Evaluation of Small Sensors for Detection of Dust at Cuyama Valley High School

Final Report Prepared for

Santa Barbara County Air Pollution Control District
Santa Barbara, CA

December 2016

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Innovative Environmental Solutions

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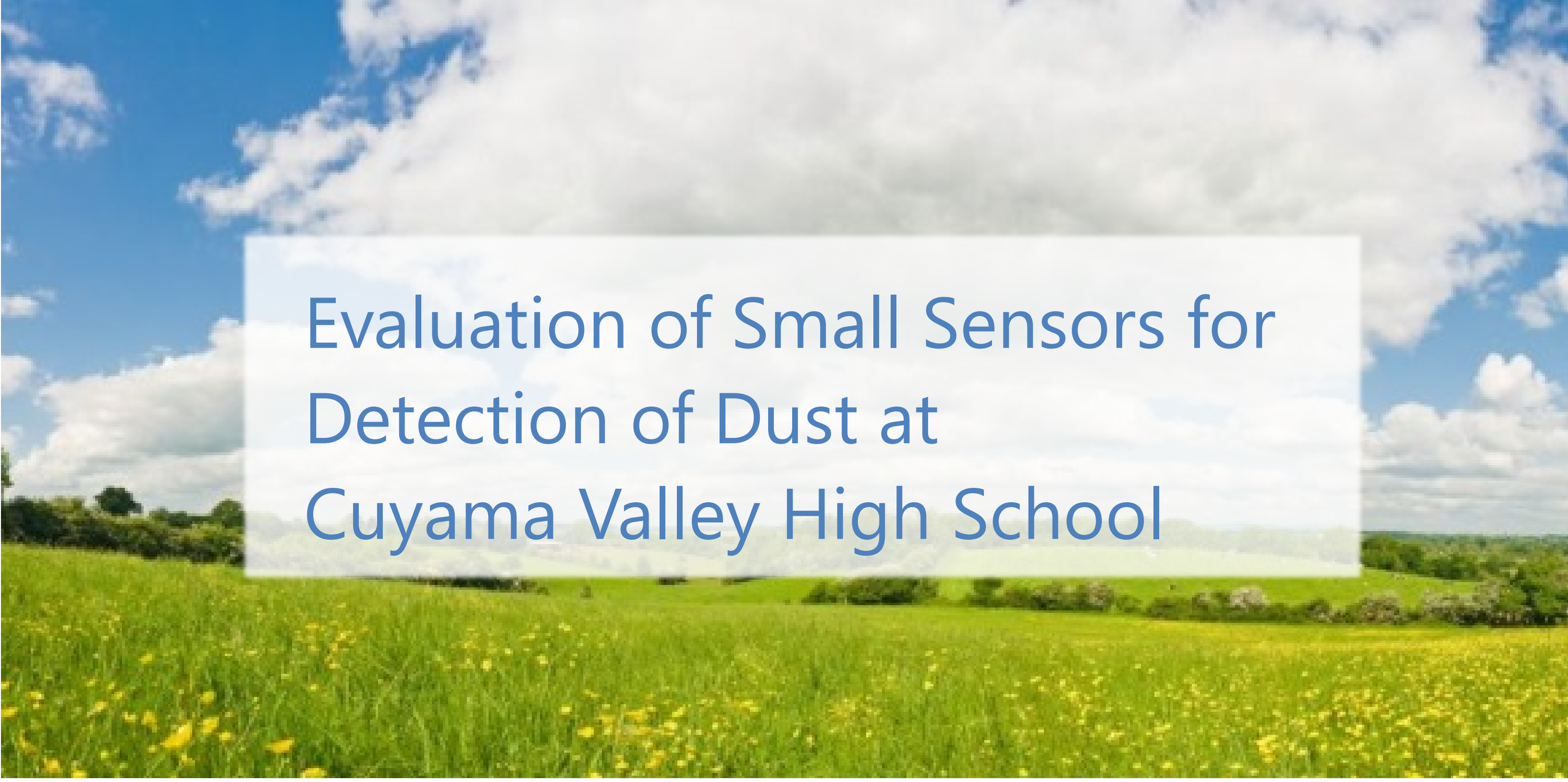

Evaluation of Small Sensors for Detection of Dust at Cuyama Valley High School

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Final Report

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1. Introduction

Windblown dust can contribute to high particulate matter (PM) concentrations, which can be harmful to human health. In areas of Santa Barbara County, strong winds in the spring and fall can create localized high concentrations of dust in the air, including at local schools. Currently, there is no cost-effective way to determine when dust concentrations are high at schools so that school administrators can take actions, such as keeping students indoors, and cancelling or rescheduling outdoor activities to reduce exposure to PM. However, the increasing availability of low-cost, easy-to-use PM sensors offers a new opportunity to monitor PM at local schools and engage school teachers, administrators, and students through their participation.

Santa Barbara County Air Pollution Control District (SBCAPCD) asked Sonoma Technology, Inc. (STI) to investigate the use of low-cost sensors for monitoring dust by conducting a pilot field study at Cuyama Valley High School in New Cuyama, California. The objectives of the study included:

1. Determine whether the low-cost PM sensors detect dust events and if so, how well they detect dust events.
2. Determine how precise the sensor measurements are and whether sensor precision is sufficient either for use in a network to monitor the spatial variability of PM, or for obtaining localized data to augment information available from the regional monitoring network.
3. Determine whether the sensors operate continuously and meet data completeness requirements for reliably detecting dust events.
4. Determine whether the sensors could be used as part of an “early warning system” to inform decisions to reduce student exposure to high PM concentrations.

To address these objectives, STI identified and acquired six low-cost PM sensor devices and designed and conducted a three-month field study to characterize the performance of the sensors for detecting dust events and quantifying their impacts. PM_{10} (PM less than 10 microns in diameter, also referred to as coarse particles) and $PM_{2.5}$ (PM less than 2.5 microns in diameter, also referred to as fine particles) concentrations were measured. Two low-cost PM sensor models were used: Alphasense to measure $PM_{2.5}$ and PM_{10}, and AirBeam to measure $PM_{2.5}$. Three of each type, recording data at 1-min temporal resolution, were deployed at Cuyama Valley High School to evaluate data quality and sensor performance. The sensors were collocated with a federal equivalent method PM_{10} MetOne Beta-Attenuation Monitor (BAM), recording data at 1-hr temporal resolution. Referred to in this report as the BAM-1020, this is the equipment used at regional air district monitoring stations to determine whether an area is in attainment of air quality standards. Also collocated with the sensors were a GRIMM 11-R dust monitor that reports particle counts in 31 size bins at 1-min temporal resolution, and an R.M. Young 05305V meteorological station that measures wind speed and direction at 1-min temporal resolution. STI performed a comprehensive data analysis to address the project objectives and evaluated all monitoring and data reporting components to develop guidelines for future deployments. STI and SBCAPCD staff also discussed the study with Cuyama

Valley High School students, prepared a data set that the students could use to answer their questions about air quality at the school, and shared the data set with the students.

This study found that

- The low-cost PM sensors examined are capable of detecting high PM concentration episodes related to windblown dust.
- Data recovery was sufficiently high for reliably detecting dust events.
- Sensor precision was sufficiently high for use in a network to identify and characterize hotspots, or to obtain localized data to augment information from the regional monitoring system.
- The sensors could be used as part of an early warning system that could inform decisions to limit exposure to PM.

2. Study Design

2.1 Overview

The field study took place from April 4, 2016, to July 6, 2016. Figure 1 shows a satellite image of the monitoring site at Cuyama Valley High School relative to nearby agricultural areas. The site was chosen due to its proximity to the school, accessibility, security, and access to power for the equipment.

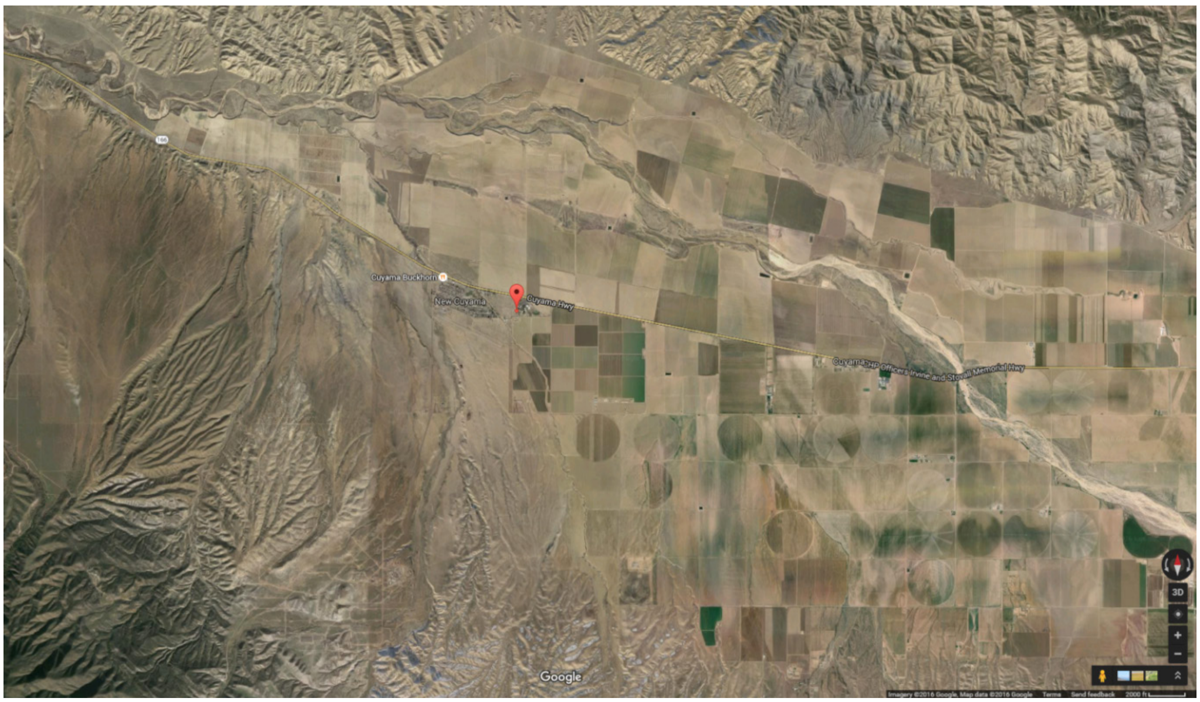

Figure 1. Satellite imagery from Google Earth showing the location of the monitoring site (red pin) at Cuyama Valley High School relative to nearby agricultural areas.

Table 1 lists the instrumentation used in the study. The equipment installed included a MetOne BAM-1020 FEM PM_{10} monitor, a GRIMM 11-R optical particle counter, six low-cost PM sensors (three Alphasense OPC-N2s that measure PM_{10} and $PM_{2.5}$ and three AirBeams that measure $PM_{2.5}$), and a R.M. Young 05305V wind sensor. These instruments were deployed from April 4, 2016, to July 6, 2016. The SBCAPCD also deployed an E-BAM at the monitoring site between April 4, 2016, and June 30, 2016; however, the analyses here focus on findings from the instrumentation deployed by STI.

The BAM-1020 was deployed to evaluate sensor[1] performance (i.e., accuracy) and data quality. The equipment measures particle mass by collecting dust on a filter tape and measuring the attenuation of Beta rays across the tape to estimate PM concentration. Three of each of the two low-cost sensor models were deployed to assess sensor precision and reliability. These sensors use light scattering to measure particle counts in units of hundreds of particles per cubic foot and use internal algorithms to convert particle counts to concentrations in units of µg/m^3. The amount of light scattering depends not only on particle count, but also on the size, shape, color, and reflective properties of the particles. The cost of a BAM-1020 is approximately $23,000. Retail cost is approximately $250 for an AirBeam sensor and approximately $500 for an Alphasense sensor.

The GRIMM was deployed to obtain particle size information and assist with interpretation of sensor performance as a function of particle size. The GRIMM is a portable aerosol spectrometer that sends single particles across a light beam and then measures the resulting scattering of light. Light-scattering properties are proportional to particle size, and the occurrence of scattering provides particle count in a known volume of air. The GRIMM reports the number of particle counts in each of 31 size bins spanning 0.25–32 µm. Mass can be calculated from GRIMM measurements using assumptions of particle density by size and particle counts.

Table 1. Summary of study instrumentation.

Instrument	Company	Measurement	Resolution	Technique
BAM-1020	MetOne Instruments	PM_{10} (µg/m^3)	1-hr	Beta attenuation
GRIMM 11-R	GRIMM Aerosol	Particle counts in 31 size bins spanning 0.25-32 µm	1-min	Light scattering
Alphasense OPC-N2	Alphasense	$PM_{2.5}$, PM_{10} (µg/m^3)	1-min	Light scattering
AirBeam	HabitatMap	$PM_{2.5}$ (µg/m^3)	1-min	Light scattering
R.M. Young 05305V	Young USA	Wind speed and direction	1-min	Propeller and vane
E-BAM	MetOne Instruments	PM_{10} (µg/m^3)	1-min	Beta attenuation

Figures 2 through 7 show the sensors and equipment installed at the monitoring site. All of the instruments were located within a few feet of one another, and the monitoring site was fenced in for security (Figure 4). The three Alphasense and three AirBeam sensors were initially housed in three boxes on a small tripod (Figure 5). Each box was equipped with a vent to allow air to be drawn in and a small exhaust fan to blow air out. The meteorological equipment was located on a second tripod.

[1] In this document, the term sensor is used to refer to the Alphasense and/or AirBeam instruments.

The BAM-1020 and GRIMM were housed in a climate-controlled shelter (Figure 6). Data collected during the study were stored onsite and transmitted in real-time to STI's servers via a cellular modem for archival within a data management system (DMS) developed for the project. Data were also made available for review on a project website.

In STI's previous experience working with low-cost PM sensors, STI has found evidence of a sampling bias associated with the orientation of the sensor sampling inlet. To assess whether there are any impacts from sampling orientation on sensor measurements, the sampling orientation for the sensors was varied as shown in Table 2. Furthermore, on June 1, 2016, Alphasense A was relocated to a third tripod so that it could sample omnidirectionally to further assess the impacts of sampling orientation (Figure 7).

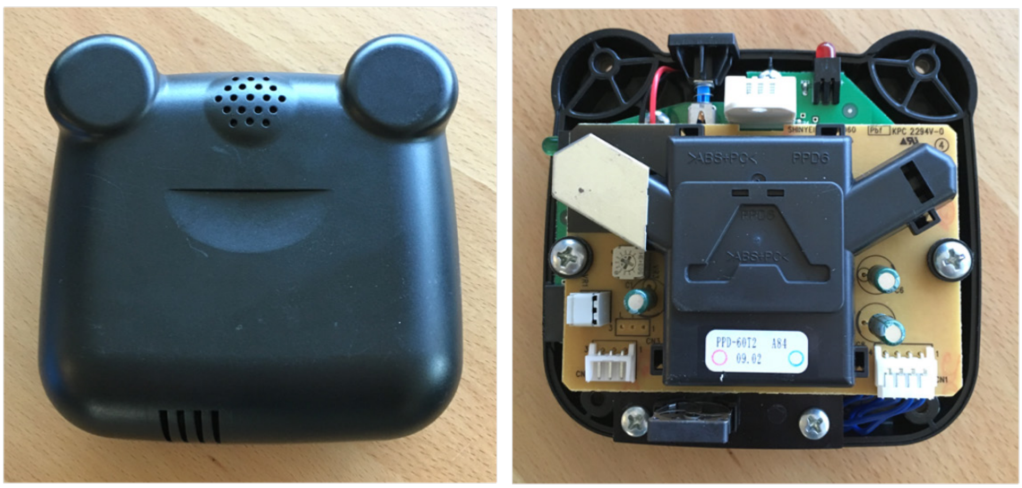

Figure 2. Photographs of the exterior (left) and interior (right) of the AirBeam sensor.

Figure 3. Photograph of the Alphasense sensor.

Figure 4. Monitoring equipment and site.

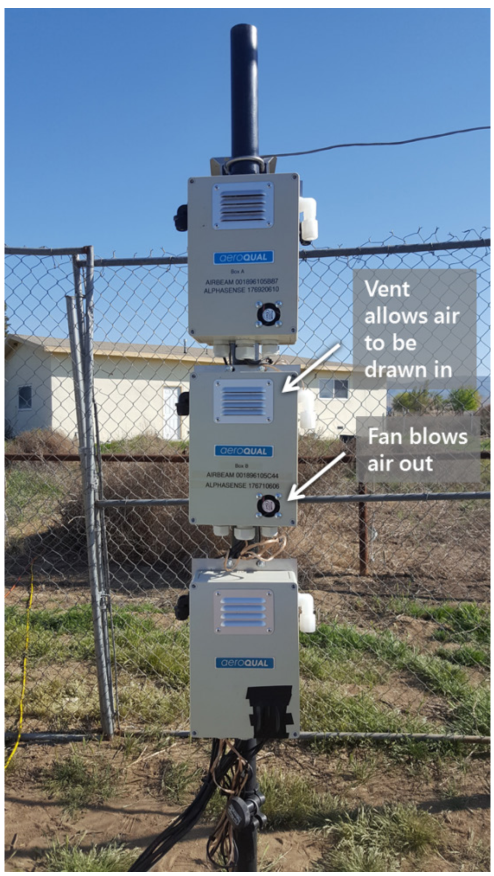

Figure 5. Housing for Alphasense and AirBeam sensors.

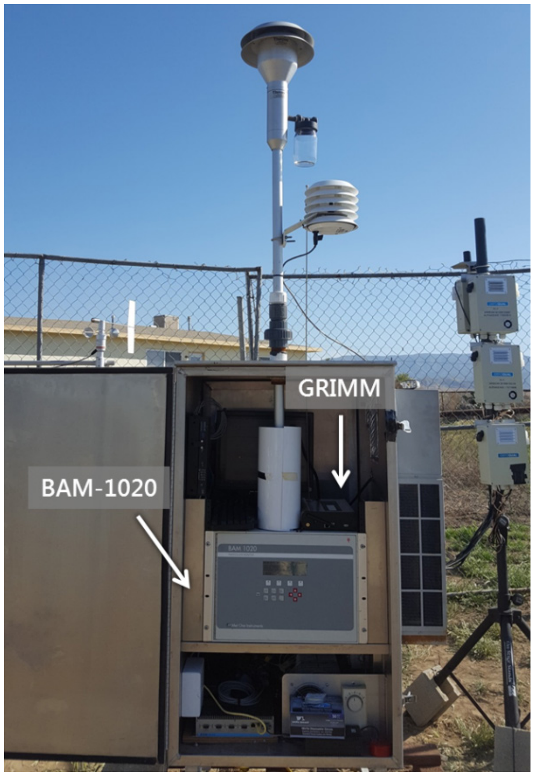

Figure 6. The climate-controlled shelter housing the BAM-1020 and GRIMM instruments.

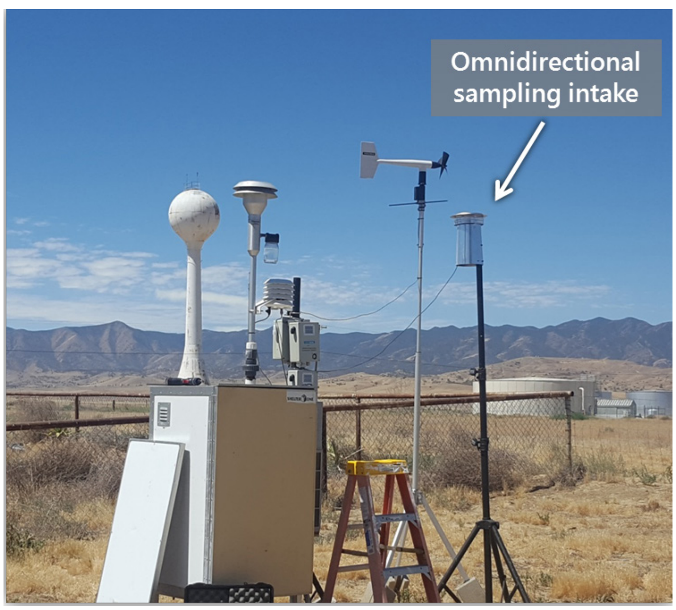

Figure 7. Site layout after June 1, 2016, when Alphasense A was relocated to another tripod (far right) and equipped with omnidirectional sampling equipment.

Table 2. Instrument sample orientation.

Instrument	Sampling Orientation
BAM-1020	Omnidirectional
GRIMM 11-R	Omnidirectional
Alphasense A	North/Omnidirectional[a]
Alphasense B	North
Alphasense C	South
AirBeam A	North
AirBeam B	North
AirBeam C	South
E-BAM	Omnidirectional

[a] Between April 4, 2016, and June 1, 2016, Alphasense A sampled from the north. On June 1, 2016, Alphasense A was relocated to a new tripod, where it sampled omnidirectionally until July 6, 2016.

2.2 Data Management and Review

During the three months of data collection, the data were reviewed daily to ensure that the equipment remained operational. Qualitative comparisons among the low-cost sensors and BAM-1020 were made by reviewing time-series and scatter plots within the DMS and project website to ensure that data from the instruments remained comparable over time. Figure 8 shows a screenshot of the project website. Additional data quality control, including time stamp review, was completed prior to analysis.

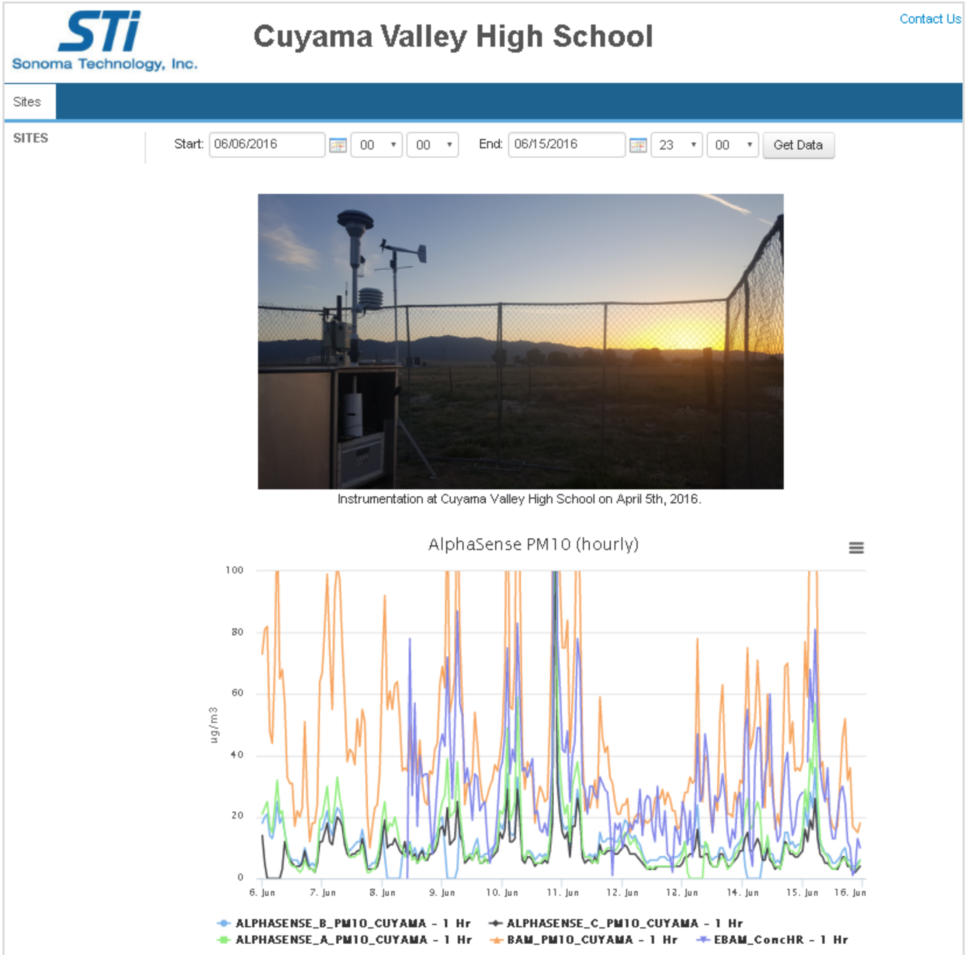

Figure 8. Project website.

Instrument setup began on April 4, 2016. During the study, the following periods of missing data and issues with data quality occurred:

- Onsite configuration of the data logging for the sensors was more challenging than anticipated. Onsite troubleshooting of issues resulted in some periods of data loss during the first week of the study.
- Following a rainstorm at the onset of the study, the GRIMM stopped working. STI worked with the manufacturer but was unable to correct the issue, and the instrument had to be replaced. As a result, GRIMM data were not available until April 22, 2016.
- The pump for the E-BAM failed in late May, and data were unavailable for the end of May and the first week of June.
- A community-wide power outage occurred on May 31, 2016, and data were not available between 4:00 p.m. and 8:00 p.m. on that day.

- Several periods of missing Alphasense data during the first half of the study were caused by communication issues between the Alphasense sensors and the data logger. The sensors were set up to connect to the data logger every minute; however, if the connection could not be made, the sensor would shut off. Once the issue was identified, data communication was reprogrammed so that the sensors would automatically turn back on after an interruption in communication with the data logger.

3. Field Study Results

This section presents an overview of the meteorological conditions and PM_{10} concentrations during the study and discusses sensor performance, which encompasses precision, accuracy, sampling orientation, meteorological impacts, reliability, drift, and the potential for early detection of high PM concentration events. Because of the instrument issues that occurred prior to April 14 (as discussed in Section 2.2), the analysis and results discussed here are for April 14, 2016, through July 6, 2016.

3.1 Air Quality and Meteorology Summary

To characterize the prevalence and timing of high PM concentration episodes at Cuyama Valley High School, we first examined meteorological data and PM_{10} measurements from the BAM-1020 over the length of the study. For the purposes of the analysis, a PM_{10} concentration threshold of 50 µg/m^3 was used to define “high PM” because this is the value of the 24-hr PM_{10} California Ambient Air Quality Standard. Figure 9 shows a wind rose for April 14, 2016, through July 6, 2016. During the study period, winds were typically light (1-2 m/s) and out of the southeast, although moderate northwesterly winds were also observed. The average wind speed was approximately 2 m/s.

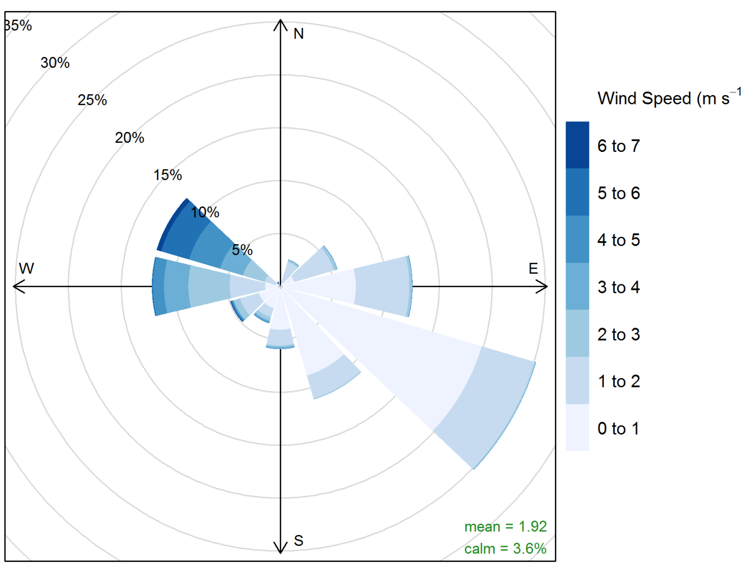

Figure 9. Wind rose for April 14, 2016, through July 6, 2016.

Figure 10 shows hourly PM_{10} concentrations recorded by the BAM-1020. High hourly PM_{10} concentrations, exceeding 50 µg/m^3, occurred frequently during the study. The average hourly PM_{10} concentration recorded by the BAM-1020 was 34 µg/m^3; the median value was 25 µg/m^3. The maximum PM_{10} concentration observed was 758 µg/m^3. While high PM_{10} concentrations exceeding 50 µg/m^3 were observed throughout the study, high concentration episodes were more prevalent in June and early July than in April and May. To examine regional transport patterns, STI modeled transport trajectories for several of the high PM_{10} concentration days identified during this study using the Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT).[2] Modeled regional transport patterns suggest that on some days, PM_{10} from the California Central Valley is transported to the New Cuyama area, contributing to the concentrations observed (not shown); however, the short-duration high-concentration events reported by the sensors (see Section 3.2.4) suggest that local transport of dust is also a major contributor to the observed high PM_{10} concentrations.

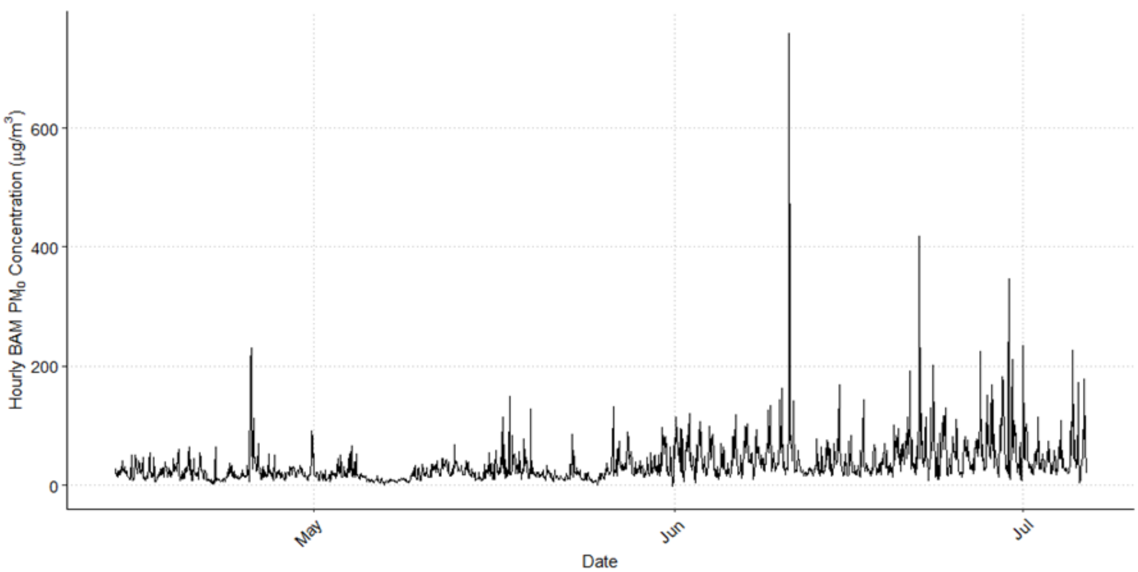

Figure 10. Hourly PM_{10} concentrations recorded by the BAM-1020 between April 14, 2016, and July 6, 2016.

[2] The National Oceanic and Atmospheric Administration's (NOAA) publicly available HYSPLIT model was used for the trajectory modeling (http://ready.arl.noaa.gov/HYSPLIT.php). HYSPLIT is a widely used model that calculates the path of a single air parcel from a specific location and height above the ground over a period of time; this path is the modeled trajectory.

Figure 11 shows daily 24-hr average PM_{10} concentrations recorded by the BAM-1020 for April 14, 2016, through July 6, 2016. Daily average PM_{10} concentrations ranged from 6.0 to 92.3 µg/m^3; concentrations exceeded 50 µg/m^3 on 18 of 84 days (21% of the time).

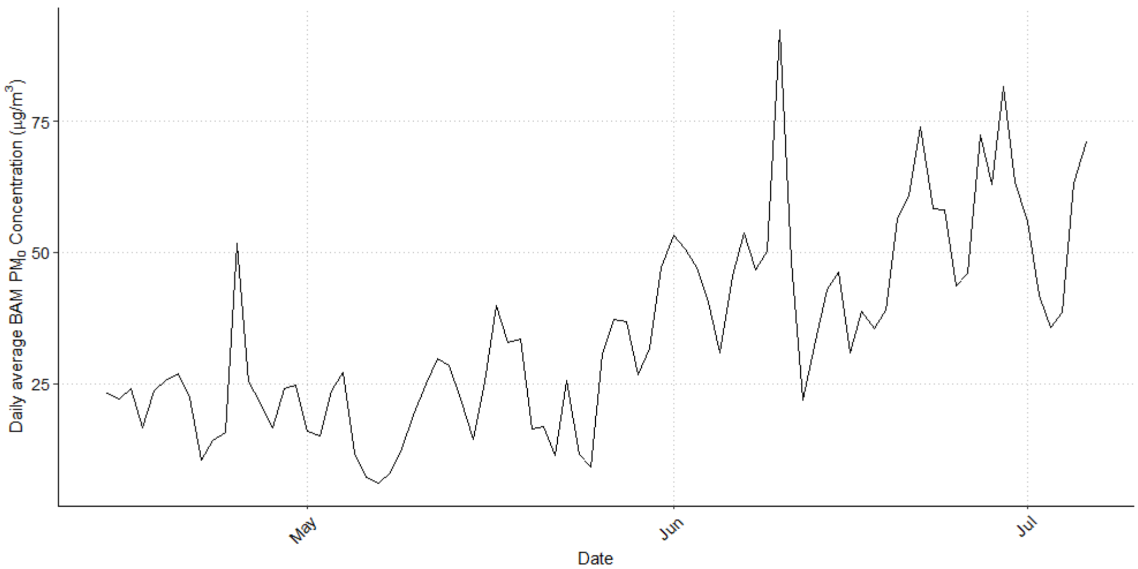

Figure 11. Daily average PM_{10} concentrations recorded by the BAM-1020 from April 14, 2016, through July 6, 2016.

To characterize wind conditions when high PM_{10} concentrations occurred, Figure 12 shows a wind rose of hourly data collected when the BAM-1020 recorded PM_{10} concentrations of 50 µg/m^3 or higher. High hourly PM_{10} concentrations typically occurred during low wind speed conditions when winds were out of the southeast, in the direction of nearby agricultural areas. However, PM_{10} concentrations were also high when there were strong winds from the northwest.

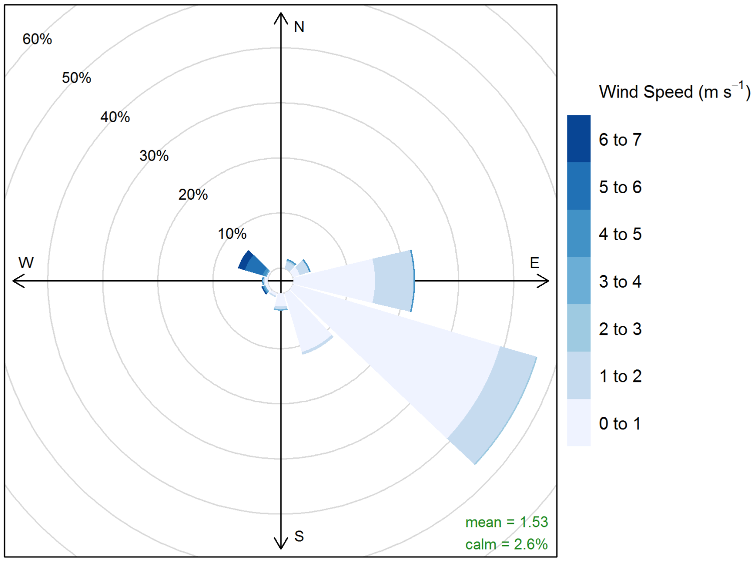

Figure 12. Wind rose for hours during April 14, 2016, through July 6, 2016, when the BAM-1020 recorded hourly PM_{10} concentrations at or above 50 µg/m^3.

Figure 13 shows the count of hourly BAM-1020 PM_{10} concentrations at or above 50 µg/m^3 by time of day. High PM_{10} concentrations typically occurred during the morning hours, between midnight and 9:00 a.m.

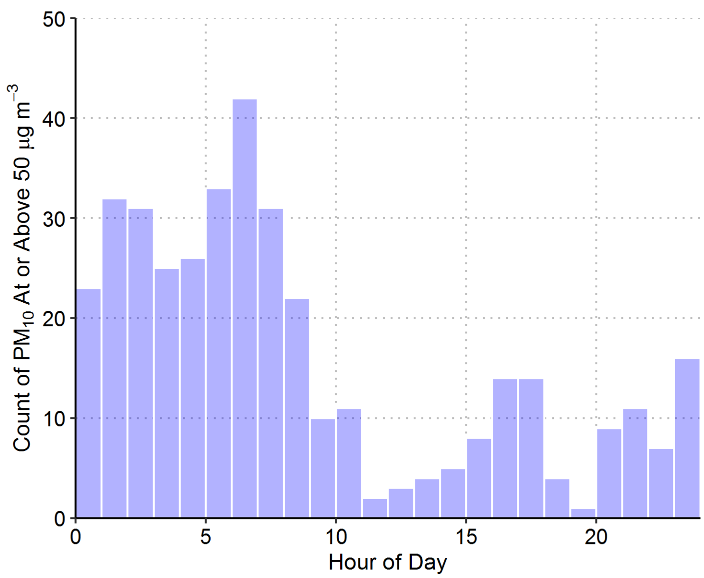

Figure 13. Hourly PM_{10} concentrations at or above 50 µg/m^3 by time of day from April 14, 2016, through July 6, 2016.

3.2 Sensor Performance

Our assessment of sensor performance is based on the assumption that there are differing degrees of trust in the measurements from different instruments. The "gold standard" is the federal equivalent method BAM-1020, with the highest degree of trust. Next are the GRIMM size distribution measurements and the E-BAM, with moderate degrees of trust. Finally are the Alphasense and AirBeam sensors that we are evaluating in this study. Sensor performance was assessed by examining sensor precision, accuracy, reliability, drift, and potential for detecting high PM concentration events.

3.2.1 Precision

To assess sensor precision, we compared 1-min average measurements among the Alphasense and AirBeam sensors. For example, Figure 14 compares 1-min average PM_{10} concentrations from the Alphasense B and Alphasense C sensors. All three sensors were well correlated with one another (R^2 = 0.81−0.90), indicating good precision, particularly at high concentrations.

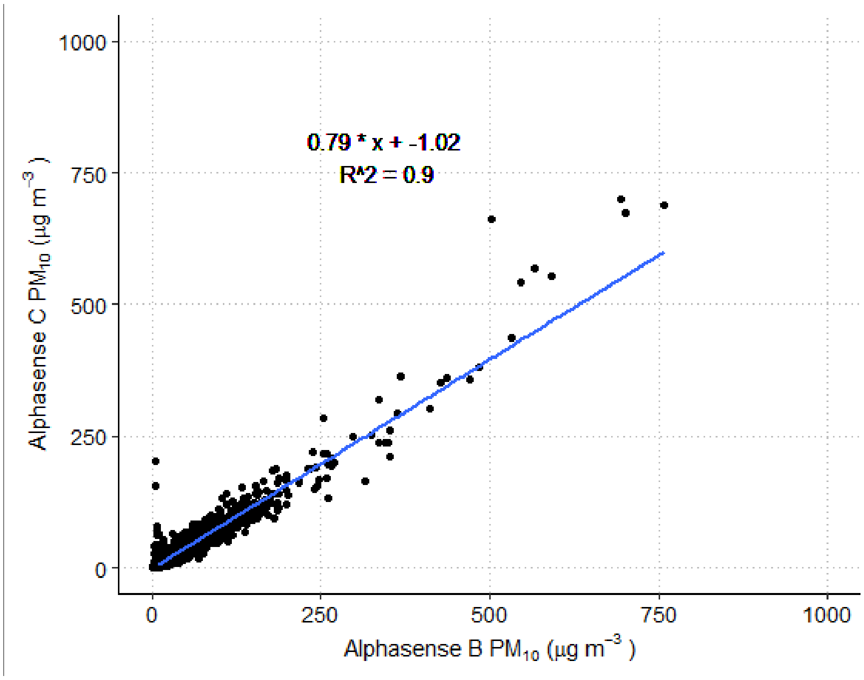

Figure 14. Comparison of 1-min average PM_{10} concentrations from Alphasense B and Alphasense C collected between April 14, 2016, and July 6, 2016.

Average $PM_{2.5}$ concentrations from the three AirBeam sensors were also well correlated (R^2 = 0.90−0.95) throughout the study (see, for example, Figure 15).

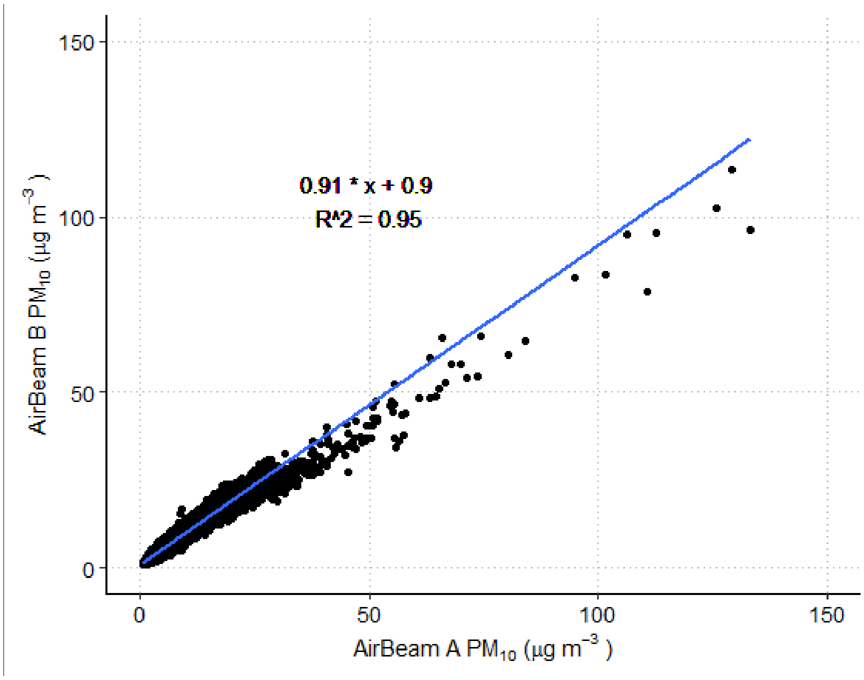

Figure 15. Comparison of 1-min average $PM_{2.5}$ concentrations from AirBeam A and AirBeam B collected between April 14, 2016, and July 6, 2016.

3.2.2 Accuracy

To assess sensor accuracy, hourly average sensor measurements were compared with hourly PM_{10} concentrations from the BAM-1020. The BAM-1020 data were treated as accurate. Figure 16 shows the relationship between hourly PM_{10} concentrations measured by the Alphasense B sensor and the BAM-1020. The Alphasense and BAM-1020 measurements are fairly well-correlated (R^2 = 0.67); however, on average, the magnitudes of the BAM-1020 measurements are more than a factor of six higher than those reported by the Alphasense B sensor (slope of best fit = 0.16). Comparisons between the Alphasense A and Alphasense C sensor data with the BAM-1020 exhibited similar results (R^2 = 0.61–0.76; slope = 0.13–0.22). The relatively good correlation between the sensors and the BAM-1020 indicates that a correction factor can be derived from the comparison between sensor and BAM-1020 measurements. The correction factor can be applied to correct the sensor bias and achieve better accuracy. For example, a correction factor of 6.25 was derived from the relationship between the Alphasense B and BAM-1020 data shown in Figure 16; this factor could be applied to the Alphasense B data to achieve better agreement with the BAM-1020. Note that the appropriate correction factor may vary by location, by sensor, and over time, particularly if drift in sensor response is an issue (see drift discussion in Section 3.2.3).

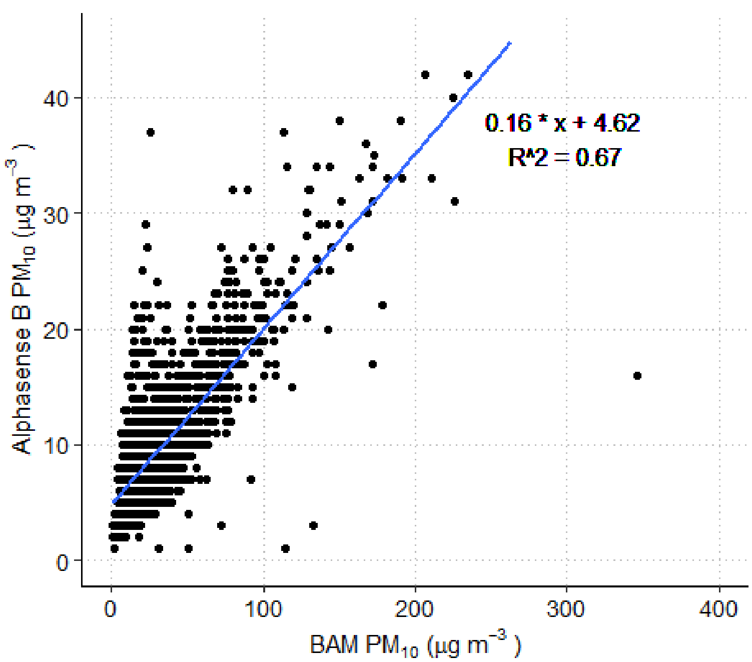

Figure 16. Comparison of hourly average PM_{10} concentrations from Alphasense B and the BAM-1020 collected between April 14, 2016, and July 6, 2016.

Similarly, Figure 17 shows the relationship between hourly $PM_{2.5}$ concentrations measured by AirBeam B and the BAM-1020. The AirBeam measurements are not as well correlated with the BAM-1020 as the Alphasense sensors are (R^2 = 0.21), and they are biased low compared to the BAM-1020 (as expected, given that the AirBeam measures $PM_{2.5}$, and the BAM-1020 measures PM_{10}). Comparisons between the AirBeam A and AirBeam C sensor data with the BAM-1020 exhibited similar results (R^2 = 0.25−0.33; slope = 0.05−0.06).

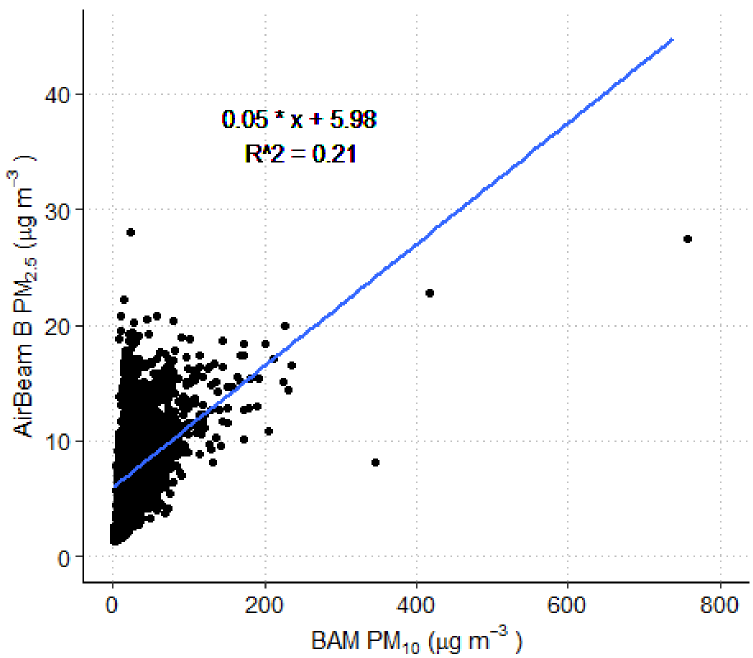

Figure 17. Hourly average $PM_{2.5}$ concentrations measured by AirBeam B versus hourly average PM_{10} concentrations measured by the BAM-1020.

Sampling Orientation

On June 1, 2016, Alphasense A was relocated to a third tripod to sample omnidirectionally so that analysts could assess whether sampling orientation impacted sensor measurements. At the beginning of the study, Alphasense A had sampled from the north; Alphasense B sampled from the north and Alphasense C sampled from the south during the entire study. Figure 18 shows the relationship between Alphasense A and the BAM-1020 during the one week before and the one week after the sensor was moved. The correlation and slope of the best fit lines between the Alphasense A and BAM-1020 increased after the sensor was moved (before: R^2=0.78, slope=0.24; after: R^2=0.90, slope=0.31). The increased correlation and slope suggest that sampling orientation may play a significant role in the PM fraction sampled by the sensor. Sampling orientation is expected to be important for sampling by the AirBeam instruments as well but was not tested as part of this study.

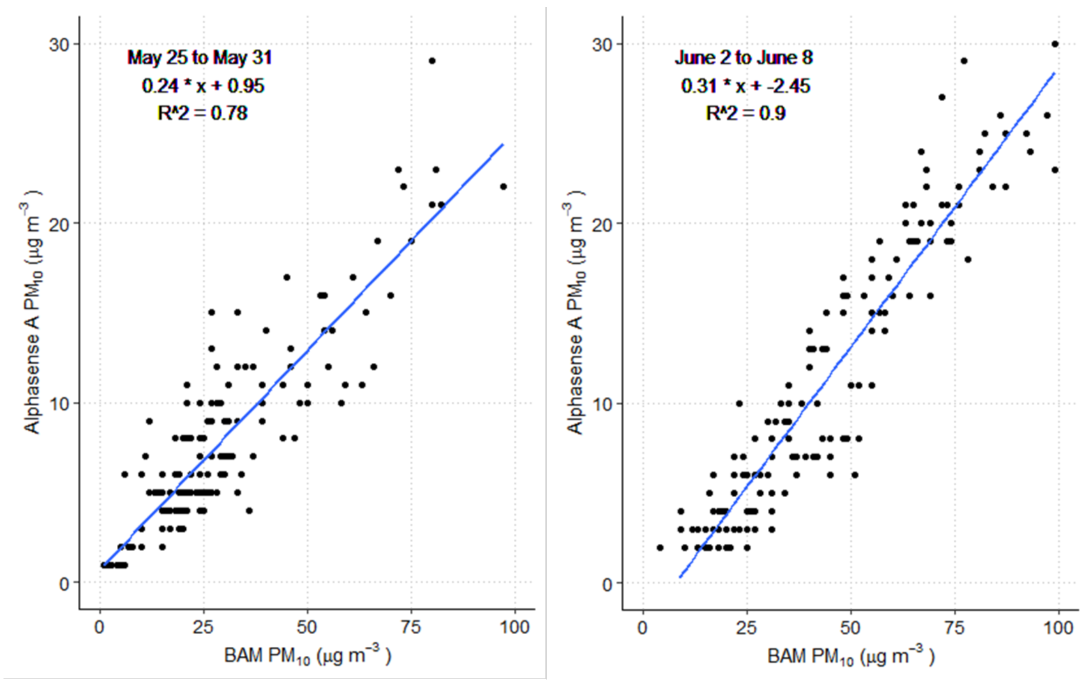

Figure 18. Comparison between hourly PM_{10} concentrations from Alphasense A and the BAM-1020 during the week before (left) and week after (right) Alphasense A was moved to sample omnidirectionally. Note: x and y axis scales are different.

3.2.3 Reliability and Drift

Data Recovery

Table 3 summarizes data recovery from April 14, 2016, through July 6, 2016. Periods of data loss that occurred during system installation (prior to April 14, 2016) are not included in the number of possible samples since data loss during those periods was not related to the performance of the sensor technology specifically. Data completeness of 75% of 1-min samples was required for each 1-hour sample. Data completeness was high (greater than 88%) on both 1-min and 1-hour average time frames for all sensors. As discussed in Section 2.2, several periods of missing Alphasense data during the first half of the study were caused by communication issues related to the data logger rather than the Alphasense sensor itself. Neglecting data loss related to the data logger issue, data recovery for the Alphasense sensors was over 99% for 1-min data and approximately 100% for hourly data.

Table 3. Data recovery for the sensors from April 14, 2016, through July 6, 2016.

Sensor	Number of Possible Samples	Number of Samples Recovered	% Recovery 1-min	% Recovery 1-hr
Alphasense A	120,181	105,934*	88.1	88.7
Alphasense B	120,181	107,613*	89.5	95.4
Alphasense C	120,181	106,204*	88.3	92.4
AirBeam A	120,181	119,548	99.5	100.0
AirBeam B	120,181	119,689	99.6	100.0
AirBeam C	120,181	119,689	99.6	100.0

* Data recovery for the Alphasense was lower during the first half of the study due to an issue related to communication with the data logger.

Drift

Drift refers to a gradual change in sensor response to the same pollutant concentration over time and is a common issue for some air quality sensing techniques. Drift in sensor response was evaluated by examining whether the relationship between measurements from each sensor and the BAM-1020 PM_{10} and GRIMM $PM_{2.5}$ changed substantially over time. Examination of the Alphasense PM_{10} and $PM_{2.5}$ data revealed that all three Alphasense sensors exhibited modest drift over the study period. Figure 19 illustrates drift from the Alphasense B sensor by showing the relationship between the BAM-1020 and Alphasense B PM_{10} near the beginning of the study and near the end of the study. The response of the Alphasense B sensor relative to the BAM-1020 decreased slowly over the length of the study. Similarly, the AirBeam sensor also exhibited modest drift when compared with $PM_{2.5}$ concentrations reported by the GRIMM, although to a lesser extent than the Alphasense. Drift in sensor response may indicate sensor degradation over time; however, it could also indicate a difference in sensor response related to a change in particle morphology or composition over the course of the study. STI contacted Alphasense regarding the drift issue; Alphasense noted that they have seen dust collect on the photodiode or the laser over time under very high PM conditions but would expect the correlation to have decreased if this were an issue for this study. They noted that dust can gather on the fan and impact the fan's performance and subsequent airflow, which would impact the magnitude of the sensor response. A future study could collect sample flow rate data for the Alphasense sensors to determine whether dust collection on the fan impacts sensor response in the Santa Barbara County area. Note that this issue could be of less concern if the sensor were used as a handheld sensor to collect data at periodic intervals rather than being sited at a location for operation 24 hours a day.

Drift in sensor response weakens the correlation between the sensor and the BAM-1020 over the entire study period, shown in Figure 16 (R^2 = 0.67). Correlations between a sensor and BAM-1020 are stronger over a shorter time period (e.g., in Figure 19, one week) than over the full three-month study (Figure 16); drift contributes to the weaker correlation over the entire study.

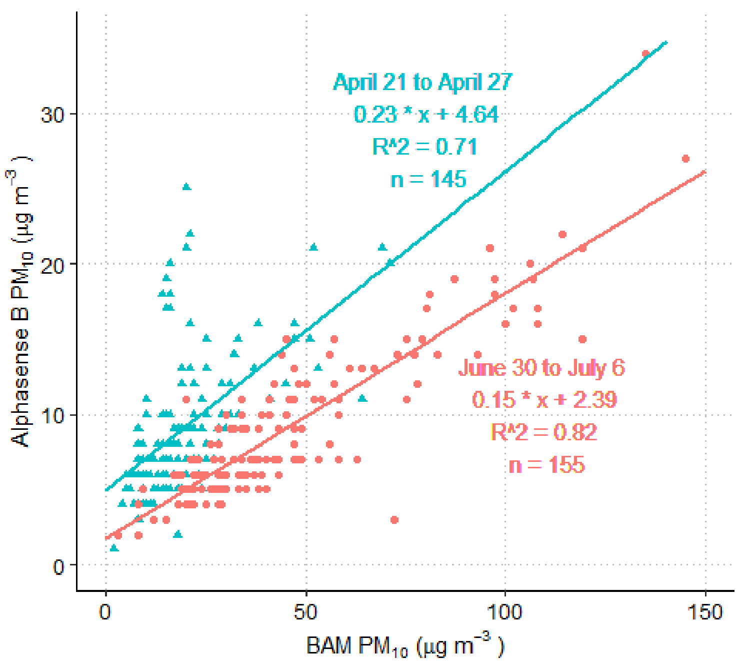

Figure 19. Comparison between hourly PM_{10} concentrations from the BAM-1020 and Alphasense B sensor near the beginning of the study (April 21-27; blue) and near the end of the study (June 30–July 6; pink).

3.2.4 Potential Use for Early Detection

To investigate whether the sensors could be useful for detecting high PM concentration events, we examined sensor response on 10 occasions when the BAM-1020 recorded PM_{10} concentrations above 200 µg/m^3. As an example, Figure 20 shows PM_{10} concentrations recorded by the three Alphasense sensors and the BAM-1020 during the evening hours on June 10, 2016. The BAM-1020 samples between minutes 0 and 52—for example, the values shown between 9:00 p.m. and 9:59 p.m.—were collected from 9:00 p.m. to 9:52 p.m. Figure 20 illustrates that background PM concentrations are typically low, and that high concentration episodes are typically short in duration (less than one hour). High temporal resolution measurements, less than 1 hour in duration, are better than 1-hr measurements for characterizing these events. In the June 10 example, Alphasense A recorded a peak concentration at 9:21 p.m., 39 minutes before the 1-hr measurement from the BAM-1020 would be available. Since the BAM-1020 does not sample eight minutes out of 60, it will miss short-duration events 13% of the time. The other 87% of the time, the 1-min data provided by sensors offer early detection of high concentration episodes, an average of 34 minutes in advance of BAM-1020 measurements.

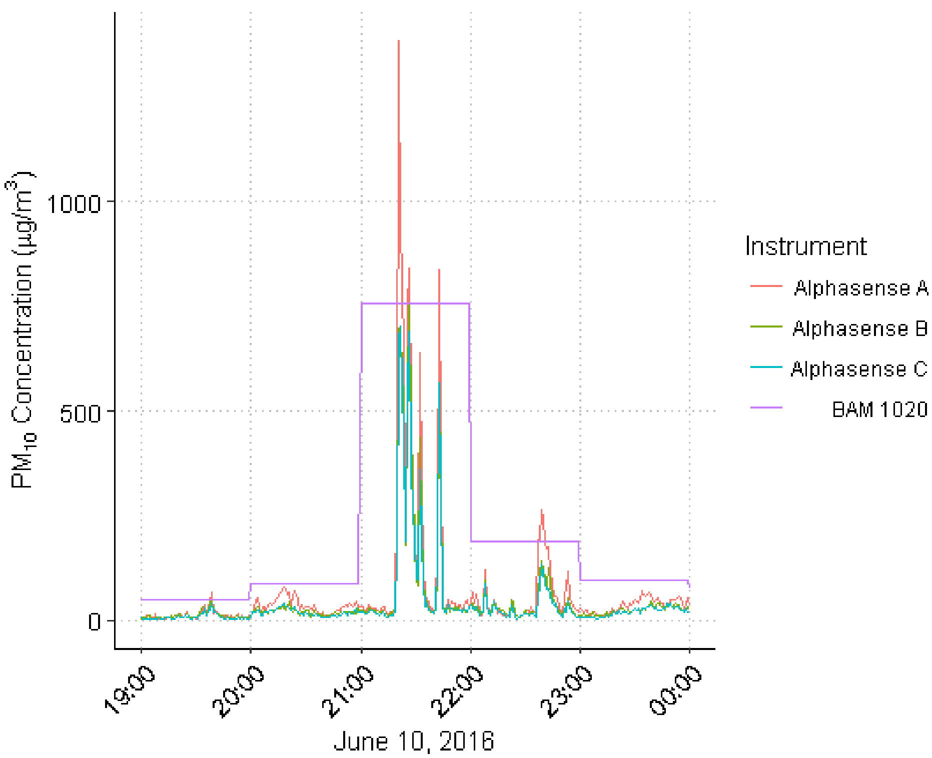

Figure 20. Hourly PM_{10} concentrations measured by the BAM-1020 and 1-min average PM_{10} concentrations measured by the three Alphasense sensors on June 10, 2016. The BAM-1020 measurements at 21:00 would have been available at 22:00.

Figure 21 shows measurements from the three Alphasense sensors and the BAM-1020 on the morning of June 23. High PM_{10} concentrations were measured between 6:00 and 7:00 a.m. by all three Alphasense sensors and the BAM-1020; however, the Alphasense sensors also reported peak concentrations at 6:59 a.m. when the BAM-1020 was not sampling. This example illustrates that in some cases, brief events occurring at the end of an hour will be missed by the BAM-1020 because of its sampling period.

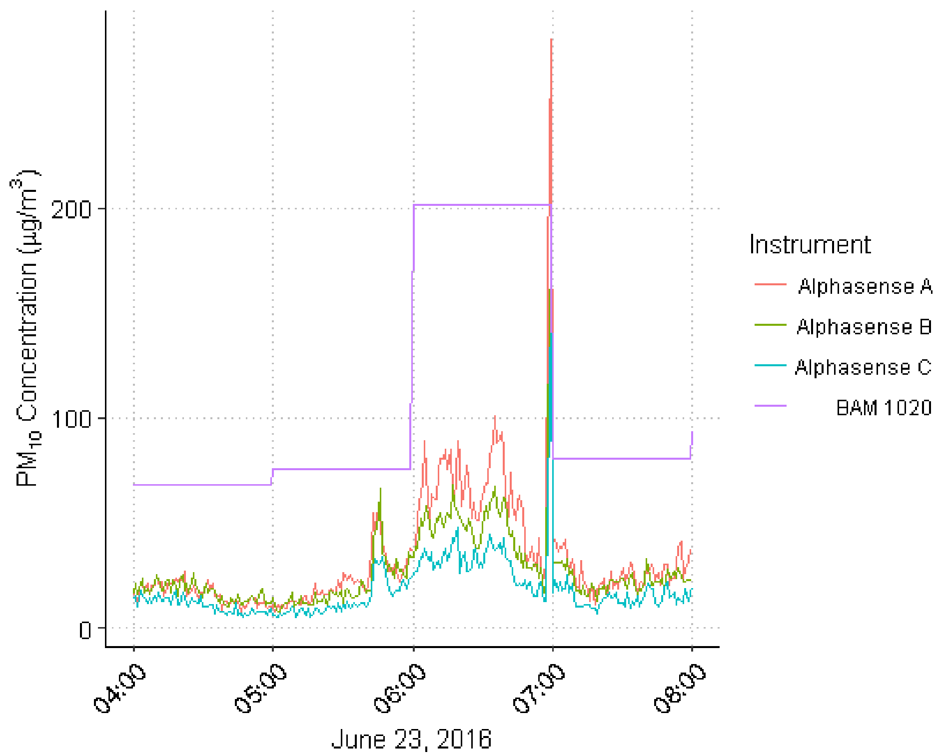

Figure 21. Hourly PM_{10} concentrations measured by the BAM-1020 and 1-min average PM_{10} concentrations measured by the three Alphasense sensors on June 23, 2016.

4. Conclusions and Discussion

This study found that the low-cost PM sensors are capable of detecting high PM concentration episodes related to windblown dust in Santa Barbara County. Comparisons between hourly data from the sensors and the BAM-1020 reference PM_{10} instrument showed that the sensor data is highly correlated with the BAM-1020 measurements; the Alphasense sensor was better correlated since it measures PM_{10}, whereas the AirBeam only measures $PM_{2.5}$. Data recovery from the sensors was high (>99%) for the two types of sensors tested once data transmission issues had been resolved, suggesting that data completeness from sensors is sufficiently high to reliably detect dust events. Comparisons between sensor and BAM-1020 measurements show that the sensors are capable of detecting events as much as 59 minutes before the time when BAM-1020 measurements would be available and that in some cases, the sensors captured high concentration dust events that were missed by the BAM-1020. These findings suggest that the sensors could be used as part of an early warning system to inform decisions to reduce exposure to high PM concentrations.

Comparisons among sensors indicate that the sensor precision is sufficiently high over a 1-min averaging period (R^2 = 0.81-0.95) that the sensors could be used in a network to monitor the spatial variability of PM and identify PM hotspots. However, this pilot study characterized sensor performance over a three-month period. The long-term reliability of the sensors was not tested. Analysis of the sensor data revealed that some drift occurs; however, drift did not impact the ability of the sensor to detect dust events over the three-month duration of this study.

We recommend focusing on the Alphasense PM sensor over the AirBeam for future studies and use because of the good performance results and because it can characterize both $PM_{2.5}$ and PM_{10}. The fact that the data from the sensors correlated well with the federal equivalent method BAM-1020 data indicates that sensors could be used to gather localized data to augment the information available from the regional monitoring network.

A long-term goal was to create a network of low-cost PM sensors to warn school personnel and others of high PM concentrations. While this project demonstrated that low-cost PM sensors can detect dust, a number of additional actions are needed to reach this goal:

- Conduct a year-long study to assess the long-term sensor reliability and performance for detecting high PM concentrations related to dust events.
- Deploy a network of at least 6 to 10 sensor nodes to examine the spatial variability of the PM events.
- Design a notification system (websites and alerting system). Get feedback from school officials and air district staff. Create the notification system and operate it on a pilot basis for the year-long study.
- Survey school officials on the usefulness of the notification system and make appropriate changes.

- Evaluate the sensor performance over the year-long period by examining data completeness, maintenance, quality, cost, and reliability.

5. School Participation

To engage Cuyama Valley High School students and teachers, SBCAPCD and STI made two visits to Cuyama Valley High School to demonstrate monitoring equipment and share an overview of the monitoring study and study findings. During the first visit on June 1, 2016, SBCAPCD and STI staff showed science students the sensor study equipment in place at the school monitoring site (Figure 22) and explained the goals and methods for the measurement study.

Figure 22. STI and SBCAPCD staff showing students the sensor equipment in June 2016.

The second visit occurred on November 2, 2016, when SBCAPCD staff spent a morning with Cuyama Valley High School physics students to provide an overview of the study and the objectives, and to describe some of the findings from the study (Figure 23). SBCAPCD staff also asked students for input on what information from the analysis results might be of most use to the students and teacher.

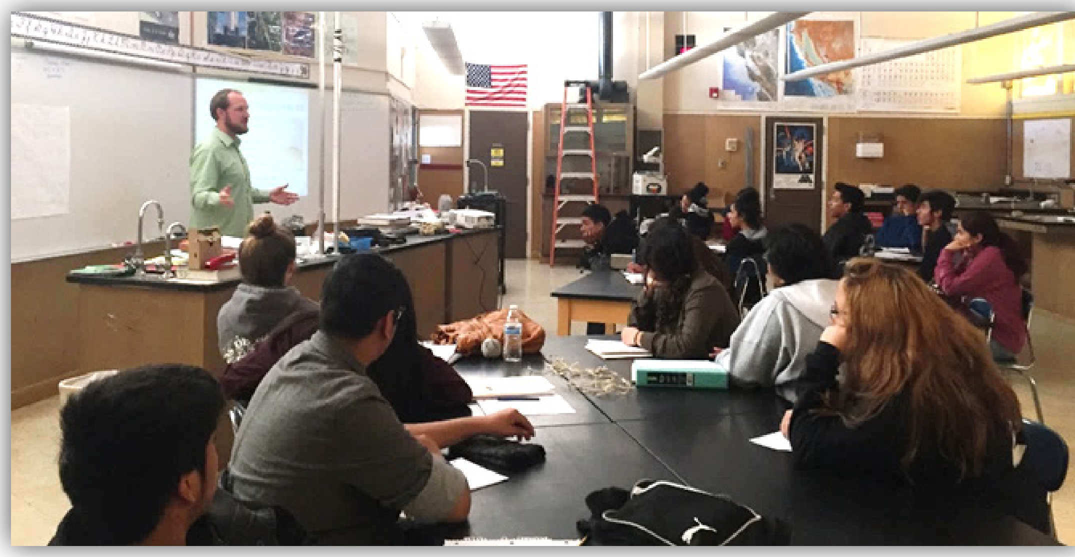

Figure 23. SBCAPCD staff talking to the students about air pollution and the sensor study during a visit to the school in November 2016.

During a presentation to the students, SBCAPCD discussed the following topics:

- SBCAPCD's mission and jurisdiction
- Various types of air pollution, with a focus on PM
- Sources of PM
- Health effects of PM exposure
- How PM has been measured and monitored historically
- Study questions and overview
- Monitoring equipment and sensors used
- Sensor performance, including precision, accuracy, and drift
- Reliability of the AlphaSense and AirBeam sensors
- Study conclusions

Following the presentation, staff showed the students a BAM-1020 reference instrument and two AirBeam PM sensors, synced with tablets for real-time data monitoring. Staff also showed the students a 400E Teledyne API ozone analyzer (Figure 24).

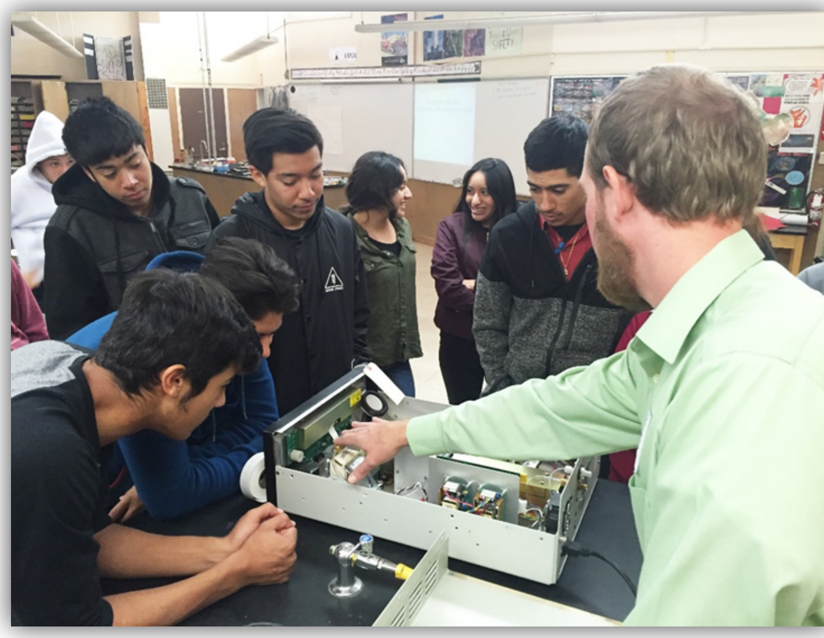

Figure 24. SBCAPCD staff showing students air quality instrumentation.

Seeing the different equipment side-by-side prompted questions from the students, including whether PM levels are elevated during sports practices or other outdoor activities. To allow the students to answer this question and to foster further discussion among the class, STI developed a data set for the students to analyze. Given the large volume of data collected during the study (see, for example, Table 3) and associated data analysis challenges of working with such a large volume of data, STI condensed the study data into a more manageable data set for the students to work with. To this end, STI provided a Microsoft Excel worksheet containing hourly average $PM_{2.5}$ concentrations from the BAM-1020, $PM_{2.5}$ concentrations from one Alphasense sensor (Alphasense A), PM_{10} concentrations from one AirBeam sensor (AirBeam A), wind direction, and wind speed (Figure 25).

	A	B	C	D	E	F	G	H	I	J
1	DateTime	Date	Time	Hour	Day of Week	BAM PM10 (ug/m3)	Alphasense A PM10 (ug/m3)	AirBeam A PM25 (ug/m3)	Wind Direction (degrees)	Wind Speed (m/s)
2	4/14/16 12:00 AM	4/14/2016	12:00 AM	0	5	27	15	15.19618	139	1
3	4/14/16 1:00 AM	4/14/2016	01:00 AM	1	5	24	25	27.14532	170	1
4	4/14/16 2:00 AM	4/14/2016	02:00 AM	2	5	15	19	20.90908	143	1
5	4/14/16 3:00 AM	4/14/2016	03:00 AM	3	5	15	11	12.83156	141	1
6	4/14/16 4:00 AM	4/14/2016	04:00 AM	4	5	24	14	12.711	140	1
7	4/14/16 5:00 AM	4/14/2016	05:00 AM	5	5	16	12	11.97668	127	1
8	4/14/16 6:00 AM	4/14/2016	06:00 AM	6	5	14	14	12.43974	148	1
9	4/14/16 7:00 AM	4/14/2016	07:00 AM	7	5	20	11	12.81238	193	1
10	4/14/16 8:00 AM	4/14/2016	08:00 AM	8	5	21	9	12.50276	34	1
11	4/14/16 9:00 AM	4/14/2016	09:00 AM	9	5	26	9	12.711	77	1
12	4/14/16 10:00 AM	4/14/2016	10:00 AM	10	5	18	6	9.29148	301	2
13	4/14/16 11:00 AM	4/14/2016	11:00 AM	11	5	26	8	9.57096	79	2
14	4/14/16 12:00 PM	4/14/2016	12:00 PM	12	5	23	7	9.85318	92	3
15	4/14/16 1:00 PM	4/14/2016	01:00 PM	13	5	21	7	8.74896	177	4
16	4/14/16 2:00 PM	4/14/2016	02:00 PM	14	5	41	11	11.6835	46	3
17	4/14/16 3:00 PM	4/14/2016	03:00 PM	15	5	25	9	11.02864	37	2
18	4/14/16 4:00 PM	4/14/2016	04:00 PM	16	5	24	7	8.88596	53	3
19	4/14/16 5:00 PM	4/14/2016	05:00 PM	17	5	27	6	6.13774	57	3
20	4/14/16 6:00 PM	4/14/2016	06:00 PM	18	5	29	8	5.58426	45	3
21	4/14/16 7:00 PM	4/14/2016	07:00 PM	19	5	31	8	5.18148	13	3
22	4/14/16 8:00 PM	4/14/2016	08:00 PM	20	5	24	7	5.56508	32	2
23	4/14/16 9:00 PM	4/14/2016	09:00 PM	21	5	20	8	5.89114	210	0
24	4/14/16 10:00 PM	4/14/2016	10:00 PM	22	5	24	10	8.26398	47	1
25	4/14/16 11:00 PM	4/14/2016	11:00 PM	23	5	19	11	9.77372	26	2
26	4/15/16 12:00 AM	4/15/2016	12:00 AM	0	6	24	12	10.43132	110	1

Data_Table_For_Cuyama_Valley

Figure 25. The Microsoft Excel spreadsheet shared with Cuyama Valley High School physics students.

As an example of an exercise that the class could complete with the data, STI also provided the teacher a second spreadsheet containing pre-calculated diurnal profiles for the entire study for the BAM-1020, Alphasense A, and AirBeam A, as well as a bar graph of the results (Figure 26). The diurnal profiles for PM_{10} and $PM_{2.5}$ are similar, indicating that PM concentrations at Cuyama Valley High School tend to be higher in the mornings than in the afternoon and evening hours, peaking at 6:00 a.m.

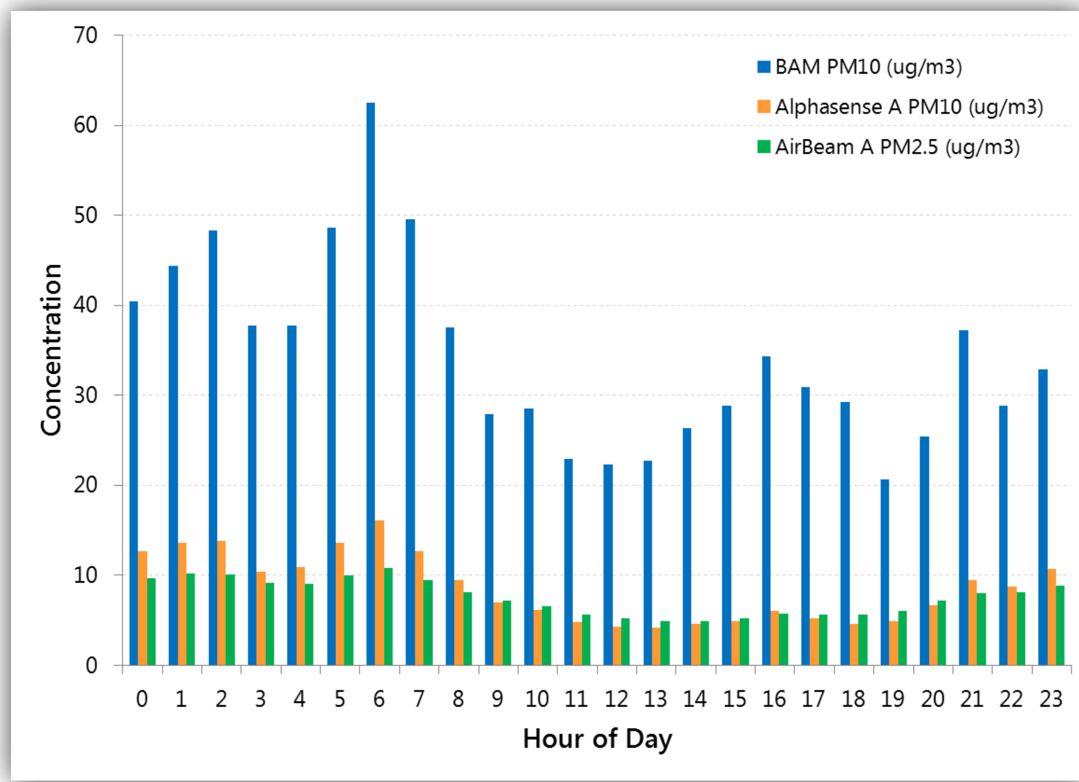

Figure 26. Average diurnal profiles for PM from April 14, 2016, to July 6, 2016.