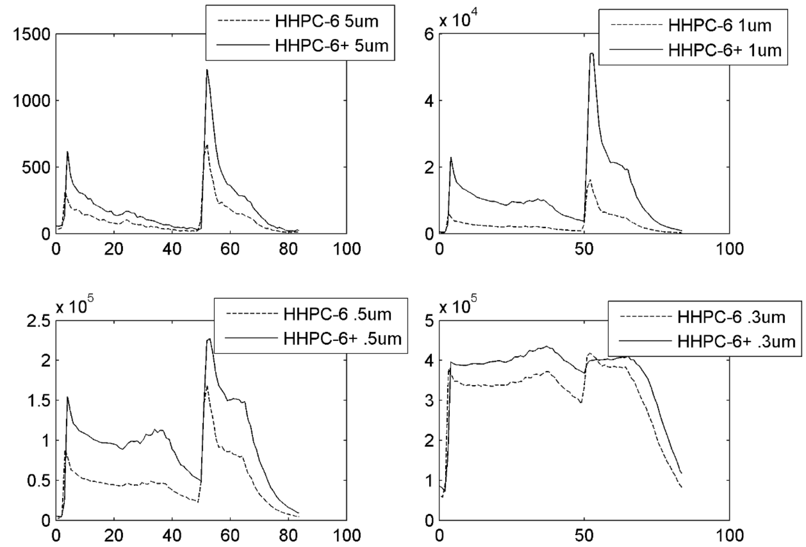

Figure 4.8: Comparison of additional HHPC size channels for the incense test, showing ppl vs time (minutes)

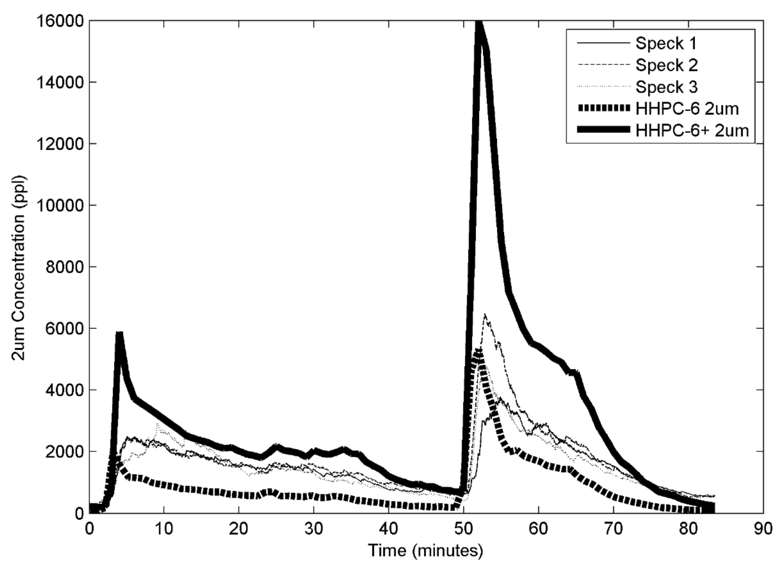

Figure 4.7: Plot of incense data over time

		Specks			HHPC-6					HHPC-6+				
		Speck 1	Speck 2	Speck 3	.3um	.5um	1um	2um	5um	.3um	.5um	1um	2um	5um
Specks	Speck 1	1.000	0.790	0.832	0.390	0.527	0.400	0.374	0.345	0.251	0.706	0.596	0.544	0.531
	Speck 2	0.790	1.000	0.907	0.343	0.736	0.694	0.670	0.618	0.171	0.775	0.894	0.874	0.834
	Speck 3	0.832	0.907	1.000	0.341	0.651	0.592	0.575	0.557	0.186	0.720	0.774	0.751	0.751
HHPC-6	.3um	0.390	0.343	0.341	1.000	0.548	0.322	0.279	0.250	0.858	0.727	0.393	0.311	0.262
	.5um	0.527	0.736	0.651	0.548	1.000	0.935	0.907	0.861	0.249	0.843	0.907	0.880	0.839
	1um	0.400	0.694	0.592	0.322	0.935	1.000	0.996	0.955	0.099	0.662	0.897	0.919	0.894
	2um	0.374	0.670	0.575	0.279	0.907	0.996	1.000	0.972	0.073	0.613	0.871	0.904	0.896
	5um	0.345	0.618	0.557	0.250	0.861	0.955	0.972	1.000	0.053	0.554	0.810	0.849	0.899
HHPC-6+	.3um	0.251	0.171	0.186	0.858	0.249	0.099	0.073	0.053	1.000	0.500	0.178	0.118	0.080
	.5um	0.706	0.775	0.720	0.727	0.843	0.662	0.613	0.554	0.500	1.000	0.831	0.749	0.681
	1um	0.596	0.894	0.774	0.393	0.907	0.897	0.871	0.810	0.178	0.831	1.000	0.989	0.938
	2um	0.544	0.874	0.751	0.311	0.880	0.919	0.904	0.849	0.118	0.749	0.989	1.000	0.962
	5um	0.531	0.834	0.751	0.262	0.839	0.894	0.896	0.899	0.080	0.681	0.938	0.962	1.000

Figure 4.9: Table of incense r^2 values. Shaded cells indicate $r^2 > .9$

4.2.4 Kitchen Test Results and Discussion

In both the calibration pre-test and the cooking test, we observed that the pairwise r^2 correlation between every Speck unit exceeds .90, and exceeds .98 for all but one unit. This demonstrates that the three monitors are internally consistent in their response to airborne particulate matter from cooking. Furthermore, the r^2 values between the three test Specks exhibit a similarly high correlation with the $2\mu m$ channels from the HHPC-6 and HHPC-6+ instruments, as well as the $1\mu m$ channel from the HHPC-6. This indicates that the Specks are most capable of detecting particles in the $2\mu m$ range.

The two HHPC monitors show strong correlation values between their corresponding size channels during the cooking test, which demonstrates the instruments' capability to detect the same particle signals. We also note the strong correlation between the HHPC-6 $1\mu m$ and $2\mu m$ channels, which may indicate a possible overlap in detection for these two sizes on this instrument. The correlation is also high between these two channels on the HHPC-6+ instrument, which indicates that the ratio between these two particle sizes remained relatively constant, or that many particles occupied the $1\mu m$ to $2\mu m$ range during this test.

The incense test was less conclusive, in that each of the five instruments demonstrated much lower correlation values. The strongest correlations in this experiment were between the $1\mu m$, $2\mu m$, and $5\mu m$ channels of the HHPC-6. The similar magnitude in error between the HHPC-6 instruments across both experiments indicates that the instruments differ in calibration. The magnitude of the error between the calibrated test Specks and the HHPC-6+ $2\mu m$ channel is notably less than the error between the two HHPC units in both experiments.

Because of the correlation discrepancy between the HHPC instruments in the incense test, we conclude that factors such as airflow and obstructions may have interfered with the even dispersal of particles between the instruments. We conducted all subsequent procedures in more controlled environments, with the instruments away from obstructions and forced air circulation to homogenize particle distribution where possible.

Both experiments exposed the instruments to very high particle concentrations. The shape of the $.3\mu m$ data from both HHPC instruments and both experiments suggest that the instruments may saturate at levels just under $5 \times 10^5 ppl$. Subsequent tests in this chapter evaluate the performance of the Speck and corresponding calibration values at lower pollution levels.

4.3 Rapid Autonomous Group Exposure (RAGE) Calibration Method

4.3.1 Open-Room Calibration

The aforementioned kitchen calibration process demonstrated the potential for individual units to be calibrated to a $2\mu m$ handheld particle counter when exposed to varying levels of particulate matter. Mass production and distribution of monitors on a commercial scale, however, requires a calibration method that meets the following key criteria:

- Repeatability: We require a means to generate repeatable and controlled $2\mu m$ particulate emissions so that each calibration instance is nearly identical.
- Scalability: The system must be replicable so that multiple manufacturing sites can calibrate prior to shipping.
- Consumable cost: The calibration substance must be readily sourced, reclaimed, and controlled at a low enough cost so as to not affect the price of the monitor.
- Efficiency: The calibration method must maximize throughput without sacrificing calibration quality or placing large demands on time or space resources.
- Automation: As much of the calibration and quality control process as possible should be automated to eliminate both the demand on human resources and the need for specialized training and experience.

Calibration of large numbers of low-cost monitors requires an inexpensive and repeatable means of generating controlled concentrations of particulate pollution. Initial methods proved inconsistent, including essential oil vaporizers and robotic vacuum cleaners with dust bins removed. The method that has proven most consistent involves powering a four-inch subwoofer underneath a lightweight container of fine polydisperse particulates. Our initial substance was local construction dirt, primarily silicate, with a mixture of fine and large particulates. A frequency of 100Hz is sufficient to vibrate the smaller particles into the air, which are then propelled in a controlled direction using a 120mm fan. The larger particles either do not leave the container or quickly fall before reaching the devices to be calibrated. Using handheld particle counters, we determined that the airborne particles that reach the calibration platform are largely at or smaller than $2\mu m$. Later, we replaced the construction dust with food grade diatomaceous earth, which exhibits a similar prevalence of small particles when aerosolized by the subwoofer at 100Hz.

The particle generator is located approximately 2.5m away from the calibration bench. The bench holds one HHPC-6+ handheld particle counter closely encircled by 10 Speck units. Using a second particle counter, we have determined an effective radius of about one foot around the HHPC-6+ within which the particle concentrations are uniformly

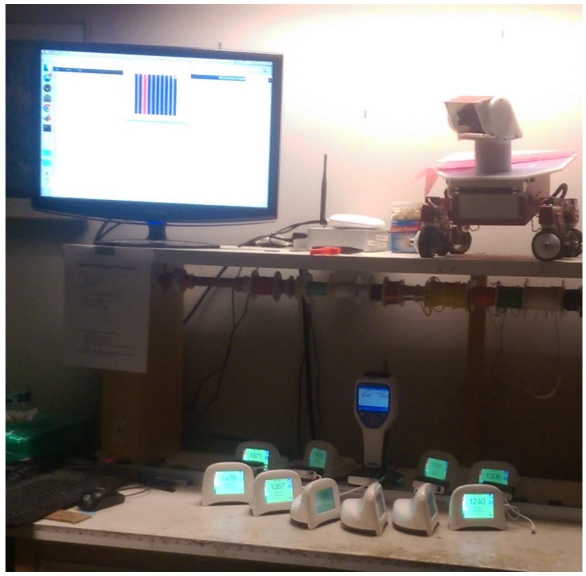

Figure 4.10: Open-room calibration setup

distributed. This dictates a batch size of 10 Specks, given that each Speck must have ample room to intake and exhaust air. This number of Specks also allows us to analyze the pairwise r^2 correlation between each device to identify outliers, which are reconditioned (usually by replacing the sensor) prior to recalibration. This process is explained in detail later in this chapter.

Communication between the Speck monitors and the calibration PC occurs over an open wireless network. The dedicated wireless router for calibration is connected via Ethernet to a Mac Mini, which serves as both the server for calibration data generated by the Specks and the host of the Matlab script used to generate the calibration constants downloaded by the Specks upon completion. The manually-controlled particle generator receives its 100Hz audio signal from a separate Macbook Pro located at the operator station. Experienced operators simultaneously control the particle generator while performing quality control checks on previously calibrated Specks and generating the labels to be applied to each passing device.

Modulating the volume of the subwoofer directly affects the particle concentrations at the calibration platform. The particle concentration is controlled to follow a repeatable step-change profile from 750 +/- 250 $2\mu m$ particles per liter to 1000 +/- 250 $2\mu m$ particles per liter. In the open-room calibration setup, the volume is controlled by the calibration operator.

The calibration constants are generated by the same minimization of percent error between the monitors and the HHPC-6+ $2\mu m$ channel as described in the previous section. Figure 4.12 exhibits the response of one batch of Specks before and after calibration to the HHPC-6+. The constants are generated in real-time by a host server connected via Wi-Fi to each Speck and via Ethernet to the HHPC-6+. Upon the completion of the calibration

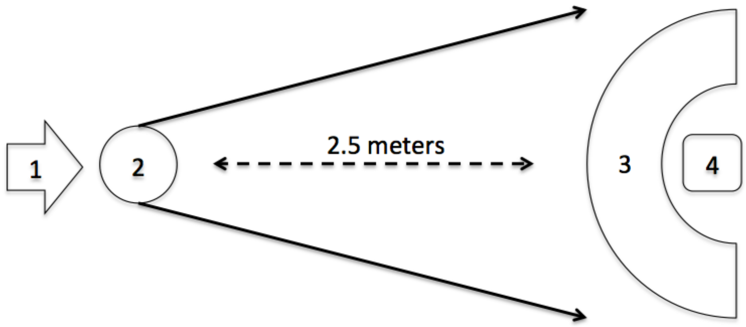

Figure 4.11: Top-down diagram of open-room calibration setup showing 1) dispersion fan, 2) acoustic particle generator, 3) effective calibration zone, and 4) reference instrument.

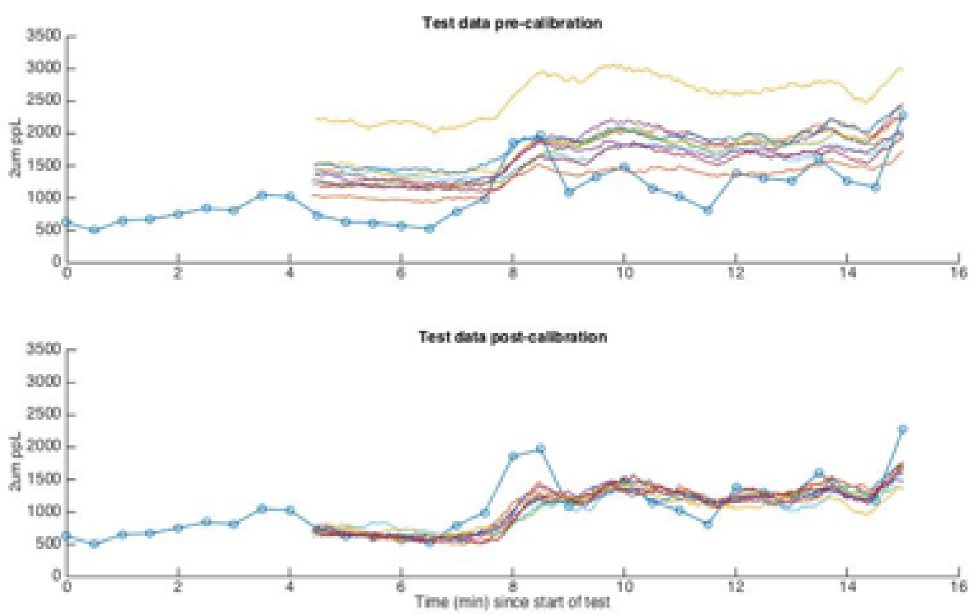

Figure 4.12: Data collected from one open-room calibration showing HHPC-6+ 2 micron data in dotted blue, with the uncalibrated Speck response (top) and fitted response (bottom) for a set of calibrated Specks.

batch, calibration files are generated by the host server, where the Specks automatically download their specific calibration file and begin displaying the new calibrated values.

The operator inspects each Speck visually to confirm functioning touch screens, fans, and Wi-Fi. In addition, the operator ensures that no Speck's mean r^2 coefficient deviates from the batch by more than 0.2, or that the graphed output of the sensor qualitatively deviates from that of the other Specks or the HHPC-6+ based on the subjective judgment of the operator. Outliers are immediately removed for reconditioning.

A single calibration batch takes approximately 20 minutes, yielding 10 Specks per batch, or 30 per hour, or two minutes per Speck. Within a 20 minute batch, approximately five minutes are required for setup, and 15 minutes for particle exposure. The first five minutes of data are unused for calibration as the Speck algorithm stabilizes in response to the initial particle concentration level of 500 $2\mu m$ particles per liter. After 10 minutes, the particle concentration is increased to 1000 particles per liter. At minute 15, all Speck calibration files are written and transmitted.

Respiratory safety is a concern when working with diatomaceous earth (DE). Particularly in its crystalline or calcinated form, DE can result in negative respiratory effects after prolonged exposure. Food grade DE is primarily amorphous silica, with less than 1% of the mass exhibiting a crystalline form. The airborne DE used in this calibration procedure is consistently below the Occupational Safety and Health Administration (OSHA) limit of 6mg/m3 of airborne DE. Nevertheless, calibration operators are trained to stay out of the path of the airborne DE and wear a respirator for comfort and precaution. The requirement for respiratory gear as well as the noise levels and dust accumulation caused by the open-room calibration routine prevents the calibration room from being cohabited by non-operators. This results in a significant space requirement for this calibration strategy.

Manually modulating the volume of the subwoofer in order to control particle concentrations often creates significant cognitive load as the number of emitted particles depends on the amount and size of particles in the container, and there is a time delay of a few seconds from when the volume is changed to when the newly emitted particles reach the calibration platform.

4.3.2 Calibration Chamber

As previously described, the open-room calibration procedure presents three primary disadvantages:

- The procedure requires an open room, and dust will collect on all surfaces.
- Operators must wear respirators due to airborne diatomaceous earth.
- Volume modulation creates significant cognitive load on the operator and is prone to user error.

We have designed an enclosed calibration chamber to address the disadvantages of the open room procedure. The chamber is a modified sandblasting booth with similar components to the calibration platform in the open-room configuration. A smaller enclosure is attached to the side of the booth, which contains the speaker cone and dust reservoir. A partition separates the two spaces, with a blower fan aperture to distribute particlesaturated air from the small enclosure to the larger one. In this way, we separate the dynamics of particle generation and chamber dosing. The seams of the chamber are sealed to prevent user exposure to DE, so in order to reduce the particle concentration when necessary, a high volume fan is installed inside the chamber opposite the particle generator with several layers of filter paper that trap the airborne diatomaceous earth when the fan is engaged. Thus, the three functions of the chamber to be controlled are the speaker cone particle generator, the dosing fan, and the cleaning fan.

The communication architecture is more centralized for the calibration chamber than that of the open room calibration procedure. The same wireless router configuration is used to communicate with the Specks and the calibration server. A small netbook acts as the calibration server and runs a minimal Linux environment as the calibration chamber eliminates the need for graphical feedback. Python replaces Matlab for all calibration scripts to eliminate the cost and complexity of licensing while reducing hardware requirements. The netbook communicates with feedback systems and controls the fans and particle generator via a custom microcontroller board equipped with a USB-to-serial connection. The microcontroller interprets pre-determined serial commands in order to control the chamber functions and report feedback values. The feedback control loop is implemented within the netbook's Python calibration scripts to eliminate the need for periodic changes to the microcontroller firmware.

In order to automate the particle generation profile (removing a significant supervision task from the operator), a previously-calibrated Speck is installed in the center of the chamber which is hardwired to give real-time feedback on internal particle concentrations. This Speck serves only as a feedback device, while the HHPC-6+ is used as the reference instrument for the generation of calibration values. We have completed 24 trial calibrations in the chamber to determine particle homogeneity inside the chamber as well as repeatability and consistency in comparison to the open-room process.

As demonstrated in fig. 4.15, the measurements of the Specks are more consistent after calibration. While the step change that we typically employ in the particulate level is not as pronounced in this test, the calibration and r^2 values were all within open-room passing criteria for each of these devices.

Of the 24 trial calibration experiments performed in the chamber, the most challenging aspect is maintaining stable particle concentrations. The side container doses the main chamber with particles using the blower fan, and a speaker cone filled with DE generates airborne particles. Because the particles deplete and their generation varies depending on the amount and density of the DE on the speaker, avoiding oversaturation is highly challenging. The filter fan is run constantly, both to keep plenty of circulation inside the chamber and to quickly remove excess particles. If the particle concentration drops below the target threshold, the dosing fan turns on, and if the fan alone is not sufficient to raise particle levels, additional particles are generated using the speaker. The calibration values are comparable with those achieved in the open room calibration method.

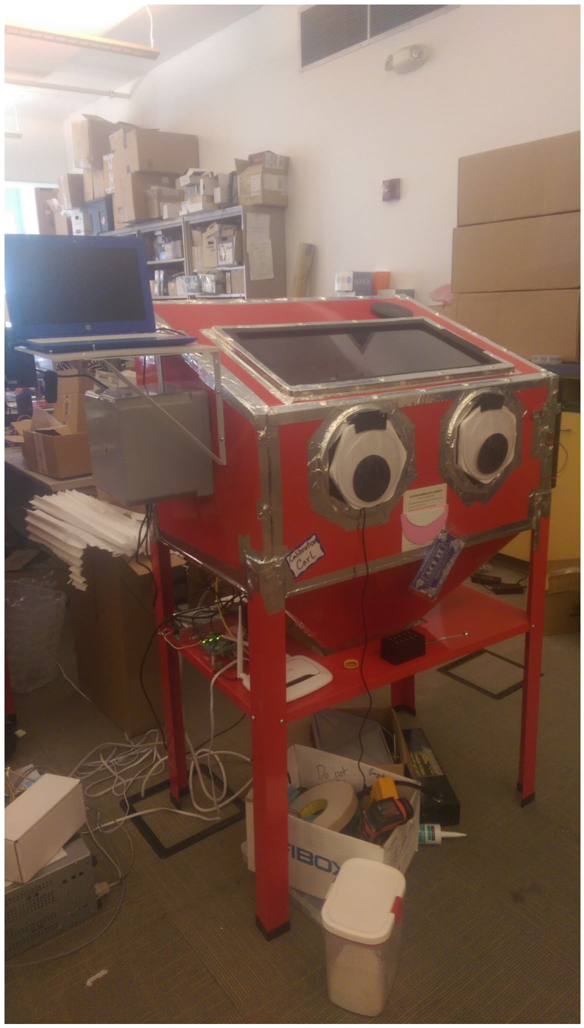

Figure 4.13: The calibration chamber, based on a modified sandblasting cabinet.

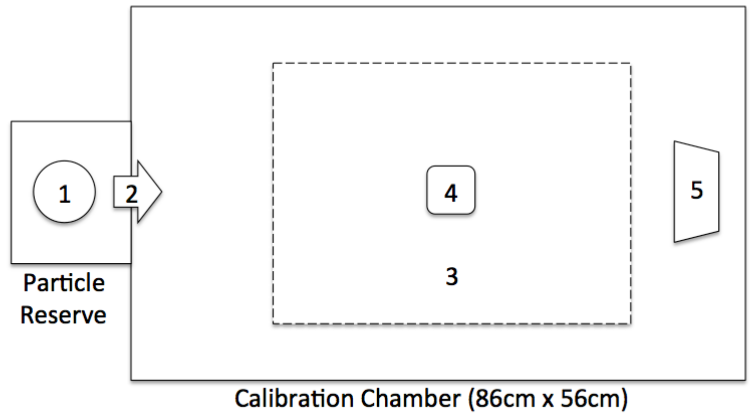

Figure 4.14: Top-down diagram of calibration chamber setup showing 1) acoustic particle generator, 2) dosing fan, 3) effective calibration zone, 4) reference instrument, and 5) filtering fan.

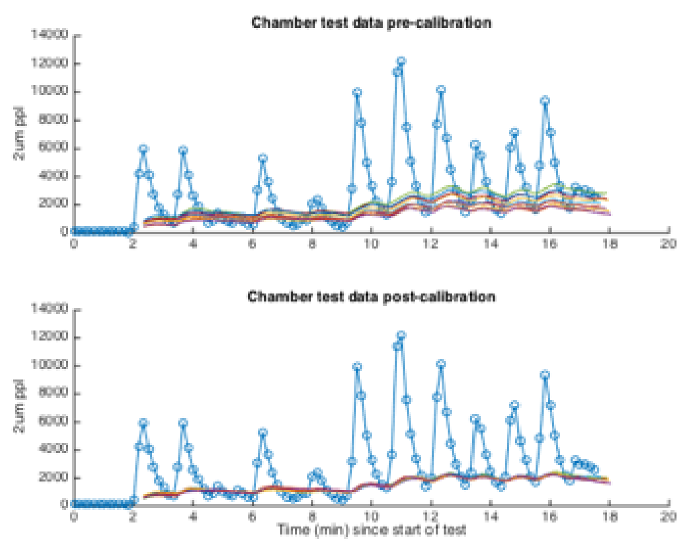

Figure 4.15: One trial calibration run in the closed calibration chamber. Note that over-shooting is a problem that may require some predictive aspects to the control loop.

4.4 Automated Quality Control

Automated quality control procedures are completed before, during and after calibration. Prior to each calibration run, each Speck is plugged into a ten-port USB power hub. The operator inspects each device to ensure that the screen is functional, as the screen is necessary for automated QC feedback. Any device with faulty WiFi will also fail these initial tests.

For each calibration batch, the server data consist of the reference instrument 2m particle counts, along with data from each uncalibrated device exposed to the same stimulus. If the number of devices that passed the WiFi test is approximately 60% or greater, an additional quality control step can be immediately performed by calculating the r^2 Pearsson correlation coefficients for each pair of uncalibrated devices. The median r^2 value from one device versus every other should indicate a quantitative level of responsive similarity with the device batch as a whole. Typically each device's median r^2 value is similar, though they vary with the amplitude and precision of the step change in the calibration profile. If any devices median r^2 value is more than 0.15 below that of the median of every other median r^2 value, this indicates a response to the calibration profile that is significantly different than the other devices in the batch. These will be removed and checked later for faulty fans or sensor components.

Additionally, if the calibration values for any given device are outside of the typical range (in the case of the Speck scaling factor, approximately 0.4 to 1.2), the Speck will fail calibration and identify itself for reconditioning.

Devices that pass these quality control tests will wirelessly download their calibration values from the server. Once each device receives its calibration file, it exits calibration mode and enters normal operation.

The final step performed on the Specks, which may vary for other types of devices, consists of labeling and human quality control. One by one, each Speck is inspected again to ensure that it has left calibration mode, its screen is still functional and responsive, and the fan is rotating without making an unacceptable noise level, as subjectively judged by the operator. These Specks are then labeled with their serial number, calibration date, batch code, and model number as well as general consumer information. An additional label consists of a serial number barcode and model number for application to the packaging.

4.5 Discussion

Some potential sources of error in the calibration process may arise from the reference instrument requiring re-calibration after being exposed to consistently high levels of particulates. Additionally, while the monitors are spaced closely together, they cannot sample identical air, so calibration position may have some impact on the calibration values they receive. The particle generator causes the smallest diatomaceous earth particles to become airborne, while leaving larger ones behind. Over time, the size distribution of the substance in the particle generator will change, and higher speaker amplitudes are needed to achieve the same 2m particle concentrations. This introduces larger particles to the devices, which may confound calibration. It is important to replace the diatomaceous earth frequently to keep calibration consistent.

All calibration data have been archived, including the pre-calibration data from each Speck and HHPC-6+. In order to improve yield and performance, the calibration algorithm and associated parameters have iteratively changed since calibration began, and multiple operators have supervised the procedure. As of November 2016, approximately 5000 calibrations and inspections have been performed by the open-room and closed chamber methods. The next chapter characterizes the performance of the calibration procedure over time as well as observed sensor drift. Subsequently, we characterize the calibrated Specks in comparison with other monitors, including FEMs and other contemporary low-cost monitors.

Chapter 5

Characterization and Comparison of Low-Cost Monitors

5.1 Characterizing Calibration

One advantage of regularly calibrating large numbers of devices in groups is the production of enough data to calculate how statistical measures of the calibration values have changed since the beginning of calibration approximately one year ago. Fig. 5.1 shows every calibrated Speck to date, excluding those that have not met the quality control standards outlined in Chapter 4. There is a general negative trend in the mean calibration values. Because of the cost function used, overshooting particle concentration targets tends to bias the calibration factors high, so we hypothesize that the explanation for the decreasing mean calibration factor is better control of particle generation. Similarly, the standard deviation of the calibration factors has decreased, as demonstrated in Fig. 5.2. The standard deviations given are calculated from all devices calibrated on a particular day. The differences in calibration factors are composed of both genuine variation in the sensors and the error in the calibration process. Given that the sensors have been drawn from the same mixed inventory for the entirety of the manufacturing period, a decreasing standard deviation in calibration factors indicates that the typical error in calibration has been decreasing over time. A histogram of all calibration values is shown in Fig. 5.3.

5.2 Sensor and Process Drift

5.2.1 A Naïve Approach to Sensor Drift

The simplest way of determining time-based changes in sensitivity for the Speck may be to compare the original calibration factor of a particular device to the calibration factor achieved in a subsequent calibration after the device has been extensively used over a period of several months. We recall, however, that the calibration procedure has been regularly modified to yield more accurate results, and thus we must statistically characterize and compensate for these methodological changes.

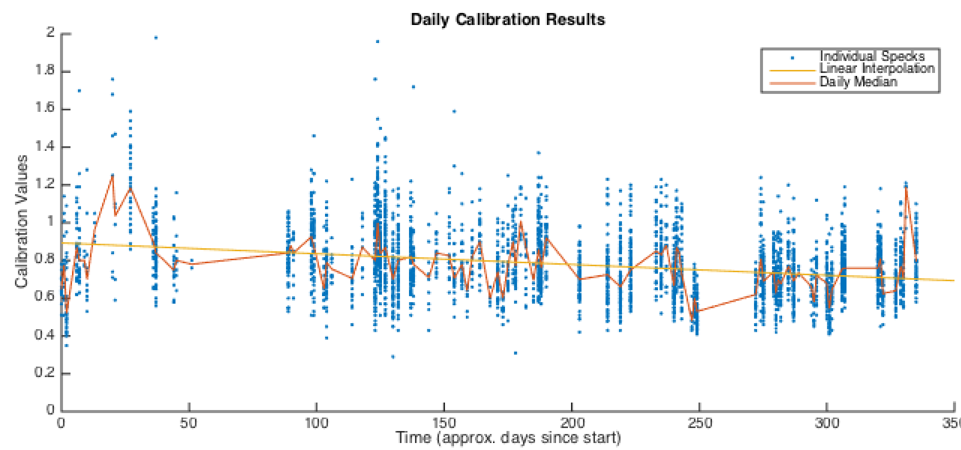

Figure 5.1: Plot of historical daily calibration values over time

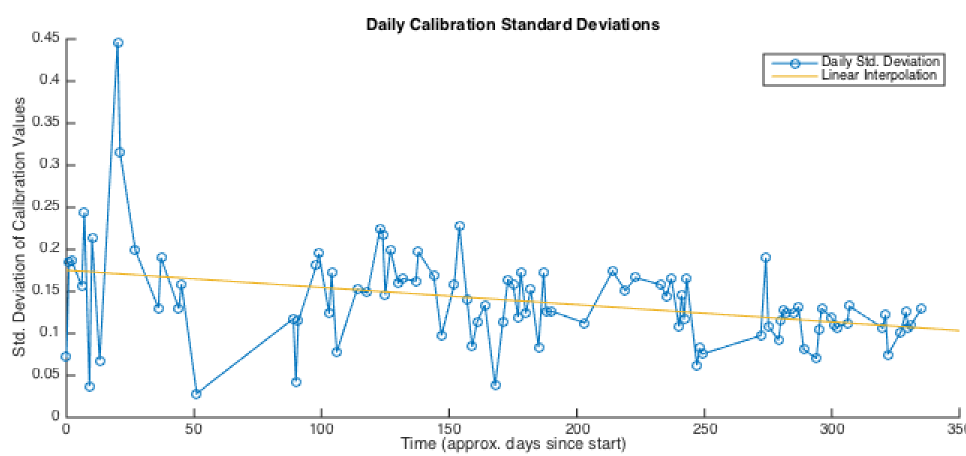

Figure 5.2: Plot of historical daily standard deviation of calibrations over time

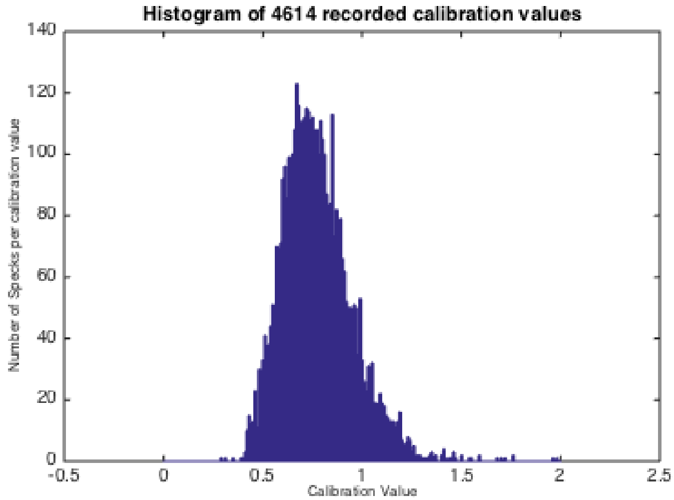

Figure 5.3: Distribution of 4614 recorded calibration values

5.2.2 Compensating for the Calibration Process

Ultimately, we wish to calculate the rate of sensor drift in terms of mean percentage per month. The distribution of the naïve drift calculated in section II can be considered as a summation of three separate distributions: the actual drift distribution and the error introduced by the first and second calibrations. The optimal calibration is given by Equation 5.1, a probability distribution of calibration values given an optimal but unknown calibration factor plus some mean bias introduced by the calibration process and a randomly distributed error with a known standard deviation. These are functions of time as both the mean and standard deviation have changed in the interval between the first and second calibrations. Equation 5.2 represents the drift between the first and second optimal calibration values. Equations 5.3 and 5.4 give the expected drift and standard deviation of the drift respectively, as a function of the first and second calibration values for each individual device as well as the means and standard deviations of the first and second calibrations across all sensors calibrated on that day.

$$c(t) = c_{optimal}(t) + N(\mu_{cal}(t), \sigma^2_{cal}(t)) \tag{5.1}$$

$$\begin{aligned} N(\mu_{drift}(t_2 - t_1), \sigma^2_{drift}(t_2 - t_1)) &= c_{optimal}(t_2) - c_{optimal}(t_1) \\ &= c(t_2) - c(t_1) + N(\mu_{cal}(t_1) - \mu_{cal}(t_2), \sigma^2_{cal}(t_1) + \sigma^2_{cal}(t_2)) \end{aligned} \tag{5.2}$$

$$\mu_{drift}(t_2 - t_1) = c(t_2) - c(t_1) + \mu_{cal}(t_1) - \mu_{cal}(t_2) \tag{5.3}$$

$$\sigma^2_{drift}(t_2 - t_1) = \sigma^2_{cal}(t_2) + \sigma^2_{cal}(t_1) \tag{5.4}$$

Drift is best expressed as a percent per unit time, and these values predict the drift for each sensor over a specific variable-length interval. The limits of the calibration values should be zero (for a sensor that reports a maximum value at every time) to infinity (a sensor that reports zero at every time), and the rate should be in percent per month. When the calibration procedure was originally conceived, the calibration values were intended to achieve a mean calibration of 1, so we may formulate the total percent drift the calibration value minus 1 (since the optimal calibration values are not known). Equation 5.5 represents the expected percent drift per month relative to 1, assuming exponential behavior and time given in months.

$$\mu_{rate}(t_2 - t_1) = (1 - \mu_{drift}(t_2 - t_1))^{\frac{1}{t_2 - t_1}} - 1 \tag{5.5}$$

5.2.3 Sensor Drift Results and Conclusions

We apply this method to a population of 29 Speck fine particulate matter sensors [36]. These sensors were calibrated twice, with a mean interval of 7.5 months of use in between. This usage was unsupervised as the Specks were part of a lending library for the Carnegie Library of Pittsburgh, and each device was checked out to multiple patrons.

We find that the mean naïve drift for 29 used Specks is -3.1% per month, with a standard deviation of 4% per month. That suggests that Specks in general will begin to respond more strongly to identical stimulus as time from calibration increases. After compensating for the decrease in mean calibration values over time for each Speck, the mean of expected drift rates is -1.08% per month with a standard deviation of 3.27% per month. Equivalently, we predict the Speck response will vary by approximately -12.2% in one year after the change in calibration procedure has been accounted for, versus -31.5% per year from the naïve approach.

These results demonstrate the need to account for a changing calibration process when estimating the rate at which a sensor changes its response over time. This is especially relevant to new low-cost sensors where effective and inexpensive calibration procedures are still in development. The results shown here for the Speck air quality monitor are generalizable for any linearly-calibrated sensing device where there exists sufficient data to characterize the bias and standard deviation of calibration values over time.

An extension of this work would be to characterize drift as a function of both the time between calibration as well as usage and particle exposure, e.g. the time the device was powered on over the interval between calibrations and the total measured particulate matter over this time period. As these devices were part of a lending library and no data from patrons was collected, we do not have access to this information. In future studies, we plan to anonymously log the number of data points created by each device as a means to estimate usage.

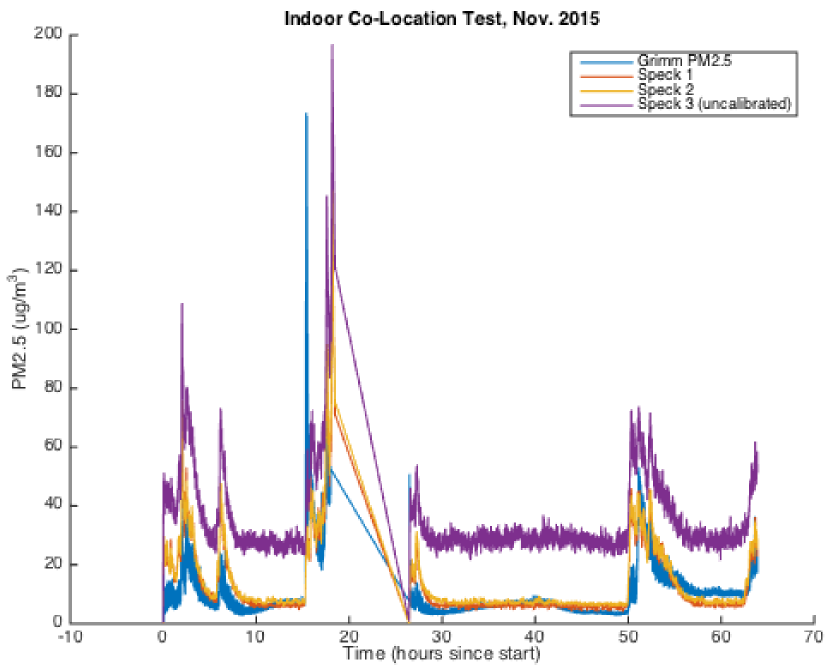

Figure 5.4: Plot of kitchen co-location experiment with three Specks and one grimm EDM180

5.3 Indoor Co-Location Test

5.3.1 Procedure

To demonstrate the size sensitivity of the Speck air quality monitor in a typical home environment, we installed a Grimm EDM 180 federal equivalence monitor (FEM) in a home kitchen along with three Speck units. Excluding approximately 8 hours where the monitor was switched off while guests were in the home, the test represents approximately 55 hours of co-located data collection.

The Grimm EDM 180 is an optical FEM that measures PM1, PM2.5, PM10, and particle counts within 31 bins representing particle sizes from 0.25 to 32 microns. The EDM 180 is configured to sample once every 6 seconds in this experiment, while the Speck is configured to measure every second. In order to compare r^2 values, 6-second averages of the Speck readings are generated at each of the EDM 180 timestamps.

5.3.2 Results

Figures 5.4 and 5.5 show the estimated $PM_{2.5}$ values for each Speck as well as $PM_{2.5}$ measured by the Grimm EDM 180 FEM. In this test, each of the three Specks slightly overestimates $PM_{2.5}$ as reported by the EDM 180, but the air quality dynamics caused by the cooking events are similarly measured by all four instruments. Speck 3 is unusual

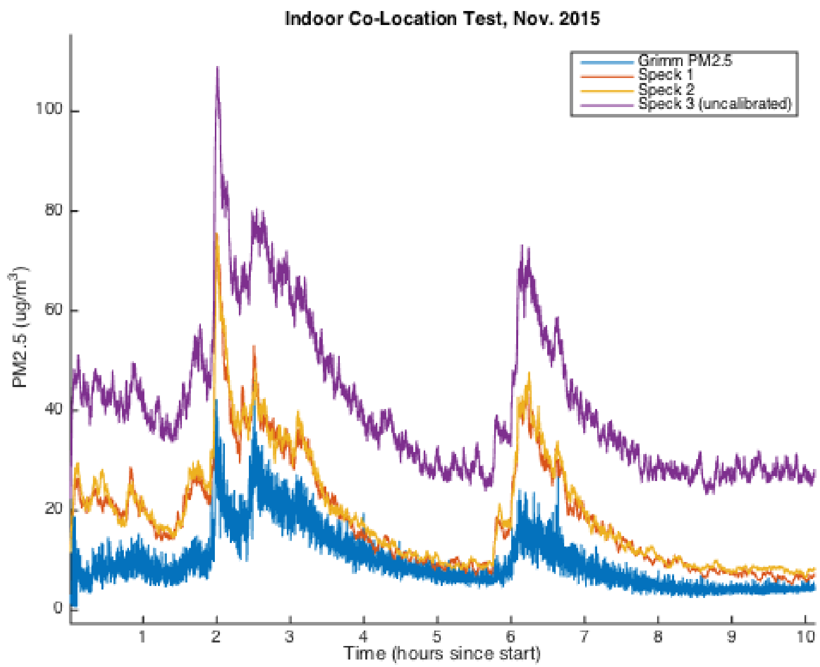

Figure 5.5: Highlighted cooking event during the kitchen co-location experiment

in that it settles at a much higher quiescent value, which may indicate that this unit is in need of cleaning or poorly calibrated.

Figure 5.6 shows the r^2 correlation coefficient for each Speck with respect to each of 30 Grimm EDM 180 bins, plot according to size. The 32 micron bin, representing the largest measured particles, is excluded because no particles this large were recorded by the EDM 180 during this experiment.

This plot demonstrates that the Speck's correlation coefficient is greater than 0.8 for particles from 0.7 to 4 microns. These values may vary somewhat by location because of different particle size distributions.

Table 5.11 shows the r^2 values between different size channels of the EDM 180. These values are similar for adjacent particle sizes. This figure demonstrates that similarly sized particles tend to appear and dissipate at the same time. Figure 5.7 visualizes these relationships as a contour plot to highlight clusters of strongly correlated particle sizes.

The Grimm EDM 180 also reports mass fractions for PM_1, $PM_{2.5}$, and PM_{10}. These values represent total mass concentrations for all particles below 1, 2.5, and 10 microns respectively. The r^2 coefficients for the three Specks versus these three values are given in table 5.8. The Speck exhibits a higher correlation with larger mass size fractions, despite having the highest correlation values with individual particle size bins between 0.7 and 4 microns in this experiment.

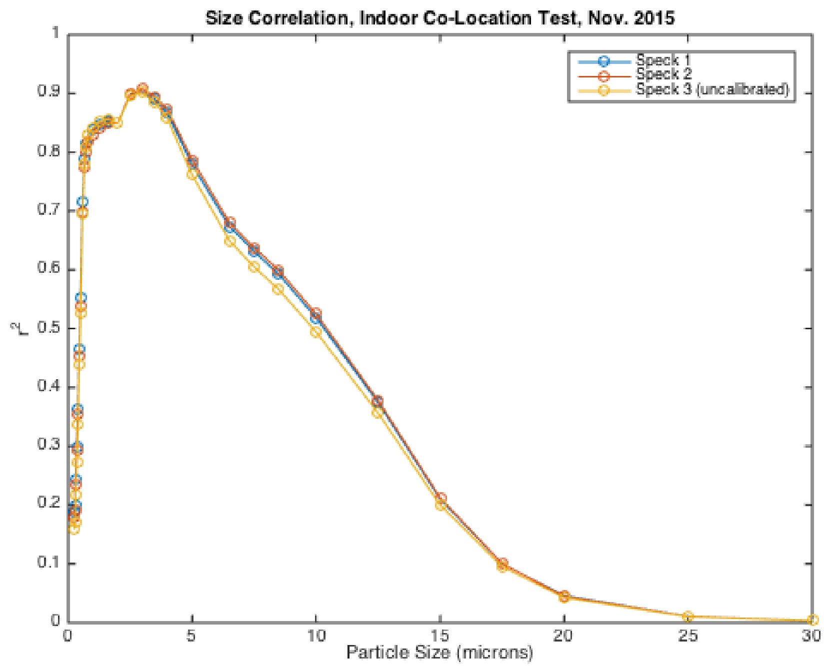

Figure 5.6: Plot of Speck correlation values with respect to particle diameter, demonstrating size sensitivity

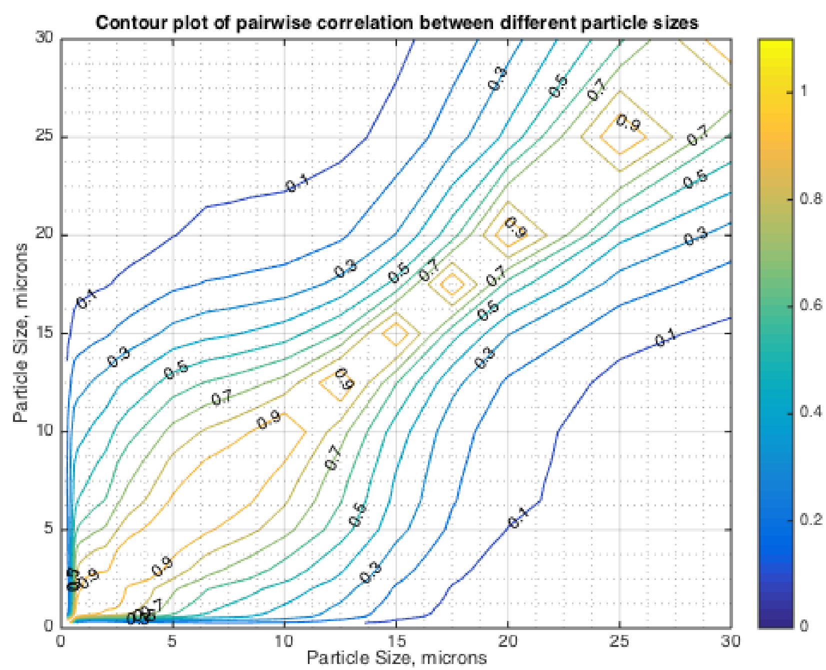

Figure 5.7: Contour plot demonstrating clusters of strongly correlated particle sizes

Speck vs. Mass Fraction r^2 coefficients

	Speck 1	Speck 2	Speck 3
PM1	0.20	0.19	0.17
PM2.5	0.46	0.44	0.42
PM10	0.83	0.83	0.81

Figure 5.8: Table of r^2 values between each Speck and PM_1, $PM_{2.5}$, and PM_{10} mass concentrations

Table 5.9 shows r^2 values for each Speck versus mass values from particles smaller than 1 micron, between 1 up to and including 2.5 microns, and 2.5 microns up to and including 10 microns respectively. This table demonstrates that the correlation coefficients are similar for the latter two ranges.

Table 5.10 shows r^2 values between each pair of PM_1, $PM_{2.5}$, and PM_{10} values from the Grimm EDM 180. As with individual particle bins, there is a non-zero correlation between each of these three mass fractions, indicating a dependency between the rise and fall of large and small particles. Independent control of smaller particle size ranges will require controlled chamber testing with aerosol size standards.

Speck vs. Ranged Mass r^2 coefficients

	Speck 1	Speck 2	Speck 3
PM1	0.20	0.19	0.17
PM2.5-PM1	0.82	0.82	0.83
PM10-PM2.5	0.83	0.84	0.81

Figure 5.9: Table of r^2 values between each Speck and total particle mass concentrations up to $1\mu m$, between $1\mu m$ to $2.5\mu m$, and between $2.5\mu m$ to $10\mu m$

Mass vs. Mass r^2 coefficients

	PM1	PM2.5	PM10
PM1	1.00	0.90	0.40
PM2.5	0.90	1.00	0.66
PM10	0.40	0.66	1.00

Figure 5.10: Table of pairwise r^2 values between PM_1, $PM_{2.5}$, and PM_{10} mass concentrations

5.3.3 Conclusions

These results show that the Speck correlates strongly to fine particulates especially in the range of 0.7 to 4 microns, and exhibits decreasing sensitivity to larger particles. While the correlation is stronger between the Speck reading and PM_{10} with $r^2 = 0.83$, there is also a nontrivial correlation of $r^2 = 0.44$ between the Speck and $PM_{2.5}$. From table 5.9, we infer that the Speck is correlates equally well to mass within the $2.5\mu m$ to $1\mu m$ range as it does to mass within the $10\mu m$ to $2.5\mu m$ range. Because PM_{10} is inclusive of $PM_{2.5}$, we conclude that the higher correlation between the Speck and PM_{10} is a result of sensitivity to particles within and slightly larger than the $PM_{2.5}$ range. While we had hypothesized a higher correlation to $PM_{2.5}$, larger particles each contribute significantly more mass than smaller particles due to the cubic relationship between radius and volume, so significant numbers of particles above $2.5\mu m$ will result in an increase in the Speck signal given any sensitivity to these larger particles.

Grimm EDM 180 r^2 coefficients

Size (microns)	0.25	0.28	0.30	0.35	0.40	0.45	0.50	0.58	0.65	0.70	0.80	1.00	1.30	1.60	2.00	2.50	3.00	3.50	4.00	5.00	6.50	7.50	8.50	10.00	12.50	15.00	17.50	20.00	25.00	30.00
0.25	1.00	1.00	0.98	0.95	0.90	0.79	0.67	0.42	0.25	0.19	0.13	0.11	0.11	0.11	0.11	0.13	0.14	0.15	0.16	0.18	0.19	0.20	0.20	0.18	0.13	0.07	0.03	0.01	0.00	0.00
0.28	1.00	1.00	0.99	0.97	0.92	0.80	0.69	0.43	0.26	0.20	0.14	0.12	0.12	0.12	0.12	0.14	0.15	0.16	0.17	0.19	0.20	0.21	0.20	0.19	0.13	0.07	0.03	0.01	0.00	0.00
0.30	0.98	0.99	1.00	0.99	0.95	0.85	0.75	0.49	0.31	0.24	0.19	0.16	0.15	0.16	0.16	0.18	0.19	0.20	0.21	0.23	0.24	0.24	0.23	0.22	0.15	0.08	0.04	0.02	0.00	0.00
0.35	0.95	0.97	0.99	1.00	0.98	0.91	0.82	0.57	0.39	0.31	0.25	0.22	0.21	0.21	0.21	0.23	0.24	0.25	0.26	0.28	0.28	0.27	0.27	0.25	0.17	0.09	0.04	0.02	0.00	0.00
0.40	0.90	0.92	0.95	0.98	1.00	0.97	0.90	0.68	0.49	0.41	0.33	0.30	0.28	0.28	0.28	0.30	0.30	0.31	0.31	0.31	0.30	0.30	0.29	0.26	0.19	0.10	0.04	0.02	0.00	0.00
0.45	0.79	0.80	0.85	0.91	0.97	1.00	0.98	0.82	0.64	0.56	0.47	0.43	0.40	0.39	0.38	0.40	0.40	0.40	0.40	0.37	0.35	0.33	0.32	0.29	0.21	0.11	0.05	0.02	0.01	0.00
0.50	0.67	0.69	0.75	0.82	0.90	0.98	1.00	0.91	0.76	0.68	0.59	0.55	0.51	0.50	0.48	0.49	0.49	0.48	0.47	0.43	0.38	0.36	0.35	0.31	0.22	0.12	0.06	0.03	0.01	0.00
0.58	0.42	0.43	0.49	0.57	0.68	0.82	0.91	1.00	0.95	0.89	0.83	0.78	0.74	0.72	0.68	0.68	0.66	0.63	0.61	0.53	0.45	0.42	0.39	0.35	0.25	0.13	0.06	0.03	0.01	0.00
0.65	0.25	0.26	0.31	0.39	0.49	0.64	0.76	0.95	1.00	0.98	0.95	0.91	0.87	0.84	0.79	0.79	0.75	0.72	0.68	0.57	0.48	0.44	0.41	0.36	0.26	0.14	0.07	0.03	0.01	0.00
0.70	0.19	0.20	0.24	0.31	0.41	0.56	0.68	0.89	0.98	1.00	0.98	0.95	0.92	0.89	0.84	0.83	0.79	0.75	0.71	0.60	0.49	0.45	0.42	0.36	0.26	0.14	0.07	0.03	0.01	0.00
0.80	0.13	0.14	0.19	0.25	0.33	0.47	0.59	0.83	0.95	0.98	1.00	0.98	0.96	0.93	0.88	0.87	0.82	0.78	0.74	0.62	0.51	0.46	0.43	0.37	0.27	0.15	0.07	0.03	0.01	0.00
1.00	0.11	0.12	0.16	0.22	0.30	0.43	0.55	0.78	0.91	0.95	0.98	1.00	0.98	0.96	0.91	0.90	0.84	0.80	0.76	0.64	0.52	0.48	0.44	0.38	0.28	0.15	0.08	0.04	0.01	0.00
1.30	0.11	0.12	0.15	0.21	0.28	0.40	0.51	0.74	0.87	0.92	0.96	0.98	1.00	0.98	0.95	0.93	0.86	0.82	0.78	0.67	0.55	0.51	0.47	0.41	0.30	0.17	0.08	0.04	0.01	0.00
1.60	0.11	0.12	0.16	0.21	0.28	0.39	0.50	0.72	0.84	0.89	0.93	0.96	0.98	1.00	0.97	0.94	0.87	0.84	0.80	0.69	0.58	0.53	0.49	0.43	0.32	0.18	0.09	0.04	0.01	0.00
2.00	0.11	0.12	0.16	0.21	0.28	0.38	0.48	0.68	0.79	0.84	0.88	0.91	0.95	0.97	1.00	0.97	0.88	0.85	0.82	0.72	0.60	0.56	0.52	0.46	0.34	0.19	0.09	0.05	0.01	0.00
2.50	0.13	0.14	0.18	0.23	0.30	0.40	0.49	0.68	0.79	0.83	0.87	0.90	0.93	0.94	0.97	1.00	0.95	0.93	0.90	0.80	0.68	0.63	0.59	0.52	0.38	0.21	0.11	0.05	0.01	0.00
3.00	0.14	0.15	0.19	0.24	0.30	0.40	0.49	0.66	0.75	0.79	0.82	0.84	0.86	0.87	0.88	0.95	1.00	0.98	0.96	0.86	0.74	0.69	0.65	0.56	0.41	0.24	0.12	0.06	0.02	0.01
3.50	0.15	0.16	0.20	0.25	0.31	0.40	0.48	0.63	0.72	0.75	0.78	0.80	0.82	0.84	0.85	0.93	0.98	1.00	0.98	0.89	0.78	0.73	0.69	0.60	0.44	0.26	0.14	0.06	0.02	0.01
4.00	0.16	0.17	0.21	0.26	0.31	0.40	0.47	0.61	0.68	0.71	0.74	0.76	0.78	0.80	0.82	0.90	0.96	0.98	1.00	0.93	0.82	0.77	0.73	0.64	0.48	0.28	0.15	0.07	0.02	0.01
5.00	0.18	0.19	0.23	0.28	0.31	0.37	0.43	0.53	0.57	0.60	0.62	0.64	0.67	0.69	0.72	0.80	0.86	0.89	0.93	1.00	0.91	0.87	0.82	0.73	0.55	0.33	0.18	0.10	0.04	0.02
6.50	0.19	0.20	0.24	0.28	0.30	0.35	0.38	0.45	0.48	0.49	0.51	0.52	0.55	0.58	0.60	0.68	0.74	0.78	0.82	0.91	1.00	0.96	0.91	0.81	0.61	0.37	0.21	0.12	0.05	0.03
7.50	0.20	0.21	0.24	0.27	0.30	0.33	0.36	0.42	0.44	0.45	0.46	0.48	0.51	0.53	0.56	0.63	0.69	0.73	0.77	0.87	0.96	1.00	0.95	0.85	0.63	0.39	0.21	0.12	0.05	0.03
8.50	0.20	0.20	0.23	0.27	0.29	0.32	0.35	0.39	0.41	0.42	0.43	0.44	0.47	0.49	0.52	0.59	0.65	0.69	0.73	0.82	0.91	0.95	1.00	0.90	0.67	0.41	0.22	0.13	0.05	0.03
10.00	0.18	0.19	0.22	0.25	0.26	0.29	0.31	0.35	0.36	0.36	0.37	0.38	0.41	0.43	0.46	0.52	0.56	0.60	0.64	0.73	0.81	0.85	0.90	1.00	0.74	0.45	0.24	0.14	0.05	0.03
12.50	0.13	0.13	0.15	0.17	0.19	0.21	0.22	0.25	0.26	0.26	0.27	0.28	0.30	0.32	0.34	0.38	0.41	0.44	0.48	0.55	0.61	0.63	0.67	0.74	1.00	0.60	0.33	0.18	0.07	0.04
15.00	0.07	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.14	0.15	0.15	0.17	0.18	0.19	0.21	0.24	0.26	0.28	0.33	0.37	0.39	0.41	0.45	0.60	1.00	0.54	0.30	0.13	0.08
17.50	0.03	0.03	0.04	0.04	0.04	0.05	0.06	0.06	0.07	0.07	0.07	0.08	0.08	0.09	0.09	0.11	0.12	0.14	0.15	0.18	0.21	0.21	0.22	0.24	0.33	0.54	1.00	0.56	0.25	0.15
20.00	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.05	0.05	0.06	0.06	0.07	0.10	0.12	0.12	0.13	0.14	0.18	0.30	0.56	1.00	0.43	0.26
25.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.04	0.05	0.05	0.05	0.05	0.07	0.13	0.25	0.43	1.00	0.58
30.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.03	0.03	0.03	0.03	0.04	0.08	0.15	0.26	0.58	1.00

Figure 5.11: Table of pairwise r^2 values between different particle size channels of the Grimm EDM 180

5.4 Comparative Testing

Until recently, only a very small number of inexpensive airborne particulate monitors have been available to the public. Because there are no ubiquitous standards for this class of monitors, design decisions affecting performance, cost, and user interaction are solely determined by the manufacturer. As discussed in Chapter 3, low-cost monitors must balance performance and cost through hardware decisions such as sensor quality and the presence or absence of a fan to increase the signal to noise ratio. Additionally, software implementation of filters or other algorithms can improve performance, and longer sampling periods may improve readings at the expense of temporal resolution.

We collected several low cost air quality monitors and co-located them in our open-room calibration setup, together with the Grimm EDM180. In order to expose the monitors in this test to ambient fluctuations in air quality as well as controlled particulate pollution events, we installed each monitor in our calibration room in front of the diatomaceous earth particulate generator. The particles are propelled by the fan in an even distribution over the monitors. Each sensor was activated simultaneously on Friday, April 15, where they operated unsupervised until Monday, April 17th. Only sensors that ran continuously over the weekend are reported. On two consecutive days, we generated a series of particle events lasting approximately 15 minutes each, punctuated by at least 30 minutes of inactivity.

5.4.1 Evaluation Criteria

Evaluation of the low-cost monitors depends on both quantitative and qualitative criteria due to the nature of these devices as consumer electronics. The monitors must meet usability standards while producing reliable and actionable data. While some of these devices contain additional sensors for pollutants such as VOCs, this section focuses exclusively on particle concentration. The criteria by which each of these monitors is evaluated is as follows.

- **Absolute error:** Are the values reported in units that can be compared against professional monitors, and do those values approximate the readings of the reference instrument? Accuracy is important for being able to compare an individual monitor's readings with regional monitors and air quality reports. Accuracy also provides context for the risk posed by the measured particles.
- **Correlation:** Are the air quality dynamics recorded by the monitor similar to those reported by the reference instrument? The dynamics (or shape) of particle events can provide insight into the source of the measured particles. If the particle levels rise very sharply, the source may be in the immediate vicinity. Very gradual changes may be regional or may be a result of diffusion from outside the home. Likewise, the rate of decrease can indicate the effectiveness of air purifiers or ventilation solutions.
- **Response time and stability:** Does the monitor respond quickly to changes in air quality events? This aspect is related to the rate of sample collection and airflow. A longer sample rate may allow for more stability in the measurement, as the sample will typically collect data over the entire interval between the present and prior

reading, but more acute changes in particle concentration may not be recorded as unique events. Sample rates that are too fast can result in noisy behavior because the monitors cannot ingest as many particles per sample. Forced airflow due to an integrated fan or pump can increase response time as opposed to devices that rely on passive ingestion of particles.

5.4.2 Speck

The Speck air quality monitor exhibits good correlation with $PM_{2.5}$ as reported by the Grimm EDM 180 ($r^2 = 0.89$ over the 1.5 hour window), preserving the shape of the particle events. While very rapid (shorter than one minute) fluctuations in air quality are filtered out by the one minute sample rate and estimation algorithms, the values displayed on the device more human-readable in real-time.

The Speck's estimate of $PM_{2.5}$ differs from the reference instrument by approximately a factor of two. This magnitude is unexpected, but may be due to formulating the conversion from particle counts to mass using an in-vivo dataset. The Speck is calibrated to the $2\mu m$ particle count channel of the HHPC-6+ and subsequently converted to mass by assuming a typical particle size distribution. The diatomaceous earth may present a distribution that varies enough to cause this error. As demonstrated in the previous in-home experiment, the error was not as pronounced between the reference instrument and Speck.

It should be noted that the Speck is compared with the mass measurement rather than a summation of particle counts because we do not know precisely what size range of particles is measured by the $2\mu m$ particle count channel of the HHPC-6+, our calibration reference instrument. Also, a cleaning event occurred between hours 50 and 55 (at approximately 5am local time), and is composed entirely of sub-micron particles. There is little or no response to this event, suggesting that one micron is about the lower detection range for the Speck's sensing element.

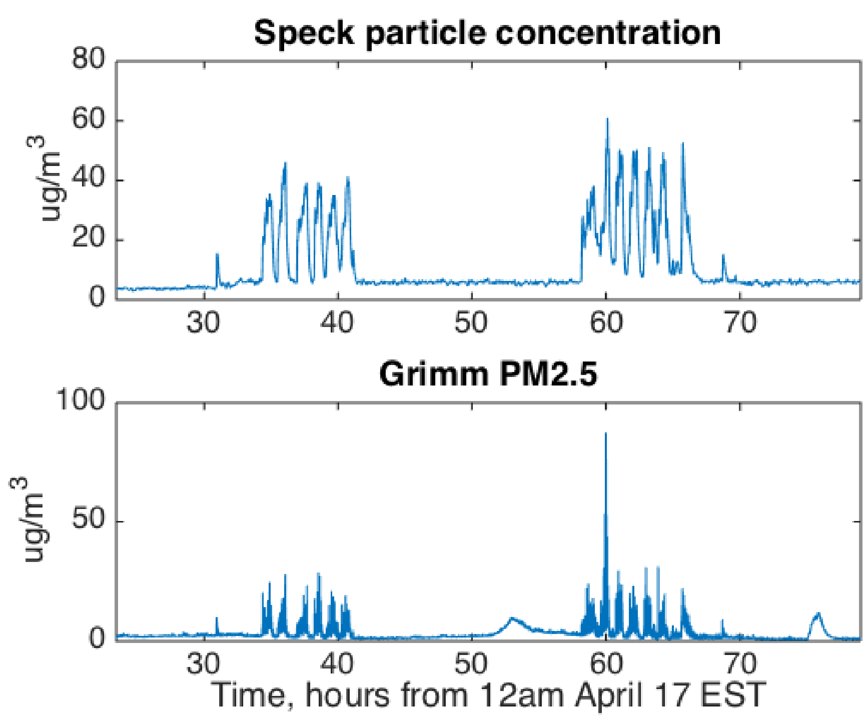

Figure 5.12: Speck vs. Grimm particle concentration, 55-hour interval

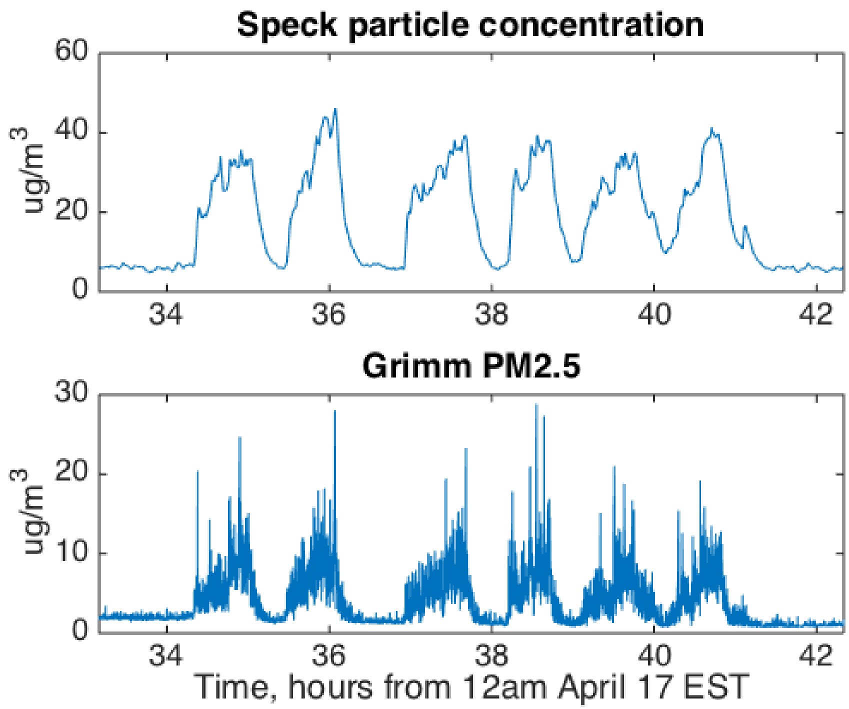

Figure 5.13: Speck vs. Grimm particle concentration, 9-hour interval

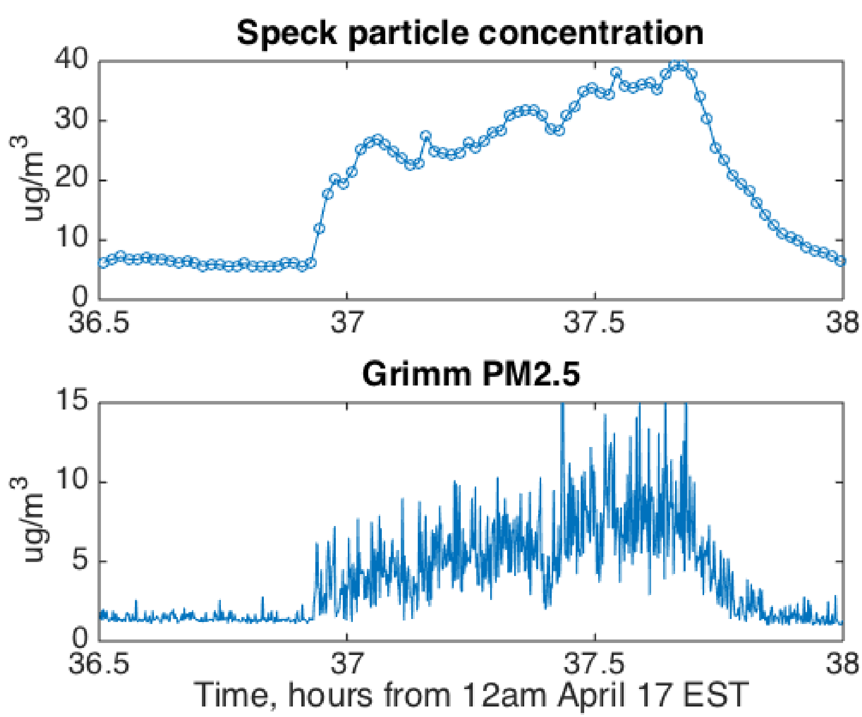

Figure 5.14: Speck vs. Grimm particle concentration, 1.5-hour interval

5.4.3 Air Quality Egg

The Air Quality Egg collects samples at a fast rate of once every five seconds, but exhibits the lowest signal to noise ratio out of the devices we tested, resulting in a poor $PM_{2.5}$ correlation of $r^2 = 0.07$ over the 1.5 hour window. We note that longer intervals have a slightly higher correlation (up to $r^2 = 0.28$) with the Grimm EDM 180, and filtering will also significantly reduce the noise in the data. The Air Quality Egg underestimates $PM_{2.5}$ by approximately 4.6 $\mu g/m^3$.

Note that the Air Quality Egg detects the spike in fine particulates occurring between hours 50 and 55, which means that the Air Quality Eggs detection range extends to sub-micron particles as well. The sensing element in the Egg is a similar but higher-cost component than what is employed in the Speck.

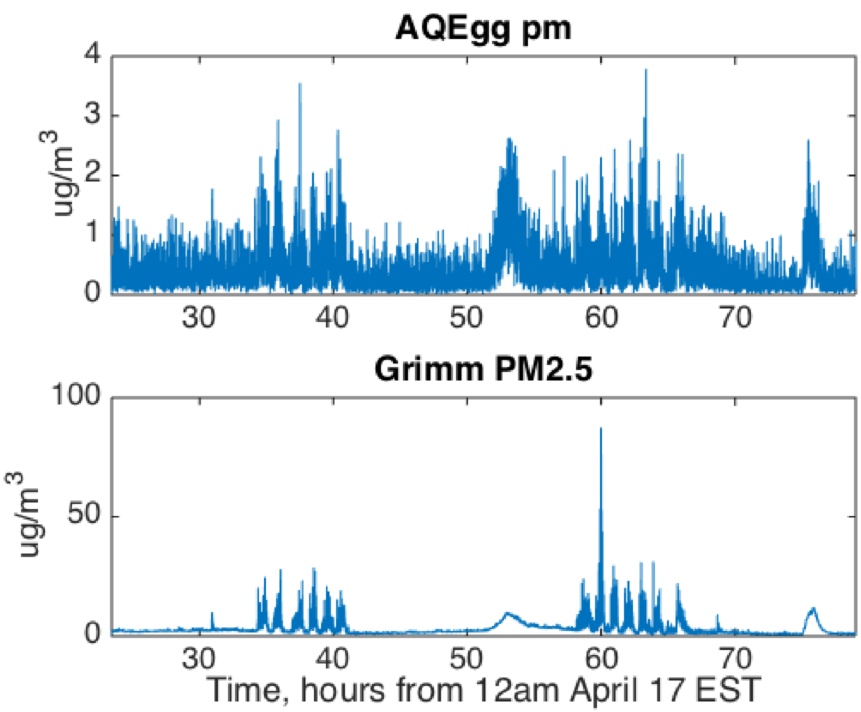

Figure 5.15: Air Quality Egg vs. Grimm particle concentration, 55-hour interval

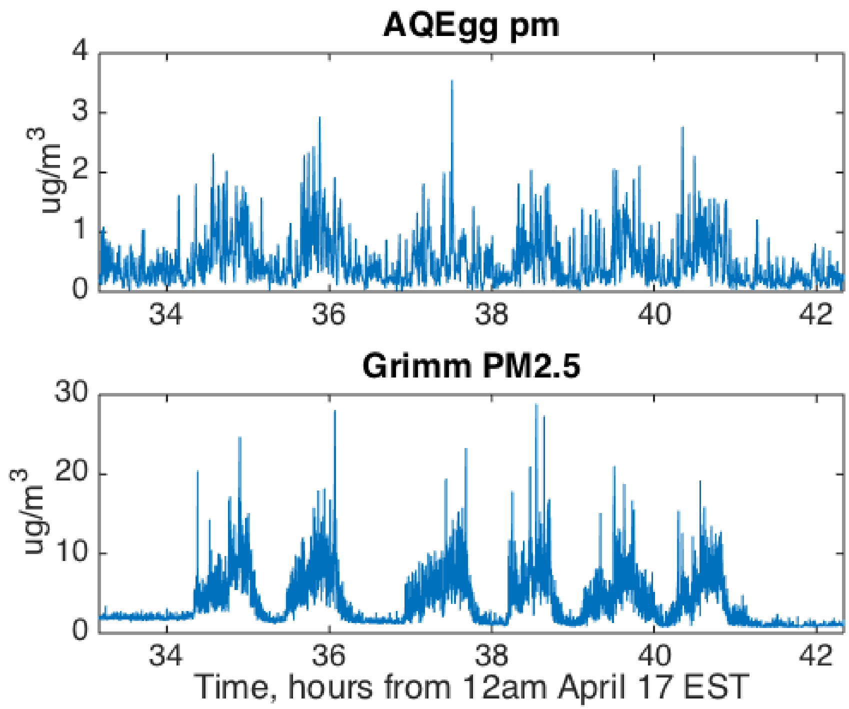

Figure 5.16: Air Quality Egg vs. Grimm particle concentration, 9-hour interval

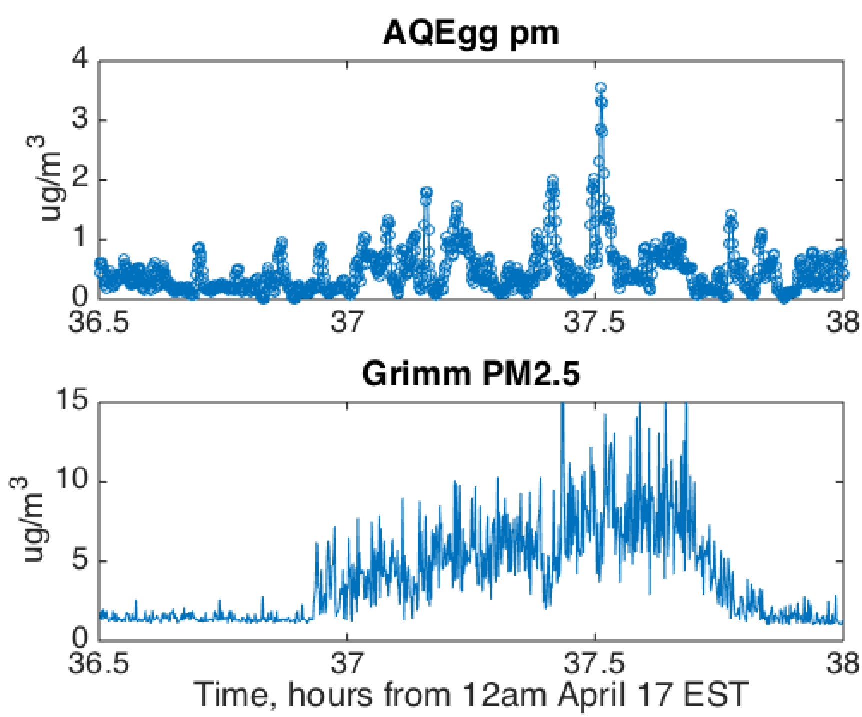

Figure 5.17: Air Quality Egg vs. Grimm particle concentration, 1.5-hour interval

5.4.4 Awair

The Awair samples once every 10 seconds and demonstrates a $PM_{2.5}$ correlation of $r^2 = 0.13$ over the 1.5 hour window with a small number of brief spikes. The individual spikes align with those detected by the Grimm EDM 180, though some seem disproportionately high.

Overall, the Awair overestimates $PM_{2.5}$ by approximately 11.9 $\mu g/m^3$. We see a small response to the early morning cleaning events such as the one between hours 50 and 55, suggesting some detection of sub-micron particles. The Awair appears to have good responsivity despite a lack of forced airflow through the interrogation volume. Despite a lower correlation, the pollution events are easily distinguishable.

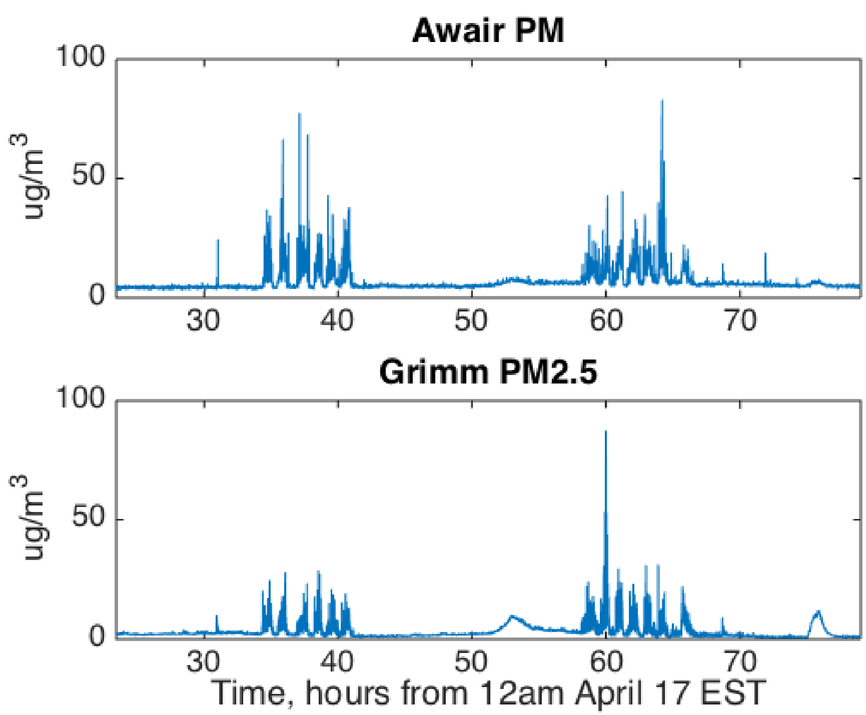

Figure 5.18: Awair vs. Grimm particle concentration, 55-hour interval

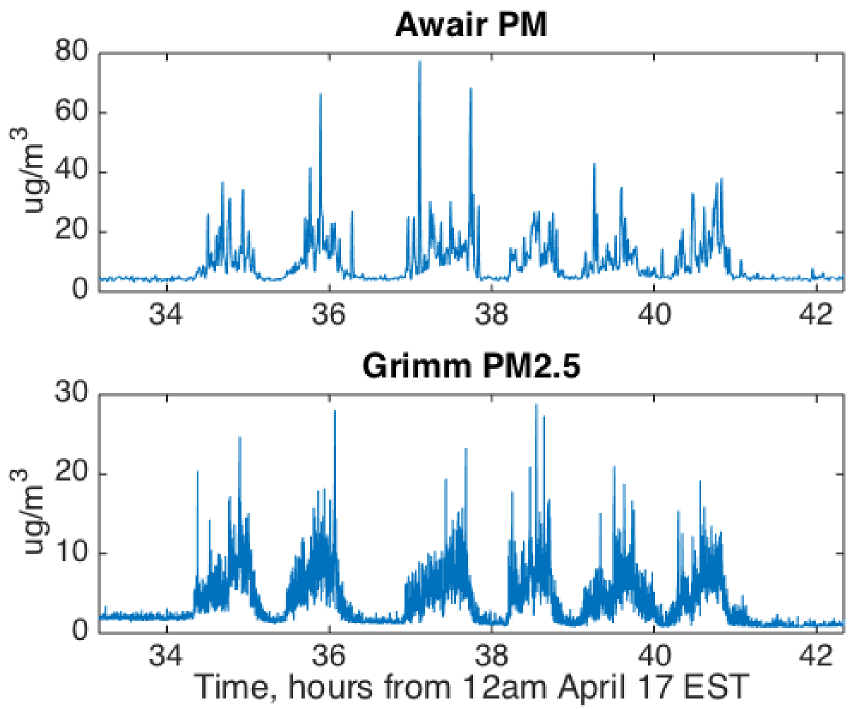

Figure 5.19: Awair vs. Grimm particle concentration, 9-hour interval

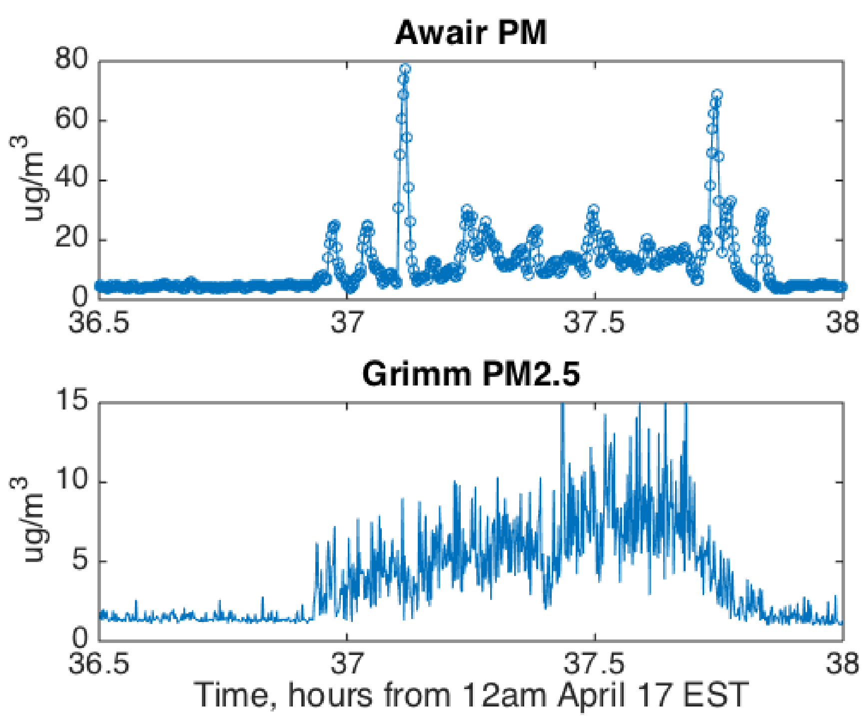

Figure 5.20: Awair vs. Grimm particle concentration, 1.5-hour interval

5.4.5 Foobot

The Foobot samples once every five minutes. While the general shape of the major air quality events is preserved, some detail in the signal is lost due to the long sampling period. Over the 1.5 hour window, the Foobot's $PM_{2.5}$ correlation is $r^2 = 0.89$, with an error of approximately 9.5 $\mu g/m^3$.

The correlation over the entire 55 hour experiment is significantly lower at $r^2 = 0.28$. The Foobot app advertises an ability to be able to learn from its measurements to improve accuracy. This may be one of the reasons for the baseline shift seen between the first and second days. The device was powered on for several days prior to the experiment and noticed several such shifts in baseline air quality that were not indicated by the Grimm or other tested monitors. The abrupt change that falls within the experiment window has adversely affected the Foobots correlation value with the Grimm EDM 180 over the full period of the experiment. It is unclear from our testing if these shifts eventually cease or become less prevalent.

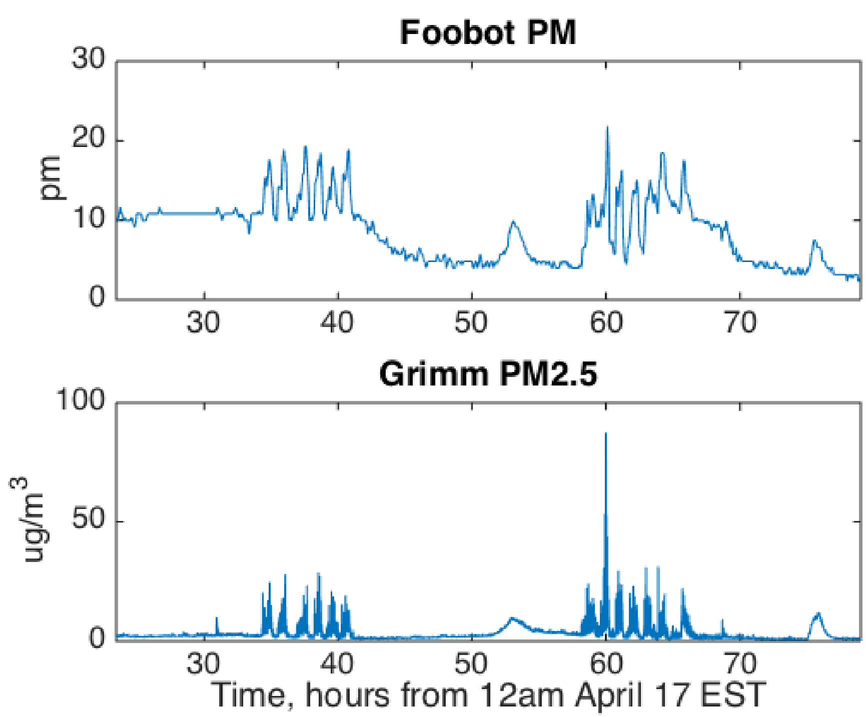

Figure 5.21: Foobot vs. Grimm particle concentration, 55-hour interval

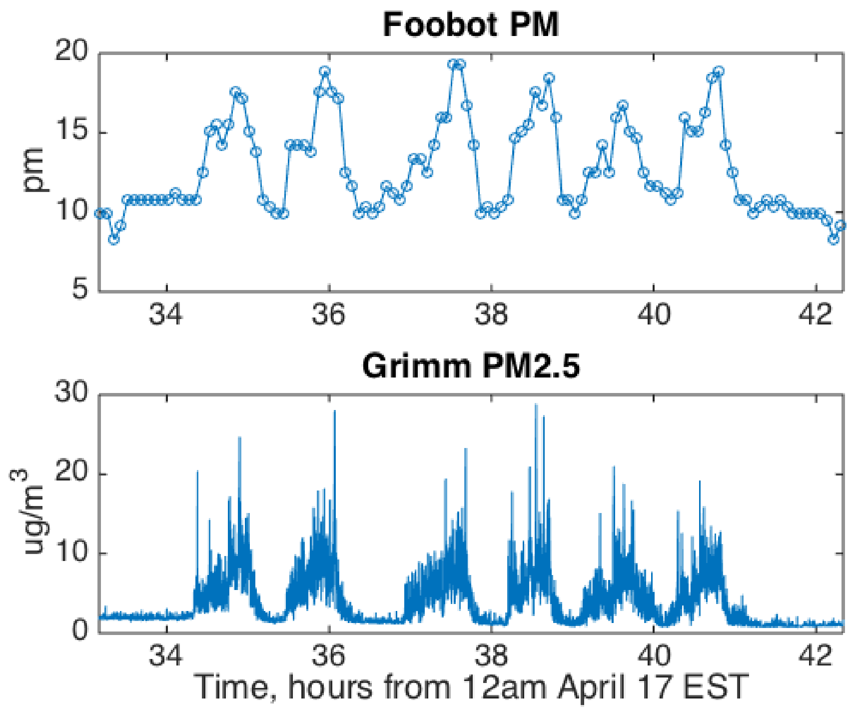

Figure 5.22: Foobot vs. Grimm particle concentration, 9-hour interval

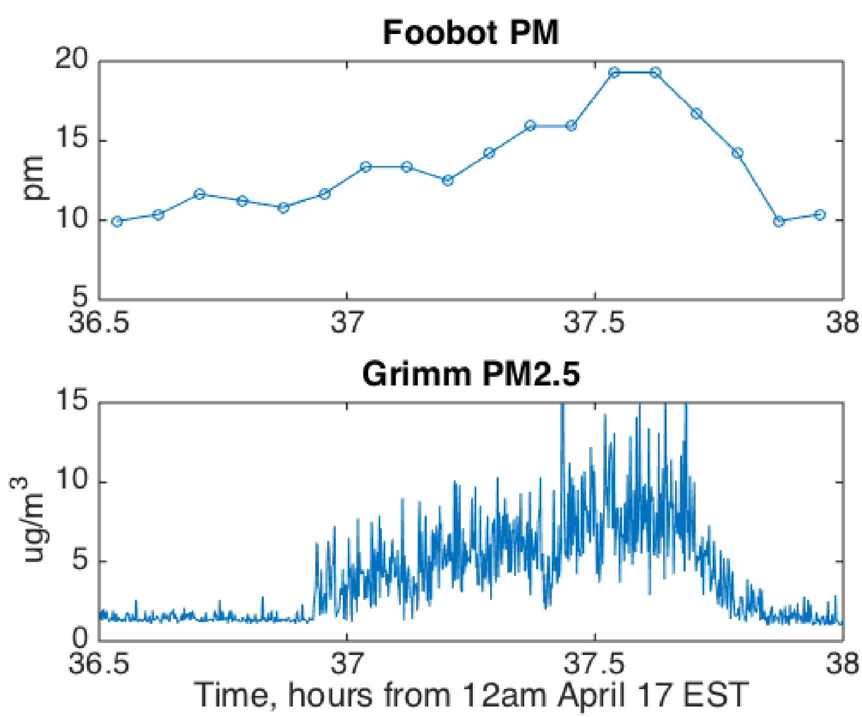

Figure 5.23: Foobot vs. Grimm particle concentration, 1.5-hour interval

5.4.6 Blueair Aware

The BlueAir Aware uses the same technology and hardware as the Foobot. Like the Foobot, the BlueAir samples once every five minutes. The BlueAir's $PM_{2.5}$ correlation is relatively high ($r^2 = 0.46$), partly because the BlueAir unit reads zero particulates outside of the main particle events, thus constituting a noiseless signal. There are only a small number of non-zero datapoints, which qualitatively may not be enough for a user to understand the shape of an air quality event.

Given the similarities in hardware, we would expect the BlueAir to closely mimic the performance of the Foobot. Instead, we observe that the $PM_{2.5}$ measurement from the BlueAir unit never exceeds 4 $\mu g/m^3$, generating an underestimation of approximately 4.6 $\mu g/m^3$. We believe this unit to be faulty, as it provides no usable non-zero datapoints outside of high particulate events. BlueAir engineers we spoke with have confirmed that this behavior is unexpected.

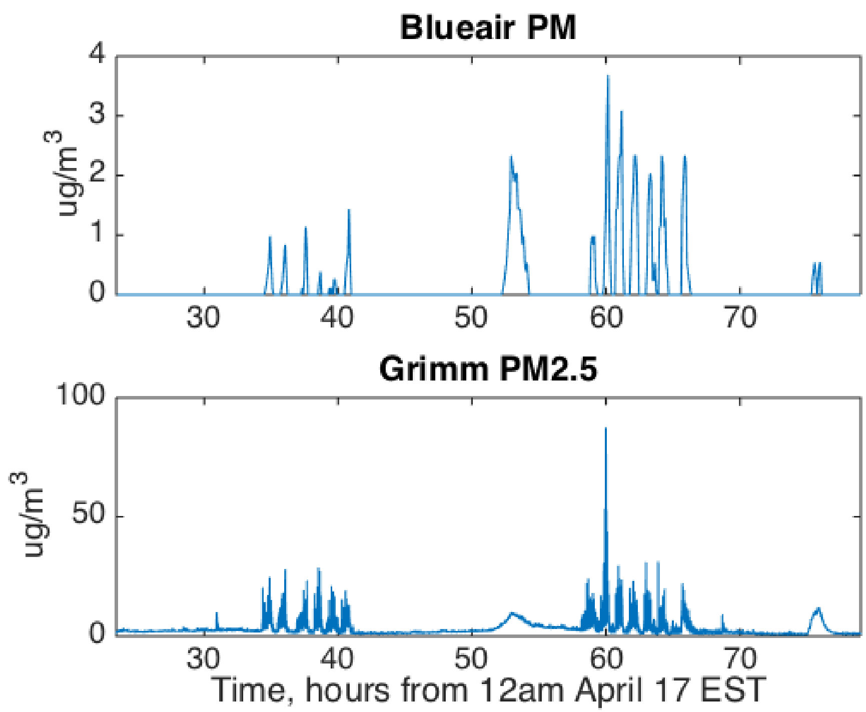

Figure 5.24: Blueair Aware vs. Grimm particle concentration, 55-hour interval

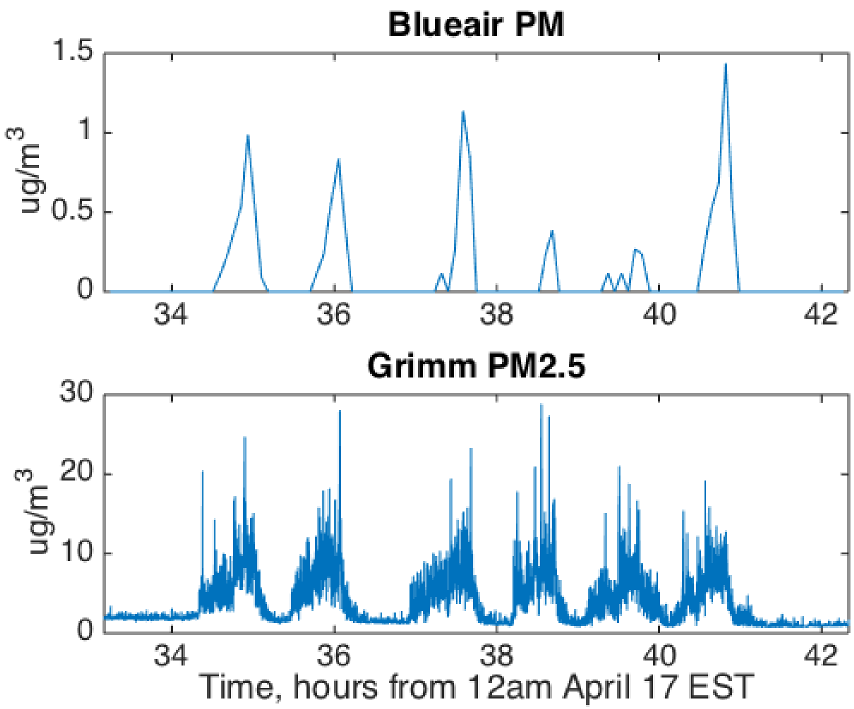

Figure 5.25: Blueair Aware vs. Grimm particle concentration, 9-hour interval

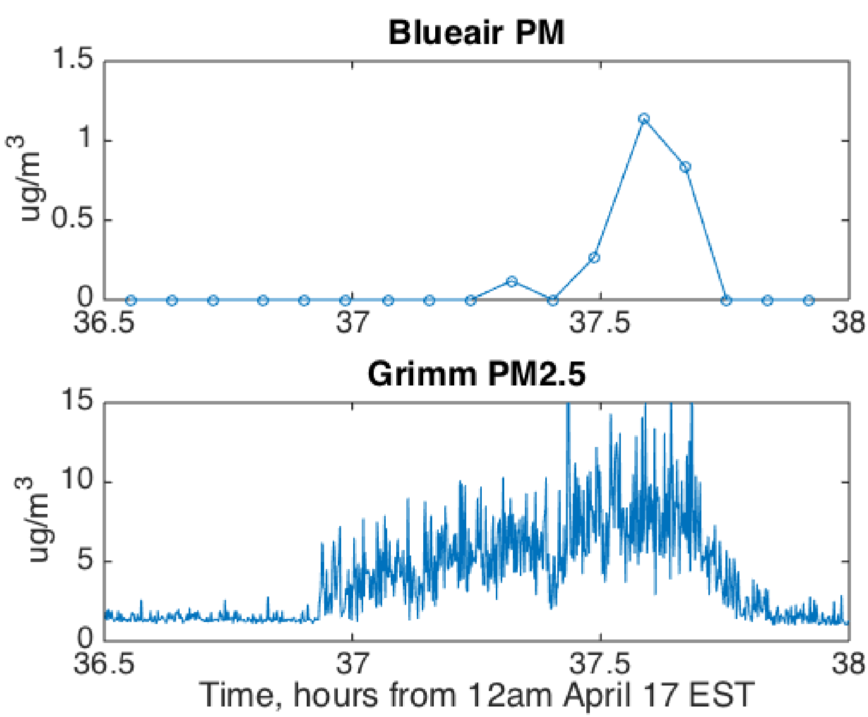

Figure 5.26: Blueair Aware vs. Grimm particle concentration, 1.5-hour interval

5.4.7 Dylos

The Dylos is unique in that it only reports particle counts rather than mass, so we compare it against the count of all particles of size 2.5 microns and below. The small particle count channel on the Dylos reacts very strongly to the event that occurs between 50 and 55 hours, and otherwise conforms to the shape of the air quality events created during testing. The Dylos exhibits a correlation of $r^2 = 0.34$ over the 1.5 hour window, which may be lower due to the decline of the Dylos measurement several minutes before the decline of the reference measurement. Over the full 55 hour period, the correlation is higher ($r^2 = 0.74$).

The Dylos particle count and Grimm particle count values differ by an order of magnitude, likely because the Dylos cannot detect the very large number of particles measured by the smallest size channels of the reference instrument. The Dylos particle count number likely corresponds to slightly different range of particles, hence the lower values. Because of the difference in units, this error cannot be compared to the previously described instruments in this experiment.

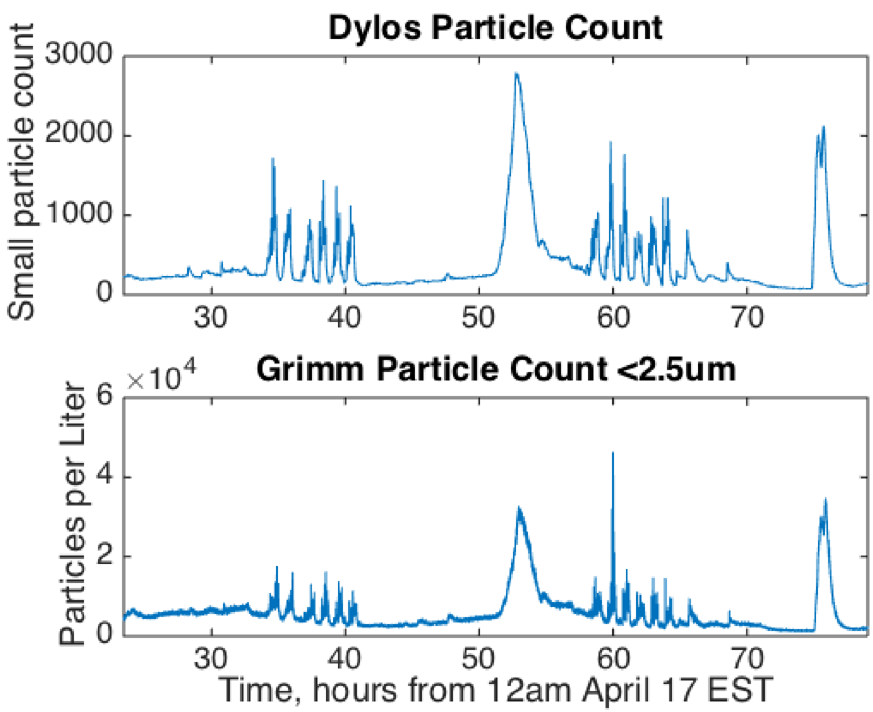

Figure 5.27: Dylos vs. Grimm particle count, 55-hour interval

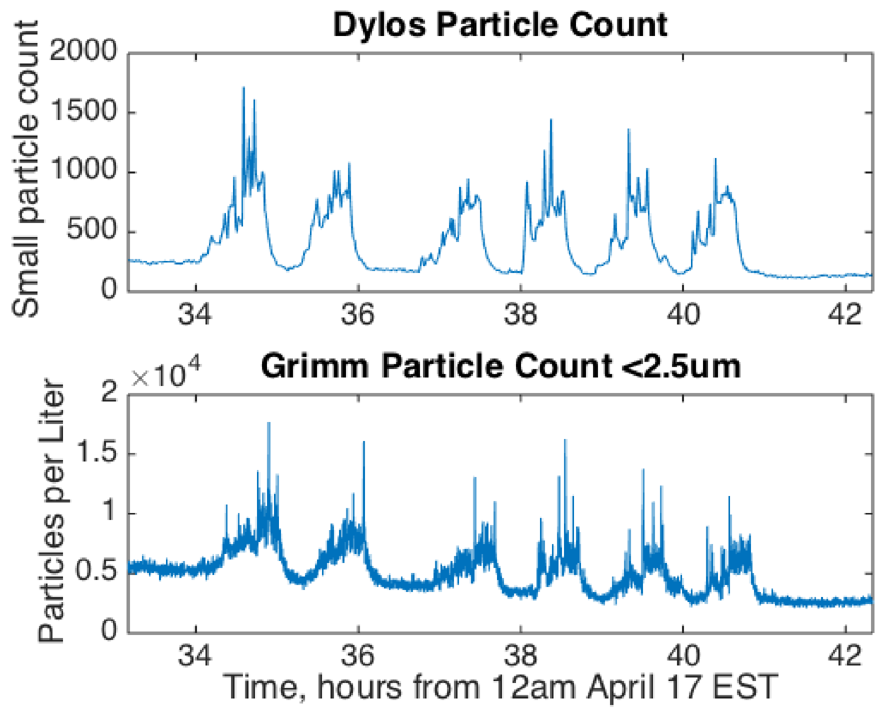

Figure 5.28: Dylos vs. Grimm particle count, 9-hour interval

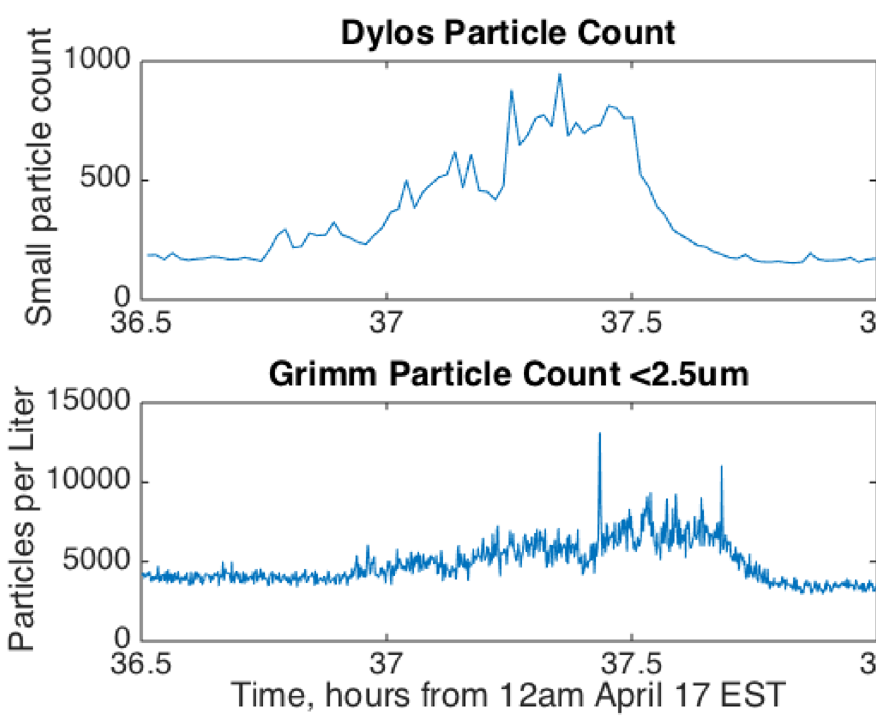

Figure 5.29: Dylos vs. Grimm particle count, 1.5-hour interval

5.4.8 Summarized Results

The following two tables 5.1 and 5.2 present the correlation and accuracy of the monitors tested in this experiment. Note that the test window strongly affects correlation based on the inclusion or exclusion of certain air quality events. Note also that the Dylos is excluded from table 5.2 as there are no comparable channels.

Table 5.1: Correlation values between monitors and reference instrument

		Correlation (r^2)		
Device	**Sampling Interval (s)**	**1.5 Hr Period**	**9 Hr Period**	**55 Hr Period**
Speck	60	**0.89**	**0.84**	0.50
AQEgg	5	0.07	0.23	0.28
Awair	10	0.13	0.29	0.29
Foobot	300	**0.89**	**0.88**	0.28
BlueAir	300	0.46	0.47	0.56
Dylos	59	0.34	0.26	**0.74**

Table 5.2: RMS mass error between monitors and reference instrument (Dylos excluded)

		RMS Error ($\mu g/m^3$)		
Device	**Sampling Interval (s)**	**1.5 Hr Period**	**9 Hr Period**	**55 Hr Period**
Speck	60	18.4	17.1	11.7
AQEgg	5	**4.6**	**4.5**	**3.8**
Awair	10	11.9	8.4	5.6
Foobot	300	9.5	9.0	6.4
BlueAir	300	**4.6**	**4.5**	**3.6**

Chapter 6

Assessment of Low Cost Air Quality Monitors and Empowerment

6.1 Introduction

Related works have established the significant health risks posed by air pollution (See Chapters 1 and 2). Controlling outdoor air quality is a significant challenge requiring regulatory changes, which can take years to accomplish. Air quality in residences, however, can be managed by individuals given sufficient knowledge and resources. In order to take action, individuals need to able to make the connection between their activities and lifestyle choices, and changes in $PM_{2.5}$ concentration levels indoors. With this insight, people may be empowered to take steps to improve the air they breathe. The value of providing people with this type of information has purportedly been observed across a wide range of domains [15], however the small sample size of some of these studies calls into question the real world efficacy of providing personalized feedback [25]. In this chapter, we assess the effectiveness of a low-cost portable indoor air quality monitor for indoor particulate matter with respect to empowering people to learn about and reduce their risk of indoor air pollution.

Pittsburgh has historically experienced high levels of air pollution stemming from coal mining and other industrial activities [22]. Despite industrial decline and efforts to regulate remaining pollution sources, there are still many invisible and visible particles contaminating the city [18]. According to a 2012 report from the Pennsylvania Department of Health, among Pennsylvania's 67 counties, Allegheny County had the 6th highest number of emergency-room visits caused by asthma (21 visits per 10,000 residents) [40]. Moreover, during 2006-2010, over 95 percent of all patients in Allegheny County admitted into hospitals through the ER were among children, where asthma was the primary discharge diagnosis [29]. Also, during the 2008-09 school year, 12.1% of Allegheny County students were reportedly diagnosed with asthma. In addition to individual health risks, this phenomenon causes significant economic impact for the community, with each asthma-related hospital stay (from 2008-10) costing over \$20,000, on average [29]. In a 2013 report, RAND estimated significant economic value associated with improved health within a scenario where Pittsburghs ozone and $PM_{2.5}$ levels are in compliance with National Ambient Air Quality Standards (NAAQS) [28]. In particular, RAND found that reducing the city's 2012 levels of $PM_{2.5}$ concentrations to meet NAAQS would be associated with an approximate economic value of $488 million. These findings were driven primarily by reductions in premature mortality among residents, and provide evidence that there may be considerable economic benefits associated with reducing or removing indoor $PM_{2.5}$ pollutants.

6.2 Pilot Study

6.2.1 Overview

Prior to the commercial release of the Speck, we conducted a pilot study to explore whether and how a low-cost particulate monitor can empower a community of users to improve the air they breathe. We provided a self-selecting sample of Pittsburgh residents with a prototype Speck air quality monitor along with supporting material, and monitored how using this device affected their perspectives and behaviors. We hypothesized that, given a sufficient support structure, typical citizens can gain the knowledge and confidence they need to investigate, discover and take action to mitigate air quality problems in their homes.

A secondary objective of this study was to discover the usability and utility of the Speck and associated support material, from the perspective of end users. Research participants were asked to rate the device and supporting material twice during the study period, so as to capture their feedback at varying stages of use.

6.2.2 Experimental Methods

Supporting Material

Based on feedback received during prior prototype testing, we concluded that typical users of home air quality monitors also require a support structure to help guide their process of discovery and action. Typical questions asked were related to what actions to take upon discovery of high levels of particulate matter in the home. While there is no single answer to this question, there are a few steps people can take as they investigate sources of and solutions to their air quality issues. Through this study, we wanted to understand which modes (or collection of modes) were most effective for conveying this type of information to the community of Speck users. We designed print material in the form of a Speck setup guide as well as a Speck website [4] to test with research participants. These media contained instructions for how to use the Speck, along with guidance on recognizing pollution sources and experimenting to uncover ways to resolve air quality problems.

In addition, it was important to design a platform through which individual Speck users could connect with others in their community (as well as researchers) to discuss air quality problems and brainstorm solutions collectively. To leverage the popularity of existing social media frameworks, we created a private Facebook page where study participants could interact with one another about their experiences with the Speck. Joining the Facebook group was an optional aspect of participation in the study, and we ensured that only participants and researchers had access to this page.

Community Selection

The target audience for this study was people in the Pittsburgh region who had some interest in learning more about their air quality. A total of 47 participants were recruited through the research groups network of local community partners. Email solicitations were sent out to individuals and community groups, who in turn passed on the call for research participants to their contacts via email and social media.

Interested individuals met in person with researchers to receive an overview of the study, provide consent to participate (if willing), and pick up their Speck. The majority of consenting participants were white females, who were approximately 25 to 50 years old. This study was approved by Carnegie Mellon University's Institutional Review Board, and accordingly, we followed appropriate protocol during the course of the study.

Data Collection and Analysis

Each participant received a Speck to use in their home for 2 to 3 weeks, and was asked to complete a total of 3 surveys. The first survey was administered before participants received the Speck to gauge their baseline level of knowledge about indoor air quality. About a week after picking up their Speck, participants received a second survey to inquire about their experiences to-date. When it was time to return their Speck, participants completed a final survey to provide their overall feedback about the Speck and supporting material, describe what they learned from the study, and share any relevant personal stories.

In addition to survey data, we also captured discussions and posts that occurred on the participant Facebook page. These anecdotes provided valuable insight into how participants used their Speck, the discoveries they made, actions they took, and air quality conversations that were sparked by the Speck. This social media platform was also useful for participants to pose questions about the Speck and its applications, which could be answered by researchers as well as other participants. Thus, the Facebook group served as a virtual community meeting place where participants could discuss their air quality findings and concerns, as well as share knowledge and ideas with each other.

Findings from this study were primarily qualitative and anecdotal. As such, survey results and Facebook posts were qualitatively examined to detect data trends and common themes in participant responses. In addition, participant quotes were compiled to create a storyboard of user experiences and feedback.

6.2.3 Results and Discussion

Speck Assessment

All participants found the Speck easy to install and use, and most (77%) agreed that the monitor met their expectations [16]. When asked to describe their overall experience with the monitor, the majority indicated that it was informative and/or useful (Table 1). The

Table 6.1: Participant perspectives on their overall experience using the Speck Air Quality Monitor. (* Participants could select more than one rating) (** This percentage is based on the total number of survey respondents (47))

Overall User Experience Rating	Number of Responses*	% of Responses**
Enjoyable	20	43%
Useful	29	62%
Informative	39	83%
Challenging	0	0%
Confusing	5	11%
Frustrating	5	11%
Other	11	23%

chief complaint was the level of noise caused by the fan in the device; this is reflected in the "Other" category.

The most popular locations for in-home Speck placement were the kitchen, bedrooms and living room, and on average, most participants left the monitor in each location for 1 to 6 days. Participants made note of their Speck reading multiple times a day, with the majority (62%) looking at the screen each time they walked into the room the Speck was in.

In terms of the hardware, participants were mostly happy with the Speck, but would have liked to see an even smaller and more portable design (including a battery pack), and longer USB cable to connect to the power supply. Some respondents also requested a better option for securing the Speck to a surface (with added weight or foot grips) so it wouldnt slide off as easily.

Apart from including a quieter fan and more robust micro-USB port, participants were primarily interested in Speck modifications that would allow them to:

- Receive alerts about significant changes in air quality; the majority wanted the alert to be in the form of a blinking light (43%) or text message (26%)
- Personalize Speck settings to be able to choose when they get alerts, alter the types of historical views that are displayed, change the color coding, etc.
- Connect to their device through a mobile phone app
- Download their data and run independent analyses on it

Overall, the Speck design and functionality were satisfactory to participants, who found the device to be a useful addition to their homes. Note that the data download feature was already implemented. However, given that participants would only have the Speck for a short time, we did not include training on how to utilize this feature as part of this small-scale study.

Perception and Behavioral Impact

Based on pre and post data from participants, we found that 53% had a different perception of their in-home air quality after using the Speck. This suggests that the use of Speck can promote greater awareness about a persons indoor environment; making the invisible particles more visible to users. Additionally, 55% of participants reported an increased level of confidence in their ability to act when the air quality is poor in their homes, hinting at a sense of empowerment among this group of users. At the end of the study, when asked if the Speck helped them feel empowered to understand and manage their air quality, 72% of participants responded positively. This provided further evidence of the Specks potential to motivate and support citizens to become more aware of their home environment and take action to improve their air quality. While the Speck was in their possession, several participants reported that they:

- Became more aware of how cooking affected air quality, and/or altered cooking habits (e.g. turning on stove vents, frying less, etc.) to mitigate these effects
- Gained a better understanding of how cleaning affected air quality, experimented with different cleaning methods, and in general cleaned more often or thoroughly
- Experimented with opening and closing windows and discovered more about how those actions impacts air quality differently
- Changed or cleaned air filters
- Added air purifiers to their homes

Thus, participants were able to gain useful insight from using the Speck, and were thereby motivated to take explicit steps to improve their air quality.

Effectiveness of Supporting Material

A notable aspect of this study was its pairing with supporting material and a social media platform for Speck users. Most participants (87%) indicated that the setup guide was useful. On the other hand, 39% of participants never visited the Speck website to obtain further tips and information. Findings highlighted that the Speck website may need to be reconfigured and supplemented (e.g. through workshops, instructional videos, step-by-step instructions, etc.) in order to improve user engagement and overall effectiveness.

The Facebook group, on the other hand, proved to be very actively utilized. 77% of participants joined the group, and 72% reported that they found it useful to connect with other users through this social media outlet. These results indicated that a community forum can enhance an individuals experience, and produce a broader body of shared knowledge and ideas. A key component missing from these community interactions was input from air quality, health and other relevant experts who could potentially further enrich the impact and utility of such forums. In particular, if policy-level decision makers are included in the conversation, these community interactions could have longer-term impact on achieving better air quality for all citizens.

Participant Quotes

Overall, results from this pilot study were encouraging and support the notion that the Speck could serve as a tool to empower a community of users to rally around common issues related to air quality. A few noteworthy examples of participant comments that further bolster this idea are given below:

- *My husband and son have asthma and the Speck has been very informative about why their symptoms are worse at night. The readings in the bedrooms are much higher vs the front of the house. Appreciate the tips to improve the air quality and on the lookout for more.*
- *Vacuuming my hardwood floor made it spike from mid 20s to an unhealthy 67 in seconds. Guess I should use a mask while cleaning, seriously.*
- *Very excited to be testing the Speck. First day with it we turned on the broiler. Dangerous levels! Woah.*
- *I really like the speck... I am putting in it my bedroom tonight to see what the readings are. My daughter has been keeping detailed notes in the notebook :)*
- *I absolutely love being able to measure the air quality of what I'm breathing in- it's a very empowering tool.*
- *Its been fun watching the reading [on the Speck] go up and down in response to predictable stimuli. For example, the reading shot up very quickly when a guest lit a cigarette.*
- *I think these [Specks] will be super useful to many, many people in the future (like asthmatics like myself)...*
- *I have learned a surprising amount about my home and work environment and have found solutions to problems. I'm breathing easier!*
- *Mostly the Speck has been fun to have and has certainly been the topic of conversation whenever someone sees it for the first time - so it has been good at initiating conversations about air quality - which is a good thing in my opinion :-)*
- *I think this [the Speck] is going to a very popular and empowering tool (just imagine this being used worldwide!)*
- *I really liked the speck. My whole family participated in following it.*
- *I found myself checking the display each time I walked past. It was a useful and interesting data point about our lives that had not been revealed before.*
- *Overall, it was a good experience. Not hard to set up, easy to monitor and it gave me a sense of relief to know that the air in my home was basically good as I live near a coke plant that exceeds particulate emission standards many days a year!*
- *The biggest surprises were how different household activities affected the readings. I had thought opening the windows would freshen the air - not so!... The [Speck] study opened our eyes to all of the ways that we could improve and control the air quality in our home. Fantastic information!*

Limitations

While findings from this study did offer useful insight to support our proof of concept, certain aspects of the study design limited the extent to which results could be generalized. A primary drawback was that participants opted into the study and thereby were not a representative sample of the larger Pittsburgh population. In particular, people of color and individuals from lower socio-economic backgrounds were under-represented in or absent from our sample, who are potentially more likely to experience and be vulnerable to impacts of poor air quality in their homes.

Additionally, the timing of participation was not consistent across all individuals, given their varying schedules and availability. As such, participation in the social media conversation occurred in phases, with the majority of contributions coming from the first and largest group of participants. Therefore, latter groups had a less impactful experience given lower participation rates during their phase of the study. Coupled with this was the short term nature of the project, which did not allow much time for participants to explore and discuss air quality topics in a deeper and more impactful manner. Longer-term studies would be needed to examine this type of interaction.

Finally, data collection methods were limited to surveys alone, which did not allow for more in-depth conversations with participants. Such approaches could have enriched our data and provided further insight into how such technology should be deployed to empower communities of users.

6.3 Pittsburgh Air Quality: Empowerment Lending Library

6.3.1 Introduction

The previous pilot study provided some insight into the potential value of low-cost air quality monitors to individuals, but due to the small sample size and significant potential for improvement regarding the assessment methods, we conducted a second study utilizing a newly-created lending library for the Speck monitor through the Carnegie public library system. While participants were still self-selected for this study, we hoped that distribution through multiple library systems would widen the demographic audience and increase the sample size of the experiment. Any Carnegie library card holder was allowed to check out a Speck fine particulate monitor free of charge and free of obligation to participate in the study. The lending library program has expanded since this research, as described at the end of this chapter. For this study, we formulated two primary research questions:

1. Does using Specks affect knowledge, perceptions and intentions regarding indoor air quality?

2. What factors are associated with knowledge and perceptions about indoor air quality?

6.3.2 Survey Protocol

When checking the Speck air monitor out of the library (Figure 2), participants were asked whether they would be interested in taking a brief survey on their views of air pollution. Of the people who checked out the Speck monitor between October 29th 2015 and May 8th 2016, 62 elected to take the initial survey. Participants electing to take the survey were asked what library location they are using, whether they have used the Speck before, and if they are checking out or returning the Speck monitor. Note that we excluded people who were returning the Speck monitor at the beginning of our study since we were interested in obtaining baseline views on indoor air pollution.

Surveys were collected using a tablet located at or near the library check-out desk. After a brief introduction to the study, participants were screened for being age 18 years or older, asked for their email address should they be interested in being entered to win 1 of 5 Speck air monitors, and for the last 6 digits of their library card number in order to link their survey to their follow-survey. Participants then took approximately 5-10 minutes to answer a series of questions related to their knowledge of indoor air pollution, health consequences of this pollution, personal risk, sources of risk in general, self-efficacy with respect to reduce risks, effective mitigation measures, measures taken or intended to take to mitigate risk, an assessment of empowerment and creativity, and basic demographic questions.

Upon returning the Speck monitor, participants were asked whether they would like to take a brief 5-10 minute follow-up survey. Participants then answered the same set of questions as before, with the addition of several questions regarding their opinions of the Speck monitor. Of the 62 people who completed the first survey, 25 completed the second. On average, participants who completed both surveys checked out the Speck monitor for 8.6 weeks (with a range of 2 days to 14.1 weeks). In this study, we included only those participants who completed both the first and the second survey.

6.3.3 Variables

- **Knowledge:** Knowledge of air pollution was assessed by asking, “How much do you know about air quality?” where 1=none and 5=everything.
- **Health:** The degree of perceived health consequences were assessed by asking, “Do you think air quality can cause or make worse the following issues?” Participants were encouraged to check all of the potential issues from a list, which included asthma and other respiratory illnesses, heart disease, diabetes, lung cancer, stroke, epilepsy, allergic responses, and other that they think applies. For our analyses, we summed the number of perceived consequences where higher counts indicated greater severity of perceived health consequences.
- **Personal risk:** Perceived personal risk with respect to indoor air quality was assessed by asking participants, “On average, how would you rate the air quality in your home?” where 1=very poor and 5=very good. For our analyses, responses were reverse coded so 1=very good and 5=very poor.

- **Objective risk:** Estimated personal exposure risk was assessed using data from textbfsource. The only location information we gathered from our participants was their zip codes, so we use average daily $PM_{2.5}$ exposure for each zip code as an estimate of the risk posed by external fine particulate matter sources.
- **Risk:** Perceived sources of indoor air pollution risks were assessed by asking, "What do you think are some of the sources of pollution inside your home?" Participants were encouraged to check all of the potential sources from a list, which included cooking, vacuuming, smoking, microwave oven, gas heating, fireplace, open windows, insulation, pets, refrigerator, and other that they think applies. For our analyses, we summed the number of perceived sources where a higher count indicates greater severity of perceived risk.
- **Self-efficacy:** Self-efficacy with respect to mitigating personal risk was assessed by asking, "How confident are you that you will know what actions to take if you learned that your indoor air quality was poor?" where 1=not at all confident and 5=extremely confident.
- **Mitigation:** Perceived effective ways to mitigate risk were assessed by asking, "What do you think are effective ways to reduce your exposure to indoor air pollution?" Participants were encouraged to check all effective ways from a list, which included installing a range hood, opening windows, closing windows, installing an air purifier, changing air filters, cleaning the house, smoking outside instead of inside, installing an air quality monitor, cleaning air filters, and other that they applies. For our analyses, we summed the number of perceived sources where a higher count indicates a greater number of effective ways to reduce risk.
- **Intention to mitigate risks:** Intent to take measures to reduce personal risk was assessed by asking participants, "In the past 3 months, have you made any changes in your home to improve the air quality?" where 1=yes, I have, 2=not yet, but I plan to, and 3=no, I have not and dont plan to.
- **Empowerment:** We used the Rogers et al. (1997) empowerment scale that includes five constructs: self-esteem-self-efficacy, power-powerlessness, community activism and autonomy, optimism and control over the future, and righteous anger. Participants indicated their agreement where 1=strongly disagree and 5=strongly agree on 9 statements related to self-esteem-self-efficacy, such as "I generally accomplish what I set out to do" (Cronbach's α =.90), 7 statements related to power-powerlessness, such as "I feel powerless most of the time" (Cronbach's α =.62), 6 statements related to community activism and autonomy, such as "People have a right to make their own decisions, even if they are bad ones" (Cronbach's α =.71), 4 statements related to optimism and control over the future, such as "People are limited only by what they think is possible" (Cronbach's α =.66), and 4 statements related to righteous anger, such as "Getting angry about something is often the first step toward changing it" (Cronbach's α =.62). We created an overall measure of empowerment by taking the mean of all 27 items (Cronbach's α =.86).
- **Innovativeness:** We used Kirtons short (1976) Adaptation-Innovation Inventory

where people rated their agreement (1=strongly disagree, 5=strongly agree) with how statements described themselves such as "When involved in a project, I forget that other people are involved and should be consulted" and "Solutions sought by tried and true methods." We created an overall measure of innovativeness by taking the mean of all 9 items (Cronbach's α =.55).

- **Demographics:** Participants were asked about their highest level of education, political affiliation, age, gender, number of children (ages 0 to 5 and 0 to18) if any, the number of co-habitating adults over the age of 65 if any, and income bracket.
- **Views on Speck monitor:** Returning participants were asked in the second survey how much they agree with statements such as "The Speck monitor helped me learn about indoor air pollution in my home" on a scale from 1=strongly disgree to 5=strongly agree.

6.3.4 Borrowing the Speck Monitor

We recruited 62 Pittsburgh library patrons who reported being, on average, 46.0 years old (SD=15.6), 45.2% male, 75.4% have at least a college degree, and 65.5% have an annual income of $51k or greater. With respect to political affiliation, 35.9% reported being a democrat, 4.9% republican, 24.6% independent, 9.8% other, and 14.8% who preferred to not respond. Nearly one-quarter (23.5%) reported having at least one child, with 45.8% of those children being younger than 5 years old. Fewer households (9.8%) had an adult who was over the age of 65 years old living at home. Nearly three-quarters (73.8%) do not suffer from a respiratory illness, with 21.3% reporting that they do and with 4.9% preferring not to answer. Most people learned about the Specks monitor from their local librarian (26.3%) followed by some other source (22.2%), a flyer (16.3%), social media (8.1%), a friend or family member (3%), and/or community meeting (1%).

6.3.5 Returning the Speck Monitor

In all, 25 library patrons elected to take the follow-up survey upon returning the Specks air quality monitor. These patrons reported being, on average, 45.4 years old (SD=14.2), 40.0% male, 74.0% have at least a college degree, and 60.0% have an annual income of $51k or greater. With respect to political affiliation, 40.0% reported being a democrat, 4.0% republican, 40.0% independent, 12.0% other, and 4.0% who preferred to not respond. Many (38.4%) reported having at least one child, with 38.5% of those children being younger than 5 years old. Fewer households (8.0%) had an adult who was over the age of 65 years old living at home. Nearly all (88.0%) do not suffer from a respiratory illness, with 12.0% reporting that they do. Most people learned about the Specks monitor from their local librarian (50.0%) followed by some other source (34.6%), a flyer (19.2%), and/or social media (7.7%). All analyses reported in the results section are for those patrons who completed both surveys.

6.3.6 Results

Does using Specks affect knowledge, perceptions and intentions regarding indoor air quality?

As shown in Tables 6.2 and 6.3, repeated-measures analysis of variance (ANOVA) revealed that people reported knowing more about indoor air quality after using the Speck monitor (M=2.77, SD=0.71) than they did before (M=2.38, SD=0.75), F(1, 24)=6.79, p=0.02, η^2=0.21. They were better able to identify health risks associated with indoor air pollution after using Specks (M=5.96, SD=1.99) than before (M=5.65, SD=1.67), F(1, 24)=4.39, p=0.05, η^2=0.15. Indeed, they also saw their personal risk with respect to indoor air pollution as being higher after using Specks (M=2.31, SD=0.62) than before (M=2.04, SD=.77), F(1, 24)=4.24, p=0.05, η^2=0.15. Despite these heightened risk perceptions, people importantly felt more confident that they could do something should they learn their indoor air quality was poor after using Specks (M=2.62, SD=0.94) than they did before, F(1, 24)=3.51, p=0.07, η^2=0.12. However, participants did not feel particularly concerned about their indoor air quality as McNemars test revealed no difference in reported intention to mitigate risk after using the Specks monitor (p=0.22).

What factors are associated with knowledge and perceptions about indoor air quality?

As shown in Table 6.6, as self-reported knowledge increased so did confidence in ability to mitigate risk (r=0.52, p<0.01) and objective risk of exposure to $PM_{2.5}$ (r=0.42, p<0.05). People who reported a greater number of ill health consequences from indoor air pollution were also those who were at greater objective risk of exposure to $PM_{2.5}$ (r=0.49, p<0.05), knew more about ways to mitigate risk (r=0.39), and were also those who felt empowered, motivated by a sense of anger, to take action (r=0.46, p<0.05). Those who knew more about ways to mitigate risk were also those rated high on community activism and autonomy (r=0.59, p<0.01), as well as optimism and belief that they can control their future (r=.45, p<.05). Perhaps unsurprisingly, those who were at most objective risk for exposure to $PM_{2.5}$ were also those who had lower household incomes (r=-0.42, p<0.05). Note that in general, these relationship tend to hold before using the Speck monitor, as seen in Table 6.5.

Typically, those who reported they learned something from using the Speck monitor said they reduced indoor air pollution, recommended the Speck monitor to friends and family, and saw the readings from the monitor as accurate were also those who were more knowledgeable and confident in ability to mitigate risk in general.

6.3.7 Conclusions

Our results suggest that use of the low cost fine particulate monitor affects knowledge, perception, and intentions regarding air quality. Users report a higher level of knowledge after using the Speck, and also report higher perceived risk than before use. Users also feel more capable of influencing their personal air quality, but remain only marginally

Table 6.2: Summary of descriptive statistics for indoor air quality

	Before (all)		Before (subset)		After (subset)	
Variables	Mean	SD	Mean	SD	Mean	SD
Indoor air quality knowledge and self-efficacy						
Knowledge	2.6	0.85	2.38	0.75	2.77	0.71
Self-efficacy	2.45	1.1	2.31	1.01	2.62	0.94
Magnitude and impacts						
Risk	3.86	2	4.15	1.01	4.08	1.55
Health	3.91	2.06	3.88	1.53	4.62	1.63
Personal risk	3.1	0.71	2.04	0.77	2.31	0.62
Mitigation	5.36	2.58	5.65	1.67	5.96	1.99
	Frequency	Percent	Frequency	Percent	Frequency	Percent
Intention to mitigate risk						
Yes, I have or Not yet, but I plan to	42	65.6	12	53.8	16	61.5
No, I have not and don't plan to	22	34.4	14	46.2	10	38.5

Table 6.3: Repeated measures analysis of variance comparing variables of interest before and after using a Speck monitor (* denotes relationship of interest)

Variables	F-statistic	p-value	partial eta
Indoor air quality knowledge and self-efficacy			
Knowledge	6.79	0.02	0.21*
Self-efficacy	3.51	0.07	0.12*
Magnitude and impacts			
Risk	0.06	0.81	0
Health	4.39	0.05	0.15*
Personal risk	4.24	0.05	0.15*
Mitigation	0.7	0.41	0.03

concerned about these risks and do not express stronger intentions to mitigate elevated levels of pollution. Greater knowledge and a motivation to take action are linked to those users who self-report air quality related health effects and those who are motivated by a sense of anger.

Our data suggest that air quality is not a major concern for most of the participants of this study who do not currently experience air quality related health effects. This may be because air quality is not a frequent conversation topic due to knowledge disparity and the difficulty in effecting regional change. Participants interviewed expressed a level of curiosity regarding air quality, however, and enjoyed taking instantaneous readings from the Speck when it was placed in an easily accessible location.

We are very interested to learn what effects more prolonged use of the Speck may be present regarding perception, knowledge, and action. The period of use in this study seemed sufficient for users to gain a baseline understanding and intuition of their indoor air quality and what actions improve or exacerbate particulate levels. This period seemed too short for users to gain an understanding of the health effects they may be experiencing during periods of elevated pollution.

Participants also reported a desire for additional sensing capabilities regarding specific groups of pollutants such as VOCs. While the implementation of low-cost and reliable air quality sensors for speciation is very difficult, the results of this study provides significant motivation for pursuing this challenge.

6.4 Expansion of the Library Program

Through our research as well as from individual feedback, we strongly believe that low-cost fine particulate monitors foster increased knowledge about air pollution, related health risks, and mitigation strategies. We have continually expanded our distribution of Speck monitors through public library systems and currently serve more than 30 library programs throughout the United States. We are currently working to fulfill a waitlist for additional programs. Each library is provided with three Speck monitors free of charge in addition to printed materials including informational flyers and comment cards to solicit feedback

Table 6.4: Correlation of variables of interest with measures of individual difference and key demographics **before using a Speck monitor** (all participants) (* denotes relationship of interest)

	Knowledge	Self-efficacy	Risk	Health	Personal risk	Objective risk	Mitigation	Innovativeness	Self-esteem/Self-efficacy	Power/powerlessness	Community activitism/Autonomy	Optimism/Control future	Righteous anger	Age	Children under 5	Adults over 65	Education	Income
Knowledge																		
Self-efficacy	0.26*																	
Risk	-0.22	0																
Health	0.12	0.18	0.54*															
Personal risk	-0.04	-0.12	0.06	0.44*														
Objective risk	0.28*	-0.05	-0.15	0.03	-0.15													
Mitigation	0	0.33*	0.55*	0.50*	0.13	-0.15												
Innovativeness	-0.23	-0.17	0.05	0.04	0.25	-0.09	-0.09											
Self-esteem/Self-efficacy	0.17	0.21	-0.02	0.06	0.27	-0.14	0.07	.41*										
Power/powerlessness	-0.11	-0.07	0.2	0.13	-0.33	0	0.13	-0.07	0.41									
Community activitism/Autonomy	-0.11	-0.12	0.1	-0.13	0.05	0.23	-0.08	0	0.22	0.2								
Optimism/Control future	0.04	-0.02	-0.13	-0.11	-0.04	-0.04	0	-0.23	0.41	-0.02	0.21							
Righteous anger	-0.1	-0.24	0.14	-0.09	0.06	0.06	-0.19	0.23	-0.07	0.23	0.43	0						
Age	0.28*	0.05	0.06	0.1	0.22	0.22	-0.06	-0.2	0.16	0.04	0.01	-0.03	0.11					
Children under 5 years old	-0.14	-0.2	-0.07	-0.34	0.2	0.2	-0.22	-0.37	0.05	0.25	0.38	0.05	0.23	0.6*				
Adults over 65 years old	0.27	0.1	0.14	0.08	.29*	.29*	0.02	-0.03	0.13	0.05	-0.07	-0.13	0	0.7*	-			
Education	-0.02	0.17	0.07	-0.18	0.28*	0.28*	-0.24	-0.12	0.01	0.21	0.06	0.07	0.01	0.1	0.4	0		
Income	0	0.09	0.07	-0.05	0.23	0.23	0.22	-0.05	0.1	0.18	0.21	0.01	-0.04	0.02	0.15	-.12	0.2	

Table 6.5: Correlation of variables of interest with measures of individual difference and key demographics **before using a Speck monitor** (subset of participants completing both surveys) (* denotes relationship of interest)

	Knowledge	Self-efficacy	Risk	Health	Personal risk	Objective risk	Mitigation	Innovativeness	Self-esteem/Self-efficacy	Power/powerlessness	Community activitism/Autonomy	Optimism/Control future	Righteous anger	Age	Children under 5	Adults over 65	Education	Income
Knowledge																		
Self-efficacy	0.15																	
Risk	-0.13	0.19																
Health	0.32	0.26	0.27															
Personal risk	0.04	0.09	-0.06	0.44*														
Objective risk	0.42*	0.29	-0.05	0.27	-0.25													
Mitigation	-0.3	-0.27	-0.01	-0.16	0.13	0												
Innovativeness	0	-0.15	-0.03	0.11	0.25	0.11	0.02											
Self-esteem/Self-efficacy	0.11	0.23	0	0.02	0.27	0.3	0.15	-0.35										
Power/powerlessness	0.05	0	0	-0.41*	-0.33	-0.08	0.09	-0.17	0.51*									
Community activitism/Autonomy	0.09	-0.14	0.06	-0.28	0.05	0.02	0.28	0.24	0.29	0.34								
Optimism/Control future	-0.14	-0.1	-0.24	-0.32	0.21	0.06	0.32	-0.27	0.56*	0.2	0.42*							
Righteous anger	0.29	0.03	0.02	-0.2	-0.05	0.18	-0.24	0.01	0.14	0.47*	0.32	0.09						
Age	0.41*	0.17	0.2	0.58*	0.06	0.01	-0.05	-0.22	0.16	-0.17	0.04	-0.03	-0.15					
Children under 5 years old	0.13	0.1	-0.6	-0.22	0	-0.56	-0.07	-.78*	0.28	0.16	-0.25	0.41	-0.15	0.79*				
Adults over 65 years old	0.24	0.19	0.24	0.50*	0.02	0.18	-0.38	-0.05	-0.05	-0.39	-0.16	-0.24	-0.31	.65*	-			
Education	0.14	0.44*	0.13	-0.15	-0.22	-0.2	-0.22	-0.31	0.12	0.15	0.08	0.01	-0.09	0.18	0.62	0.33		
Income	0.07	0.02	-0.07	-0.25	-0.24	-0.42*	0.17	-0.24	-0.01	0.12	0.19	0.13	-0.2	0.24	0.72*	-0.12	0.39	

Table 6.6: Correlation of variables of interest with measures of individual difference and key demographics **after using a Speck monitor** (subset of participants completing both surveys) (* denotes relationship of interest)

	Knowledge	Self-efficacy	Risk	Health	Personal risk	Objective risk	Mitigation	Innovativeness	Self-esteem/Self-efficacy	Power/powerlessness	Community activitism/Autonomy	Optimism/Control future	Righteous anger	Age	Children under 5 years old	Adults over 65 years old	Education	Income	Learn	Easy	Reduce	Accurate
Knowledge																						
Self-efficacy	0.52*																					
Risk	-0.06	-0.03																				
Health	0.23	0.27	-0.12																			
Personal risk	0.17	0.07	-0.24	0																		
Objective risk	0.42*	0.04	-0.14	0.49*	0.11																	
Mitigation	-0.06	0.12	0.37	0.39*	-0.19	-0.05																
Innovativeness	-0.05	-0.31	0.01	0.25	0.3	0.11	0.29															
Self-esteem/Self-efficacy	0.07	0.22	-0.17	0.36	0.09	0.3	0.22	-0.35														
Power/powerlessness	-0.14	0.22	-0.1	0.26	-0.13	-0.08	0.17	-0.17	0.51*													
Community activitism/Autonomy	-0.38	-0.12	0.31	0.34	-0.07	0.02	0.59*	0.24	0.29	0.34												
Optimism/Control future	-0.25	-0.02	-0.06	0.21	-0.15	0.06	0.45*	-0.27	0.56*	0.2	0.42*											
Righteous anger	0.08	0.05	0.15	0.46*	-0.02	0.18	0.05	0.01	0.14	0.47*	0.32	0.09										
Age	-0.15	0.13	-0.13	0.11	-0.05	0.01	-0.18	-0.22	0.16	-0.17	0.04	-0.03	-0.15									
Children under 5 years old	-0.14	0.58	-0.09	-0.58	0.14	-0.56	-0.45	-0.74*	0.1	-0.28	-0.51	0.6	-0.4	0.44								
Adults over 65 years old	-0.28	-0.15	-0.13	0.05	-0.1	0.18	-0.41	-0.08	-0.05	-0.01	-0.11	-0.22	0.08	.48*	0							
Education	-0.04	0.4	0.07	-0.08	-0.39	-0.2	0.01	-0.33	0.04	0.28	0.04	-0.02	0.01	2	0.61	0.25						
Income	0.13	0.19	0.23	-0.32	-0.3	-0.42*	0.08	-0.17	-0.16	0.16	0.06	0.02	-0.2	0.17	0.57	-0.2	0.26					
Learn	0.44*	0.48*	-0.03	.48*	-0.06	0.05	0.43*	-0.04	0.38	0.33	0.31	0.31	0.26	-0.04	-0.12	-0.34	-0.02	0.08				
Easy	0.38	0.38	-0.25	0.18	0.23	0.1	0.08	0.03	0.4	0.43*	0.2	0.24	0.07	-0.14	-0.12	-0.12	-0.15	0.12	0.73*			
Reduce	0.61*	0.57*	-0.09	0.45*	0.04	0.19	0.27	-0.09	0.23	0.32	-0.16	0.01	0.15	-0.13	-0.2	-0.27	0.25	0.01	0.69*	0.40*		
Recommended	0.59*	0.53*	-0.17	0.53*	0.02	0.21	0.32	0.1	0.24	0.16	-0.02	0.09	0.02	-0.21	-0.07	-0.2	0.26	-0.04	0.73*	.53*	0.81*	
Accurate	0.17	0.31	0.24	0.51*	-0.43*	0.07	0.49*	-0.18	0.52*	0.4	0.29	0.48*	0.13	0	0	-0.06	0.2	0.23	0.74*	0.52*	0.48*	

from library patrons. As this is the first distribution of air quality monitors through community centers that we know of, improving the process and the resources provided to library staff and patrons is an ongoing process. We have developed webinars to assist with communication and initiation, and where possible, we strive to make introductions to local community members who may be able to assist in the effort. We hope that the national lending library program will set a precedent for libraries as the center for community action on local air pollution.

Chapter 7

Conclusions

Air pollution is an often invisible hazard, responsible for millions of premature deaths annually and countless adverse health effects, including cardiovascular disease, respiratory illness, decreased cognitive function, and low birth weight. Poor air quality is a worldwide phenomenon, affecting populations in rural and urban areas in both developed and developing nations. Common outdoor urban air pollution includes automotive exhaust and industrial byproducts, while more rural areas may be affected by fire and byproducts from resource extraction such as hydraulic fracturing operations for natural gas and oil. Cooking fires pose a severe health risk in developing countries, especially when these fires are located inside of homes with poor ventilation. Wood and charcoal are typically used as fuel, but other organic matter such as leaves or even manure are used where other resources are scarce.

Despite these global impacts on human health, air pollution is often invisible and difficult to measure. Air pollution is a multidimensional concept, and includes substances such as volatile organic compounds, carbon dioxide, ozone, nitrogen and sulfur oxides, and fine and coarse particulate matter. Specialized equipment used by regulatory agencies to monitor these substances are typically too large and expensive to be owned by individuals. Advances in sensing and processing technology have now realized smaller and less expensive air quality monitors that are accessible to citizen science groups and individual users. The availability of low-cost air quality monitors has revealed a number of difficult questions which researchers now seek to answer. These questions include but are not limited to:

- How does the performance of low-cost air quality monitors compare with established federal reference methods and federal equivalence methods?
- What precision can be expected between monitors of the same type as well as between models that differ in model and manufacturer?
- How does the performance of these devices change under typical use over a period of time?

These broad questions cannot be answered without first determining methods for characterizing and evaluating low-cost air quality monitors. Because the sensing technology in these devices may not measure the quantity of interest directly (as in the case of particulate matter), economical and effective calibration methods must also be developed. Therefore, this thesis addresses the following:

Thesis Question 1: Can an inexpensive air quality monitor based on mass-manufactured sensors be calibrated efficiently in order to achieve inter-device agreement in addition to agreement with professional and federally-endorsed particle monitors? Calibrated low-cost devices demonstrate increased inter-device agreement as well as greater agreement with reference monitors, with the caveat that any measures of performance are highly sensitive to operating conditions. Monitors must be compared within identical environments that meet the required operating conditions of each device.

Additionally, as air quality monitoring technology has only recently become accessible to individuals, we address the impact of this technology through the following:

Thesis Question 2: Can an inexpensive air quality monitor increase the confidence and capacity of individuals to understand and control their indoor air quality? Participants report a higher level of self-reported knowledge and confidence regarding air quality and mitigation strategies after using low-cost air quality monitors for three weeks, though the impact of these devices on behavior has yet to be observed.

In this thesis, we limit our experimental scope to fine particulate matter ($PM_{2.5}$). While $PM_{2.5}$ is just one indicator of air pollution, it is a ubiquitous pollutant with numerous health impacts and can indicate the presence of a variety of airborne substances from dust to smoke. Additionally, we focus primarily on the use of low-cost fine particulate monitors in indoor environments where individuals directly impact their air quality on a hyperlocal scale. We have designed and manufactured low-cost commercial fine particulate monitors (Specks) for individual use, which has enabled us to collect a large quantity of data during and after the development of calibration and characterization procedures.

7.1 Designing Low-Cost Fine Particulate Monitors

The development of the Speck began with attempts to create a custom optical solution capable of measuring fine particulates. We later began to design our device around the DSM-501a dust sensor because of its extremely low cost and greater signal to noise ratio. Using a pre-built optical solution decreased the cost of fabrication, which in turn afforded the ability to add additional components for usability such as a color touchscreen and WiFi connectivity. These features also aided in the development of automated calibration procedures and quality control measures.

7.2 Calibration and Characterization of Low-Cost Fine Particulate Monitors

Early experiments with pre-production Speck prototypes revealed that variability in mechanical and electrical tolerances resulted in a range of responses and sensitivities to identical stimuli. Experiments in home environments involving multiple Specks co-located with a handheld reference instrument allowed us to optimize a Kalman filter algorithm to increase correlation between the Specks and the reference instrument, and device-specific scaling constants (calibration factors) to normalize the magnitude of each Speck's response.

The mass manufacture and commercial release of the Speck necessitated the development of a more repeatable and time-efficient calibration method in order for the calibration throughput to match or exceed the demand. Efficient calibration also enabled us to keep the cost of the device low. Quality control measures were integrated into this process, and we continued to automate the process to decrease the risk of operator error and further reduce the cost of calibration. Finally, in order to reduce the size requirement for calibration and to allow for the future implementation of multiple parallel calibration procedures, we developed an enclosed and automated calibration chamber.

We conclude that low-cost calibration procedures are possible, and can reduce the variability between devices. Furthermore, calibration of multiple monitors simultaneously enables the identification of devices which do not correlate well with the co-located sample of the population. Calibrating the entire device rather than just the sensing component reduces the error caused by multiple system characteristics such as airflow and electronic component tolerances.

Using a sample population of monitors circulated through the public library system as well as the data collected from every calibration batch, we concluded that it is critical to evaluate the effect of gradual changes to the calibration procedure in order to calculate rates of sensor drift. Because we continued to optimize and automate the calibration procedure for the Speck monitors, the mean and variance of the calibration values changed over time. This allowed us to compensate for the majority of the discrepancies between the original and post-deployment calibration values for the circulated devices. This compensation is only feasible if calibration batch data is saved in a standardized format, but is important for any new sensing device where the calibration procedure itself is continually improved or otherwise altered.

Concurrently, we performed several experiments to characterize low-cost particulate monitors. The goal of characterization is to determine the performance of a sensing device in comparison with a reference instrument. Additionally, it is important to understand how data from different monitors of a similar sensing type (fine particulate matter, by example) can be compared and contrasted. We confirmed that many factors must be accounted for in any characterization or comparison experiment. First, co-location environments must conform to the operational parameters of each device. Co-location experiments where the Speck was placed outdoors consistently yielded poor results, as infrared sunlight and other environmental conditions greatly interfere with the optical sensor and device airflow. Second, differences in sampling rate must be equitably accounted for by averaging all data points of a faster monitor to correspond to the beginning and end of each sampling period of the slowest instrument. Third, performance must be evaluated across multiple time intervals, as high correlation across a brief period of time does not ensure a similar correlation over longer periods, and likewise a high correlation over a long period of time does not indicate high correlation over a brief event. More generally, it is important to evaluate both long-term trend behavior as well as responsiveness to brief events.

Operators must also be aware of the underlying assumptions for each device to be tested. For example, the Speck does not directly sense the smallest particles in the $PM_{2.5}$

mass fraction, but in formulating a mass value it is assumed that the size distribution is relatively constant and the smallest particles also do not contribute to a large portion of $PM_{2.5}$. For particulate monitors that report count or mass by size channel, the bounding upper and lower size must be known for each instrument to be compared. For example, the $2\mu m$ channels of the Grimm EDM-180 and the Hach HHPC-6+ cannot be directly compared because the size range of the EDM-180 $2\mu m$ channel is far narrower than that of the HHPC-6+.

7.3 Impact of Low-Cost Fine Particulate Monitors on Individuals

Users self-reported a higher level of knowledge about indoor air quality and were better able to identify health risks associated with indoor air pollution after borrowing a fine particulate monitor from their local library. Accordingly, users reported a higher level of perceived risk after borrowing the monitor but also hightened confidence that they could take action in the event that their monitor reported poor air quality. Despite the heightened perception of both risk and confidence regarding indoor air pollution, users did not reveal an intent to mitigate these risks.

Participants who reported negative health consequences from indoor air pollution also experienced higher risk of exposure to $PM_{2.5}$ and were more knowledgeable regarding ways to mitigate that risk. Risk mitigation knowledge was also associated with community activism and autonomy, along with a feeling of optimism regarding their control over their future. These relationships were present in participants prior to their introduction to the Speck air quality monitor.

We conclude that an inexpensive air quality monitor such as the Speck can increase the confidence and capacity of individuals to understand and control their indoor air quality based on the study of individuals borrowing monitors from local libraries. We claim that knowledge of indoor air quality is of critical importance given the multitude of negative health risks posed by fine particulate matter and other airborne pollutants and the potential for individuals to significantly impact their personal exposure through their daily behavior. We were surprised to learn that increased knowledge regarding risks and mitigation strategies did not seem to be significantly related to an increased intent to reduce personal exposure. Optimally, we would like to see users of personal air quality monitors taking steps to improve their air quality, but even among our self-selected participants, we did not see evidence that a brief intervention is sufficient to produce this behavior. As we will discuss in the final section, a longitudinal study should be conducted to further study the long-term effects of low-cost air quality monitors on perception and behavior.

7.4 Final Observations

7.4.1 Low-Cost Sensing

The Speck is one example of a device with an inexpensive sensor where Kalman filtering improves performance. As demonstrated in Chapter 3, the raw signal from the bare sensing element is very noisy and unusable without additional processing, even with the added fan to increase airflow and particle exposure. Additionally, the sensitivity of each unit varies. These challenges are not unique to air quality sensing, and may present themselves in any device utilizing low-cost components that may not be well characterized. We present the following recommendations for low-cost sensing projects in general:

- **Increasing exposure:** If the phenomenon to be measured is sparse, increasing the sensor's physical exposure to the phenomenon may improve its signal-to-noise ratio. For example, if low levels of infrared light need to be measured, optical filters for the desired wavelength and focusing lenses may provide a more usable signal. In the case of the Speck, exposure to particulate matter is increased using a low-speed fan to draw more particles through the optical chamber.
- **Signal processing:** Multiple signal processing methods exist for converting raw data to usable measurements. For any sensing application, the advantages and disadvantages of any proposed method must be carefully considered, including delay, computational cost, and responsiveness. The Kalman filter employed in the Speck incorporates an assumption that particle concentration tends to increase rapidly and decrease slowly. Similar Kalman filter models may be employed for other sensor types, though this may result in decreased performance in environments where any assumptions do not remain valid (such as outside environments in the case of the Speck). Often, a low-pass filter may be sufficient without any further complexity.
- **Calibration:** When considering calibration methods, it is important to determine whether the variability in the calibration process is less than the variability in the sensor population to be calibrated. Calibration will only be effective if it does not introduce more uncertainty than is already present. Additionally, in the case of low-cost devices, the cost of any calibration process should be less than the cost of using higher-cost components that would eliminate the need for the process altogether.
- **Quality Control:** The quality control methods in this thesis serve to remove sensors that are either broken or exhibit lower sensitivity. Similar quality control procedures, either autonomous or manual, can serve to improve the performance of the device population.

7.4.2 Affordances for Personal Monitoring

Many of the anecdotal responses from the users surveyed in Chapter 6 are related to the ability to receive at-a-glance measurements of air quality around the home. Many users placed the devices in prominent locations that they would pass during their daily routine. Others reported using the on-device measurements and historical graphs as conversation tools when discussing air quality with their family and guests. Many home air quality monitors upload data to either a website or, more frequently, a phone app. The Speck is unique because of its bright interactive display, and we believe that this feature is important in rendering the monitor as an educational conversation piece in the home. The Speck is designed to be visible, unlike other home monitoring devices like smoke alarms. For those seeking to create personal sensing devices that promote conversation and a deeper understanding of otherwise invisible phenomena, we strongly recommend the addition of affordances such as real-time data displays and features that make the device easily recognizable in the home.

7.4.3 Effective Disruption of the Deficit Model

The relationship between citizens and air quality is considered by some authority figures to follow a "deficit model" [11], where individuals are believed to be resistant and distrustful of assessments of air quality due to their lack of scientific understanding and knowledge. On the contrary, citizens appear to evaluate rather than assimilate these assessments, as they often conflict with their personal observations of their environment and health. Citizens are often dissatisfied with the unidirectional communication methods around air quality, but typically only have anecdotal evidence to contribute.

Air quality monitors such as the Speck can empower individuals to generate quantitative evidence. Despite this advantage, as we have previously stated, air quality is a multi-faceted and complex topic. Without proper contextual understanding, quantitative measurements taken by individuals can be misinterpreted, and we have observed that confirmation bias plays a major effect in the interpretation of data from the Speck.

One illustrative anecdote involves a user who was concerned with the effects of hydraulic fracturing on her local air quality. As evidence of elevated air quality near one of the fracturing sites, the user emailed photos taken from the inside of her car with the Speck held in one hand and the fracturing site visible in the background. The user considered the photos to be strong evidence, and while the Speck reading was elevated, multiple factors may have caused this reading beyond the effect of proximity to the fracturing site. The vehicle's windows were closed, and the emissions from the vehicle as well as dust or lint may have contributed to the high measurements. Additionally, the Speck is intended for stationary, indoor use. Motion, significant external airflow, and exposure to sunlight all alter the Speck measurements. Thus, it is important that users of the Speck have at least a basic understanding of air quality dynamics as well as the limitations and operating principles of the monitor.

This anecdote occurred during an early deployment of prototype Specks and motivated the development of a comprehensive user guide in addition to air quality resources intended for non-experts. When introducing new technology for personal monitoring and citizen scientists, it is critical to also provide the resources and guidance to properly use the technology and interpret the resulting data.

We believe individuals possessing adequate knowledge and understanding to combine gathered data with anecdotal evidence can disrupt the deficit model. Citizens are already engaging critically with air quality science, and the effective use of quantitative personal measurements can elevate their relationship with data from consumer to contributor. Likewise, other interests of citizen science can benefit from low-cost monitoring technology, such as water quality, soil analysis, and ecology. Community groups and individuals must establish their credibility to scientific and regulatory authorities, and thus it is critical that users of new technology are provided with the knowledge and understanding needed to effectively collect and interpret data. To this end, we assert that the development of new resources is equally as important as the development of new low-cost monitoring technology.

7.4.4 Automation and Employment

Unemployment of non-technical individuals due to increasing automation in industry is a common concern for robotics researchers and engineers. We present the automated calibration chamber in this thesis as a means by which automation reduces the barrier to employment. The amount of expertise and technical knowledge required to manually calibrate the Speck monitors poses a significantly greater barrier than the training required to operate the calibration chamber. Similar automated techniques can be used for other emerging technology to separate the quantitative and qualitative aspects of calibration and quality control. This allows an individual to become a calibration specialist through training to identify the subjective requirements for the technology (such as acceptable fan noise, aesthetic quality, etc.) without having to be an expert in statistical techniques or computer science. Especially with respect to startups, this provides an entry point for all individuals to become involved with the development of new technology regardless of their previous background.

7.5 Future Research Opportunities

This thesis has demonstrated that a low-cost fine particulate monitor can be built using an inexpensive optical dust sensor, and that accuracy and inter-device precision are improved through the use of Kalman filtering and calibration. The calibration procedure for such a device may be primarily autonomous and can include quality control measures to identify any monitors which do not meet specific performance criteria.

The calibration chamber was designed to further autonomize the calibration procedure while minimizing space requirements. Because the demand for newly-calibrated Speck monitors waned at approximately the same time as the chamber was completed, and because the supply of uncalibrated Specks has been temporarily depleted, there has been no need to pursue the operation of multiple parallel calibration chambers. A human operator is still needed between calibration batches to manually install and remove Specks from the calibration chamber, but no intervention is needed during the batch. Future research could assess the cognitive load placed on the operator as a function of multiple interleaved calibration chambers, as well as the technical requirements and additional considerations needed for each chamber to wirelessly identify its co-located batch members. Finally, as particulate matter is only one aspect of air pollution, the generalized methods presented in this thesis may be used by future researchers to calibrate and characterize sensors for different pollutant species such as VOCs, CO_2 and ozone.

While the results in this thesis support the hypothesis that low-cost air quality monitors can improve users' knowledge and confidence regarding the risks posed by air pollution and fine particulate matter, the short duration of the studies did not enable us to make any conclusions about long-term effects of low-cost monitors on participant behavior or changes in health. Additionally, the participants in these studies were self-selected and the results for a wider population may vary. A longitudinal study is needed to properly assess the hypothesis that prolonged use of a low-cost monitor such as the Speck can ultimately lead to lower personal exposure and mitigation of health risks through self-motivated behavioral modification. The monitor must also act as a component in a larger system of resources including community frameworks, online and printed reference material, and technical support. Such a study should strive to reach a larger sample population across a wider demographic through incentive recruitment and coordination with multiple community organizations. The proposed study would require significant funding and the cross-disciplinary support of multiple researchers, but as the interest and prevalence of low-cost monitors continues to increase, such an effort should be possible in the near future.

Appendix A

Pilot Study Surveys

Speck Pilot Baseline Survey

Baseline Information

Hello,

Thank you again for participating in our Speck user study!

Before you begin using the Speck, we would like to understand how much you know about air quality in general, and how aware you are of the air quality in your home. This initial survey should only take about 5 minutes to complete. Please be open and honest in your responses – there are no wrong answers!

Sincerely,
The CREATE Lab Speck Team

***1. Speck Number (can be found on the box or on the bottom of the Speck)**

***2. How knowledgeable would you say you are about air quality in general?**

- ○ Very knowledgeable
- ○ Quite knowledgeable
- ○ Somewhat knowledgeable
- ○ Not knowledgeable

3. Do you think air quality can cause or exacerbate the following health issues? *Please check all that apply.

- ☐ Asthma and other respiratory illnesses
- ☐ Heart disease
- ☐ Diabetes
- ☐ Lung Cancer
- ☐ Stroke
- ☐ Epilepsy
- ☐ Allergic responses

4. What kind of a residence do you currently live in?

- ○ Rented house
- ○ Owned house
- ○ Rented apartment or condo
- ○ Owned apartment or condo
- ○ Other (please specify)

***5. On average, how would you rate the air quality in your home?**

- ○ Very good
- ○ Good
- ○ Fair
- ○ Poor
- ○ Very poor

Speck Pilot Baseline Survey

***6. Are you confident that you will know what actions to take, if you learned that your indoor air quality was poor?**

- ○ Very confident
- ○ Quite confident
- ○ Somewhat confident
- ○ Not confident

7. What do you think are some of the sources of pollution inside your home?** ***Please check all that apply.

- ☐ Cooking
- ☐ Vacuuming
- ☐ Smoking
- ☐ Microwave oven
- ☐ Gas heating
- ☐ Fireplace
- ☐ Open windows
- ☐ Insulation
- ☐ Refrigerator
- ☐ Other (please specify)

***8. Are you aware of what kind of air filtration system is installed in your home?**

- ○ Yes
- ○ No
- ○ I don't have one

***9. Do you have a hood vent or ventilation fan over your stove?**

- ○ Yes
- ○ No
- ○ I don't know

Speck Pilot Baseline Survey

10. In the past, have you taken any of the following steps to improve the air quality in your home?** ***Check all that apply.

- ☐ Changed the filter
- ☐ Cleaned the filter
- ☐ Installed a stove hood vent
- ☐ Installed an air purifier
- ☐ I have not taken any steps to improve the air quality in my home
- ☐ Other (please specify)

11. Please use this space to share any other comments or thoughts you may have about the Speck or this user study.

Speck Pilot Mid-Study Survey

Mid-Study Check-in

Hello,

Thank you again for participating in our Speck user study!

This second survey asks a few questions about your experiences with the Speck so far and should only take 5 – 10 minutes to complete. We truly appreciate your open and honest feedback!

Sincerely,
The CREATE Lab Speck Team

***1. Speck Number (can be found on the box or on the bottom of the Speck)**

***2. Have you been able to successfully set up the Speck in your home?**

- Yes
- No
- Have not tried it yet

***3. How would you describe your experience installing the Speck?**

- Very easy
- Easy
- Moderate
- Difficult
- Very difficult

4. If you had difficulty installing your Speck, please describe your experience. *Please check all that apply.

- Confusing
- Frustrating
- Overwhelming
- I did not experience any difficulty setting up the Speck
- Other (please specify)

***5. Based on your experiences so far, how would you rate the following resources?**

	Essential	Very Useful	Somewhat Useful	Not Useful	N/A (I have not used this)
Speck Setup Guide					
Speck Website (http://specksensor.org)					
Speck Users Facebook Group					

Speck Pilot Mid-Study Survey

6. If you saw a spike in the Speck reading in the past week, how did that make you feel?** ***Please check all that apply.

- ☐ Nervous
- ☐ Stressed
- ☐ Uncertain about what to do
- ☐ Curious to find the source
- ☐ Motivated to fix the issue
- ☐ Skeptical about the reading
- ☐ I did not see a spike

7. If you saw a drop in the Speck reading in the past week, how did that make you feel?** ***Please check all that apply.

- ☐ Satisfied
- ☐ Relieved
- ☐ Confused
- ☐ Motivated to identify the cause
- ☐ Skeptical about the reading
- ☐ I did not see a drop

8. Have you become aware of or learned anything new about the air quality in your home after using the Speck? ***Please explain briefly.***

9. Based on readings you've seen on the Speck during the past week, have you made any changes in your home to improve the air quality?** ***Please briefly explain your response.

Yes, I have:

Not yet, but I plan to:

No, I have not and don't plan to:

10. Please use this space to comment on the experiences you've had so far with the Speck and supporting material (setup guide, website and Facebook group) .

Speck Pilot Final Survey

Intro Message

Hello,

Thank you again for participating in our Speck user study!

Now that you have been using the Speck for about two weeks, we would love to hear your overall thoughts about the Speck and supporting material. This final survey is more detailed and should take 20 – 30 minutes to complete. Please be open and honest - we truly appreciate your feedback!

Sincerely,
The CREATE Lab Speck Team

Speck Pilot Final Survey

Baseline Information

***1. Speck Number (can be found on the box or on the bottom of the Speck)**

***2. On average, how would you rate the air quality in your home?**

- Very good
- Good
- Fair
- Poor
- Very poor

3. What do you think are some of the sources of pollution inside your home? *Please check all that apply.

- Cooking
- Vacuuming
- Smoking
- Microwave oven
- Gas heating
- Fireplace
- Open windows
- Insulation
- Refrigerator
- Pets
- Other (please specify)

***4. Are you aware of what kind of air filtration system is installed in your home?**

- Yes
- No
- I don't have one

***5. Do you have a hood vent or ventilation fan over your stove?**

- Yes
- No
- I don't know

***6. Are you confident that you will know what actions to take, if you learned that your indoor air quality was poor?**

- Very confident
- Quite confident
- Somewhat confident
- Not confident

Speck Pilot Final Survey

***7. How knowledgeable would you say you are about air quality in general?**

- Very knowledgeable
- Quite knowledgeable
- Somewhat knowledgeable
- Not knowledgeable

Speck Pilot Final Survey

Experience with the Speck

8. How would you describe your overall experience using the Speck? *Please check all that apply.

- ☐ Enjoyable
- ☐ Useful
- ☐ Informative
- ☐ Challenging
- ☐ Confusing
- ☐ Frustrating
- ☐ Other (please specify)

***9. Would you say that the Speck met your expectations as an air quality monitor?**

○ Strongly Agree ○ Agree ○ Neutral ○ Disagree ○ Strongly Disagree

10. In which rooms/locations of your home did you place the Speck? *Please list.

***11. On average, how long did you keep the Speck in each room?**

- ○ 1 to 3 days
- ○ 4 to 6 days
- ○ 7 to 9 days
- ○ 10 to 14 days
- ○ Other (please specify)

Speck Pilot Final Survey

***12. How often did you look at the Speck reading?**

- Each time I walked into the room it was in
- Multiple times a day
- Once a day
- Less than once a day
- Only when I thought there was a problem
- Other (please specify)

13. Were you surprised by Speck readings in any specific rooms/locations? ***Please explain briefly.***

14. What action, if any, did you take to improve your air quality based on what you learned from using the Speck? ***Please explain briefly.***

***15. How would you like to be alerted about significant changes in your air quality, if at all?**

- Blinking light
- Sound
- Text message
- Email
- Voicemail
- I do not want alerts

Other (please specify)

16. Would you want the capability to personalize the Speck settings so that you can, for example, choose when you get alerts, alter the types of historical views that are displayed, change the color coding, etc.? ***Please explain briefly.***

Speck Pilot Final Survey

17. The next version of the Speck will include a quieter fan and a more robust micro USB port. Apart from these modifications, what other changes would you suggest for the Speck (e.g. shape, size, color, screen, displayed information, portability, etc.)? ***Please explain briefly.***

Speck Pilot Final Survey

Experiences with Supporting Material (e.g. website, Facebook group, etc.)

***18. Based on your experience in this study, how would you rate the following resources?**

	Essential	Very Useful	Somewhat Useful	Not Useful	N/A (I did not use this)
Speck Setup Guide	○	○	○	○	○
Speck Website (http://specksensor.org)	○	○	○	○	○
Speck Users Facebook Group	○	○	○	○	○

19. Is there anything you would change in the Speck Setup Guide to make it more useful? *Please explain briefly.*

20. What other information (if any) would you have liked to see on the Speck website (http://specksensor.org)? *Please explain briefly.*

***21. Do you think it is useful to have a discussion platform (on Facebook or elsewhere) for Speck users?**

○ Essential ○ Very Useful ○ Somewhat Useful ○ Not Useful

○ Other (please specify)

Speck Pilot Final Survey

Overall Experience

***22. What is your opinion about the following statement?**
"The Speck helped me feel empowered to understand and manage my air quality."

- Strongly Agree
- Agree
- Neutral
- Disagree
- Strongly Disagree

***23. Has the Speck been useful for your home?**

- Strongly Agree
- Agree
- Neutral
- Disagree
- Strongly Disagree

***24. Are you likely to purchase a Speck in the near future?**

- Strongly Agree
- Agree
- Neutral
- Disagree
- Strongly Disagree

***25. How much would you be willing to spend on a Speck?**

- Between $50 and $100
- Between $100 and $150
- Between $150 and $200

26. Please use the space below to share any anecdotes or notable experiences you had during this study. *We'd love to hear your stories!*

27. If you have any other thoughts, questions or comments about your overall experiences using the Speck and associated material, please list them here. *We truly appreciate your open and honest feedback.*

Appendix B

Metro 21 Surveys

Screening

Which library location are you using?
(e.g. Squirrel Hill, East Liberty, Hazelwood, etc.)

Have you used the Speck before?

- ○ Yes
- ○ No

Are you checking out the Speck monitor?

- ○ Yes, I am checking out the Speck monitor.
- ○ No, I am returning the Speck monitor.

Survey 1 Welcome

Thank you for your interest in the Speck indoor air monitor. We are researchers from Carnegie Mellon University interested in learning about your views of indoor air pollution in your home. We will ask you some questions about indoor air pollution. You will then be asked some demographic questions.

The survey should take about 5-10 minutes. You must be 18 or older to participate. You will be asked to take a short follow-up survey when you return the monitor to the library. You will be entered to win 1 of 5 Speck indoor air monitors upon completing both surveys.

If you have any questions about this study, you should contact Co-Principal

Investigators, Gabrielle Wong-Parodi, Engineering and Public Policy, 129 Baker Hall, 5000 Forbes Avenue, Pittsburgh, PA 15213, gwongpar@cmu.edu or Beatrice Dias, Robotics Institute, NSH 4627, Forbes Avenue, Pittsburgh, PA 15213, (412) 268-2568, beadias@cmu.edu. If you have questions later, desire additional information, or wish to withdraw your participation please contact one of the Co-Principal Investigators by mail, phone or email in accordance with the contact information above.

If you have questions pertaining to your rights as a research participant; or to report objections to this study, you should contact the Research Regulatory Compliance Office at Carnegie Mellon University. Email: irb-review@andrew.cmu.edu. Phone: 412-268-1901 or 412-268-5460.

Are you age 18 years or older?

- ○ Yes
- ○ No

If you are interested in entering to win the 1 of 5 Speck indoor air monitors, please enter your email address. You will receive an email at the conclusion of the study only if you have won 1 of the 5 monitors. Your email address will be kept strictly confidential and will not be shared with anyone.

In order to link your first survey with the follow-up survey, please enter the last 6 digits of your library card number (this information cannot and will not be used for any other purposes):

Knowledge assessment

In this section, we'd like to find out what you think about air quality.

How much do you know about air quality?

None	A Little	Some	A Lot	Everything
○	○	○	○	○

Do you think air quality can cause or make worse the following health issues? Please check all that apply

- ☐ Asthma and other respiratory ilnesses
- ☐ Heart disease
- ☐ Diabetes
- ☐ Lung cancer
- ☐ Stroke
- ☐ Epilepsy
- ☐ Allergic responses
- ☐ Other ______

On average, how would you rate the air quality in your home?

Very poor	Poor	Fair	Good	Very Good
○	○	○	○	○

What do you think are some of the sources of pollution inside your home? Please check all that apply

- ☐ Cooking
- ☐ Vacuuming
- ☐ Smoking
- ☐ Microwave oven
- ☐ Gas heating
- ☐ Open windows
- ☐ Insulation
- ☐ Pets
- ☐ Refrigerator
- ☐ Other

☐ Fireplace

Mitigation assessment

In this next section, we'd like to know a bit more about your views on air quality.

How confident are you that you will know what actions to take if you learned that your indoor air quality was poor?

Not at all confident	A little confident	Somewhat confident	Very confident	Extremely confident
○	○	○	○	○

What do you think are effective ways to reduce your exposure to indoor air pollution? Please check all that apply

☐ Installing a range hood
☐ Opening windows
☐ Closing windows
☐ Installing an air purifier
☐ Changing air filters
☐ Cleaning the house
☐ Smoking outside instead of inside
☐ Installing an air quality monitor
☐ Cleaning air filters
☐ Other

In the past 3 months, have you made any changes in your home to improve the air quality?

○ Yes, I have
○ Not yet, but I plan to
○ No, I have not and don't plan to

Empowerment and creativity

Please indicate your agreement with the following statements (1=strongly disagree, 5=strongly agree):

	Strongly Disagre
I generally accomplish what I set out to do	○
I have a positive attitude about myself	○
I am usually confident about the decisions I make	○
I am often able to overcome barriers	○
I feel I am a person of worth, at least on an equal basis with others	○
I see myself as a capable person	○
I am able to do things as well as most other people	○
I feel I have a number of good qualities	○
I feel powerless most of the time	○
Making waves never gets you anywhere	○
You can’t fight city hall	○
When I am unsure about something, I usually go along with the group	○
Experts are in the best position to decide what people should do or learn	○
Most of the misfortunes in my life were due to bad luck	○
Usually, I feel alone	○
People have no right to get angry because they don’t like something	○
People have a right to make their own decisions, even if they are bad ones	○
People should try to live their lives the way they want to	○
People working together can have an effect on their community	○
People have more power if they join together as a group	○
Working with others in my community can help to change things for the better	○
People are limited only by what they think possible	○
I can pretty much determine what will happen in my life	○
I am generally optimistic about the future	○

Very often a problem can be solved by taking action ○
Getting angry about something is often the first step toward changing it ○
Getting angry about something never helps ○

Rate your agreement with how much the following statements describes you (1=strongly disagree, 5=strongly agree):

Thinking characterized by precision, reliability, efficiency, prudence, discipline
Interested in finding problems to solve
If rules don't fit, bend them a bit
Solutions sought by tried and true methods
Can maintain high accuracy for long periods of work
Bending the rules for one person is unfair to the rest
Impractical, unpredictable, change-oriented type
Command of specialized knowledge
When involved in a project, I forget that other people are involved and should be consulted

Demographics

Now we'd like to know more about you.

Where did you learn about the Speck monitor (please check all that apply)?

- ☐ Community meeting
- ☐ Flyer
- ☐ Librarian
- ☐ Social media

☐ Friend/Family

☐ Other ______

Are you male or female?

○ Male

○ Female

In what year were you born?

______

What is your zip code?

______

How many children under the age of 18 live in your home?

______

Are any of those children under the age of 5?

○ Yes

○ No

How many adults over the age of 65 live in your home?

______

Do you, or does anyone else in your home, suffer from a respiratory illness such as asthma or COPD?

- ○ Yes
- ○ No
- ○ Prefer not to answer

What is the highest level of education you have completed?

- ○ Less than high school
- ○ High school/GED
- ○ Some college
- ○ 2 year college degree (Associates)
- ○ 4 year college degree (BA, BS)
- ○ Masters
- ○ Doctoral (PhD) or Professional (MD, JD)
- ○ Prefer not to answer

Do you consider yourself to be:

- ○ Democrat
- ○ Republication
- ○ Independent
- ○ Other ____________
- ○ Prefer not to answer

What is your annual household income ($)?

- ○ 0-15k
- ○ 16-30k
- ○ 31-50k

- 51-75k
- 76-100k
- 101-125k
- 126-150k
- 151-175k
- 176k+
- Prefer not to answer

Please leave any final comments about the survey below:

Survey 2 Welcome

Welcome back!

Thanks again for your interest in the Speck indoor air monitor. As a reminder, we are researchers from Carnegie Mellon University interested in learning about your views of indoor air pollution in your home. We will ask you some questions about indoor air pollution. You will then be asked some demographic questions.

We would appreciate it if you could take a short follow-up survey to the one you took earlier. You must be 18 or older to participate. It should take about 5-10 minutes. You will be entered to win 1 of 5 Speck indoor air monitors upon completing both surveys.

If you have any questions about this study, you should contact Co-Principal Investigators, Gabrielle Wong-Parodi, Engineering and Public Policy, 129 Baker Hall, 5000 Forbes Avenue, Pittsburgh, PA 15213, gwongpar@cmu.edu or

Beatrice Dias, Robotics Institute, NSH 4627, Forbes Avenue, Pittsburgh, PA 15213, (412) 268-2568, beadias@cmu.edu. If you have questions later, desire additional information, or wish to withdraw your participation please contact one of the Co-Principal Investigators by mail, phone or email in accordance with the contact information above.

If you have questions pertaining to your rights as a research participant; or to report objections to this study, you should contact the Research Regulatory Compliance Office at Carnegie Mellon University. Email: irb-review@andrew.cmu.edu. Phone: 412-268-1901 or 412-268-5460.

Are you age 18 years or older?

- ○ Yes
- ○ No

If you are interested in entering to win the 1 of 5 Speck indoor air monitors, please enter your email address. You will receive an email at the conclusion of the study only if you have won 1 of the 5 monitors. Your email address will be kept strictly confidential and will not be shared with anyone.

In order to link your first survey with the follow-up survey, please enter the last 6 digits of your library card number (this information cannot and will not be used for any other purposes):

Views on Speck

Please indicate your agreement with the following statements (1=strongly disagree, 5=strongly agree):

	Strongl Disagre
The Speck monitor helped me learn about indoor air pollution in my home.	◯
The Speck monitor was easy to use.	◯
The Speck monitor helped me reduce my personal exposure to indoor air pollution.	◯
I recommended the Speck monitor to a friend or family member.	◯
My Speck readings were typically good.	◯

Are you interested in providing input and advice for local community or library events around air quality and Speck?

◯ Yes, sure!

◯ No, thank you

Thank you for your help! Please enter your email address below so we can get in touch with you about participating in such events.

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