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Evaluation of Field-deployed Low Cost PM Sensors

Office of Research and Development
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Disclaimer

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Acronyms and Abbreviations

AC/DC	alternating current/direct current
ACE	Air, Climate, and Energy Program
AIRS	Ambient Air Innovation Research Site
FEM	federal equivalent method
FRM	federal reference method
GC-MS	gas chromatograph–mass spectrometer
GFCI	ground fault circuit interrupter
GMT	Greenwich Mean Time
GSM	Global System for Mobile Communication
hi-vol	high volume
NAAQS	national ambient air quality standards
NERL	National Exposure Research Laboratory
NO_2	nitrogen dioxide
NRMRL	National Risk Management Research Laboratory
OAQPS	Office of Air Quality Planning and Standards
ORD	Office of Research and Development
PID	photoionization detector
PM	particulate matter
$PM_{2.5}$	particulate matter of diameter 2.5 microns or less
ppb	parts per billion
ppm	parts per million
QAPP	quality assurance project plan
R^2	coefficient of determination
RH	relative humidity, i.e., water vapor content of air expressed as a percentage of vapor pressure of water at a given temperature and pressure
ROP	research operating procedure
RTP	Research Triangle Park
SIM	subscriber identity module
UTC	Coordinated Universal Time
VAC	volts alternating current
VDC	volts direct current
VOC	volatile organic compound

WA	work assignment
WA COR	WA Contracting Officer’s Representative

Executive Summary

Background

Particulate matter (PM) is a pollutant of high public interest regulated by national ambient air quality standards (NAAQS) using federal reference method (FRM) and federal equivalent method (FEM) instrumentation identified for environmental monitoring. PM is present in the atmosphere in concentrations that can vary greatly according to location, temperature, and a number of circumstances that influence local air quality. Citizen scientists and other researchers have a desire to monitor this pollutant, and there is a need for increased accessibility to portable and economical monitoring and sampling equipment. The evolution of low cost PM sensors has resulted in a number of such instruments becoming commercially available. However, this evaluation was not conducted to assess the suitability of these PM sensors to serve as either FRM or FEM sampler instruments. This activity represents the first step in evaluating some of the commercially available low cost PM sensors and comparing their data-collection capabilities to that of collocated FEM samplers during field evaluations.

Study Objectives

As part of its Air Climate & Energy (ACE) research program on emerging technologies (ACE EM-3), the US EPA developed a research effort with the goals of: conducting a world-wide market survey of low cost PM sensors (<$2500), acquiring such sensors, and then conducting collocated field evaluations of these sensors in direct comparison with FEM instrumentation. A total of eight such devices were obtained and sited in the established PM sensor test platform on the US EPA's RTP, NC campus (AIRS). The collocated $PM_{2.5}$ FEM instrumentation with 5-minute time resolution provided the means to investigate both short duration and daily (24-hr) comparisons between the test devices and the FEM response. Potential data confounders such as temperature and relative humidity were obtained to aid in the investigation. The relationship between FEM response and the various sensors was established in a regression. Ancillary findings related to ease of use, portability, data collection efficiency, among others, were established based upon our experiences over approximately one month of continuous operation.

Study Approach

Direct manufacturer contact, as well as internet searches, surfaced eight prospective low cost sensors meriting incorporation into this study. In some instances, sensor developers contacted the research team and expressed interest in having their device evaluated. Any device accepted under such conditions was incorporated without restrictions or direct involvement of the developer. Despite there being a large number of PM sensors on the market, many appeared to lack specific properties that discouraged us from incorporating them into the research. We focused on sensors that demonstrated direct reading, provided either true or estimated size cut point data (preferably $PM_{2.5}$), and were responsive to at least some outdoor monitoring. Not every sensor that was evaluated met these criteria. Recent sensor-related conferences hosted by EPA[1] and other scientific exchanges (including peer review literature[2,3]) clearly indicated that PM sensors reporting only particle number (or counts) were both available at low cost and may prove comparable to more expensive light scattering (nephelometric) and direct mass measuring (Tapered Element Oscillating Microbalance-TEOM) instrumentation. A number of these devices were secured and evaluated to meet the apparent growing use rate among both research professionals and citizen scientists.

Concerning outdoor monitoring applications, only one of the sensors evaluated came fully weather protected, and allowances (shelters) were developed to protect the remaining devices. In several instances, the sensor developers expressed that their devices were primarily intended for indoor monitoring. Regardless of how a manufacturer defines the applicability of a given low cost PM sensor, it is highly likely that citizen scientists and others would try to use such devices to the greatest extent possible while perhaps ignoring cautions about primary siting requirements. Outdoor monitoring is a prime example of such a scenario, and was therefore fully assimilated into the study design. As a result, one might consider the performance characteristics defined in this report as potentially representing a worst-case scenario. Regardless, we protected all sensors from weather conditions (ambient temperature, moisture, stray light) to the best of our ability.

For approximately one month, these collocated low cost sensors were cited on a PM monitor test platform with a Grimm Model EDM180 $PM_{2.5}$ (EQPM-0311-195) FEM on the US EPA's RTP, NC campus. The units operated continuously during this time with the exception of data recovery, flow checks/calibration, and general servicing as required by the various manufacturers. Once the monitoring period was completed, data from the FEM, sensors and meteorological findings were compared to determine how these variables influence low cost sensor response.

Sensor Performance Results

Discreet statistical evaluation of sensor performance was established with respect to collocated data associated with the Grimm FEM. When possible, resulting regression characteristics were optimized with respect to data normalization and influence of confounders.

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[1] EPA Air Sensors Workshop, 2014. Posters, presentation slides, and abstracts. https://sites.google.com/site/airsensors2014/home

[2] Hagler, G., Solomon, P.A., and Hunt, S.W. New Technology for Low-Cost, Real-Time Air Monitoring; *EM* January 2014, 6-9.

[3] Watkins, T., Snyder, E., Thoma, E., Williams, R., Solomon, P., Hagler, G., Shelow, D., Hindin, D., Kilaru, V., Preuss, P. Changing the paradigm for air pollution monitoring. Environmental Science and Technology, 47: 11369-11377 (2013).

Ease of Use Features Evaluation

Concerning ease of use features, several key findings were evident. In general, these included, but were not limited to:

- *Power Requirements*: None of the units tested had the ability to operate for extensive (multi-day) periods without electrical assistance. Since our goal was to obtain as much collocated data as possible, we purposefully removed such a variable (battery life) from the research. That being said, certain sensors required specific power supplies (such as a USB computer connection), while others simply required a ‘step-down’ 115V transformer. Upon battery power alone, the sensors would expect to operate from 8 hours to 3 days, depending upon sensor type.
- *Data collection/transmission/storage/recovery:* There were numerous data collection/transmission/storage/recovery approaches observed between the various sensor devices. Therefore, extensive efforts had to be performed to ensure data recovery to perform the evaluations. Cellular communication, WiFi hot spots, direct storage via laptops, or electronic tablet connections had to be established, developed, or in some cases unexpectedly refined as to the manufacturer’s suggested protocols. Data communication issues had to be fully vetted to ensure both consistent and reliable data recovery.
- *Data Schemes:* Data schemas were widely variable between the sensors evaluated. This lack of standardization across manufacturers and the often-unique pattern of their data formatting (and the types of data being reported) made data recovery and insertion into statistical analysis schema somewhat difficult. Individual data recovery programs often had to be established for each sensor so that data could be recovered. In some instances, communication with the developer was necessary to understand what their output was so that we could correctly identify variables for analysis.
- *Installation and WiFi considerations*: Almost all of the low cost sensors were easy to install following our development of weather-shielded assemblies. Their low mass and small sizes were highly advantageous for siting. Even so, all of the units had to have external power supplies. Some of the sensors required direct computer connections, which in our opinion minimizes its capabilities relative to outdoor use. Even so, it should be recognized that manufacturers are not necessarily trying to market these as outdoor-worthy PM samplers. It cannot be underestimated that when used outdoors, establishment of data communication can be difficult, especially if cellular communication or a local WiFi hot spot is required. In our situation, we were able to establish a local WiFi hot spot or other needed communication requirements. We sometimes had to work directly with a manufacturer to develop digital data storage internal to the unit or via other means such as transferrable data storage card when necessary to ensure sufficient data recovery for our purpose.

Sensor Performance Characteristics

With rare exception, most of the low cost PM sensors demonstrated an ability to provide at least some short duration response variability (some on the order of 1 second). Data clearly indicated that time weighted averages of approximately one to 5 minutes are more acceptable when it came to end users being able to understand the general response encountered by the simple noise of the instrument itself.

- *Precision:* Only the MicroPEM was evaluated for precision capabilities. Three collocated sensors were operated for a period of approximately one month and their general inter-variability established.
- *Linearity:* The sensors typically provided coefficient of determination (R^2) in comparison with FEM measures of < 0.8. In a number of situations, there was little or no statistical agreement ($R^2 < 0.1$). Estimates of either particle count or algorithm-based mass concentrations ($\mu g/m^3$) were equally capable of reasonable FEM agreement or equal lack of agreement. Since all algorithm-based mass concentration estimates are only as good as the base light scattering determination itself, it would appear that much of the lack of agreement probably lies with the latter. As established by the design of the field studies reported here, a reasonable estimation of mass concentration from particle counts could have been established for one of the sensors (Dylos DC1100).
- *Relative Humidity and Temperature Changes*: There was wide disparity in the response of individual sensors to extremes of either RH or temperature challenge. Both minimal impacts as well as extreme impacts were observed as they relate to the sensors successfully reporting the challenge concentrations as environmental conditions changed. Some of this was expected due to the very nature of the sensing mechanism (approach) often employed in low cost sensors. Considering that all of the sensors tested were based upon light scattering principles where particle hydroscopic properties are known to be an influencing factor in mass concentration estimation, it is uncertain why such a wide range in RH influence (as noted by R^2 relationships) were obtained. Likewise, some sensors were highly collinear with respect to changes in outdoor temperature while others showed no such relationship.
- *Response Range:* Response range of the sensors varied widely. It was not unusual to see multiple order of magnitude differences between sensors and the concentrations they were reporting. It should be clearly stated here that environmental impacts of relative humidity and temperature are often a significant influence in sensor response (light scattering). RH was not accounted for with sensor algorithms, with only one exception (MicroPEM), and therefore a widespread variety of responses with changing meteorological conditions was to be expected. Light scattering optics, cell geometry, and other key engineering features are known to be highly influential relative to nephelometric response and therefore the variability observed here in the findings reflects not only the physics of light scattering devices in general, but also how such features have or have not been incorporated into these low cost devices.

Conclusions

While both the discreet performance characteristics and ease of use characteristics for each device were highly variable, some of the devices appeared to provide reasonable agreement with the collocated FEM mass concentration estimates. The frequent lack of agreement between the sensor and the FEM is a clear indication that citizen scientists and others employing such devices (especially under outdoor monitoring conditions) must remain aware of the uncertainty surrounding the data being generated. At times, meteorological conditions (temperature, RH) had a significant impact upon low cost sensor responses and it was necessary to remove some data to improve the performance statistics. It should be noted that the end users of these devices need to understand where data exclusion might be necessary, as often little or no instructions on such matters are clearly defined by the sensor manufacturers. It would appear that collocation in the general test area would provide a reasonable approach for end users to ascertain the ability of a low cost sensor to be provide useable data. The information provided in this report represents a first step towards ensuring that the next generation of low cost air quality sensors has even more capabilities, meeting a wide variety of air quality monitoring needs. The study also provides potential low cost sensor users with key information regarding sensor performance and the criteria that must be addressed in order to collect data successfully.

1.0 Introduction

EPA's Office of Research and Development (ORD) recently performed a sensors/ applications challenge in response to an EPA-sponsored new technology workshop[4,5]. This challenge is a high priority for EPA and one in which ORD's National Exposure Research Laboratory (NERL) is taking a leadership role[6]. Consequently, EPA established as a priority providing critical feedback to groups or individuals considering the use of citizen science application community-based data collections. As PM is a pollutant of great interest, the NERL sought out novel sensor technologies for the measurement of ambient particulates through a general appeal to inventors and developers of these technologies.

The effort reported here aimed to provide data for identifying which technologies might prove valuable in measurement of PM for a variety of potential users.

As part of this evaluation, we obtained a total of eight PM sensors costing under $2500. This is a general cost consideration we anticipate being a ceiling for many citizen scientists. It is recognized that a sizeable number of potentially more accurate PM sensors exist at higher cost ($3-$6K) but these were purposefully excluded from the testing due to the consideration defined above. Table 1-1 lists the sensors purchased for evaluation. Research operating procedures (ROPs) were developed for each sensor prior to testing.

Table 1-1. Sensors Acquired for Evaluation

Sensor	Manufacturer	City/State	~Cost	Website
CanarIT	AirBase	Israel	$1500	http://www.myairbase.com/#!technology
CairClip $PM_{2.5}$	CairPol	Méjannes les Alès, France	*	http://www.cairpol.com/index.php?lang=en
Speck	Carnegie Mellon	Pittsburgh, PA	$150	http://specksensor.org/
DC1100	Dylos	Riverside, CA	$300	http://www.dylosproducts.com/ornodcairqum.html
831	Met One	Grants Pass, OR	$2050	http://www.metone.com/particulate-831.php
MicroPEM	RTI	Research Triangle Park, NC	$2000	http://www.rti.org/page.cfm/Aerosol_Sensors
Eco PM	Sensaris	Crolles, France	*	http://v2.sensaris.com/store/index.php?route=product/product&product_id=66
PMS-SYS-1	Shinyei	Chuo-ku, Japan	$1000	http://www.shinyei.co.jp/STC/optical/main_pmmonitor_e.html

* Manufacturers had not yet established a consumer-based cost point at the time of EPA acquired these devices for evaluation. These devices were acquired at costs ranging from $500 to $1000.

4 https://sites.google.com/site/airsensors2014/home

5 Vallano, D., Snyder, E., Kilaru, V., Thoma, E., Williams, R., Hagler, G., Watkins, T., Air Pollution Sensors. Highlights from an EPA workshop on the evolution and revolution in low cost participatory air monitoring. Environmental Manager. December 2012. 28-33 (2012).

6 http://www.epa.gov/heasd/airsensortoolbox/

2.0 Materials and Methods

"Bowl on pole" sensor shelters were devised and constructed for the field evaluations. The shelters, shown in Figures 2-1 through 2.1-2, were constructed in-house of aluminum. Thermostated thermal heating pads were attached to the tops of the bowls in an attempt to maintain interior shelter conditions where the sensors were housed at or above 6^{o} Celsius. Even so, it must be recognized that these heaters were purposefully selected to provide for a minimal degree of general heating and that internal temperatures of the sensors registering at or just below freezing were sometimes observed. These aforementioned enclosures were constructed to ensure sensor protection from windblown rain as well as direct sunlight upon the inlets of the devices. The shelters did not fully protect the inlets of the devices from the effects of any face velocity issues (wind speed and/or its direction). Even so, the interface of the sensor inlet did attempt to place a shield between the immediate sensor inlet opening and the ambient atmosphere. That shield is viewable in Figure 2-1 with the sensor often placed directly above or its inlet in one of the openings to provide unencumbered access to ambient conditions. Effects of sensor PM starvation or stagnation would not be expected to have occurred under the test conditions.

Figure 2-1. "Bowl on pole" sensor enclosure in closed (left) and open (right) positions.

2.1 PM Sensors

Figure 2.1-1. AIRS sampling platform with all shelters shown.

The on campus Ambient Air Innovation Site (AIRS; RTP, NC) was selected for all PM sensor testing. The custom-made "bowl on pole" shelters were attached to the railing of the monitoring platform as shown in Figure 2.1-1. In order from left to right were the Dylos DC1100, the Met One model 831, the Carnegie Mellon Speck, the RTI MicroPEM, the CairPol CairClip, and the Sensaris Eco PM. The AirBase CanarIT included its own shelter and was placed to the right of the Sensaris Eco PM.

Two aluminum shelters were used to house a laptop computer for data recovery from all sensors and most of the electrical connections. Any connections that could not be made inside the aluminum high volume (hi-vol) shelter were encased in a zip-lock bag that was closed with zip ties to further protect against water. The setup inside one of the hi-vol shelters is shown in Figure 2.1-2. All power and data lines were secured in place with zip ties. With the exception of the MicroPEM, primary data collections reported here were performed during the November-December 2013 time period. The MicroPEM was operated during July 29-September 2, 2014.

Note that the Sensaris Eco PM and the AirBase CanarIT both transmit their data to proprietary websites. As such, data recovery for these sensors was performed via an internet download.

Figure 2.1-2. Hi-vol shelter opened with laptop displayed (left) and with wiring and laptop inside (right).

The previously mentioned operation schedule is intended to provide a general understanding of the data collection periods for each of the sensors evaluated in this report. It should be clarified that initial investigation (~ 30 day) collocation trials involving the RTI MicroPEM were performed in the fall/winter of 2013 and that data were successfully captured. Data findings from these evaluations were voluntarily provided to the manufacturer. The device had results indicating generally poor agreement with the collocated FEM. Further discussions with the manufacturer indicated significant hardware and/or software upgrades had been performed. To provide the greatest value to the scientific community at large, we obtained upgraded versions of the device and summarily retested them. Only the retest findings for this sensor are being reported here. It should be recognized that the retest conditions were conducted during summer/fall conditions as compared to generally colder conditions for the remaining sensors. It should also be mentioned here that the Airbase CanarIT is now no longer available under that name following its acquisition by a secondary party (Perkin-Elmer) and is now marketed as the ELM[7]. Discussions with this new vendor indicated significant changes to the original device we tested have occurred. We have no data findings to report on this upgraded device at this time.

Table 2.1: Summary of Sensors Evaluated

Sensor	Method	Size Fraction	Measurement Unit	~ Weight (lb)	Shortest Time Resolution	Base Power Accessory	Data Retrieval Method
AirBase CanarIT	Optical	Undefined	ug/m^3	~5	20 sec	AC/DC Adapter	Proprietary Web Server
CairClip PM	Optical	$PM_{2.5}$	ug/m^3	~0.4	1 min	Battery	Proprietary Software
Carnegie Mellon Speck	Optical	Undefined	Particle counts	~0.5	1 sec	USB	Proprietary Software
Dylos DC1100	Optical	Undefined	Particle counts	~4	1 min	AC/DC Adaptor	Proprietary Software
Met One 831	Optical	<10µm	ug/m^3	~4	1 min	Battery	Proprietary Software
RTI MicroPEM	Optical	$PM_{2.5}$	ug/m^3	~1	10 sec	Battery	Proprietary Software
Sensaris Eco PM	Optical	$PM_{2.5}$	ug/m^3	~0.5	<1 min	USB	Proprietary Web Server
Shinyei PMS-SYS-1	Optical	$PM_{2.5}$	ug/m^3	~0.5	1 sec	Power Circuit Board	Proprietary Software

2.1.1 PM Reference Analyzers

A Grimm Technologies, Inc. (Douglasville, GA) Federal Equivalent Method (FEM) Model EDM180 $PM_{2.5}$ (EQPM-0311-195) monitor and an RM Young (Model 41382VC) RH and temperature sensor were operated by EPA's Office of Air Quality Planning and Standards (OAQPS) alongside meteorological instrumentation at the AIRS monitoring station on the EPA campus in Research Triangle Park (RTP), NC. The established reference method operation was

[7] http://elm.perkinelmer.com/

covered under a QAPP for that study[8,9]. Data from the Grimm were available during the data collection period of the sensor evaluation as 1-min, 5-min, or 60-min averages. Sensors tested in this study featured time resolutions between 1-s and 5-min. We selected a matched data integration period (average) of 5 minutes for comparison with the sensors. General relationships between the Grimm response and environmental conditions are reported in Figure 2.1.1-1.

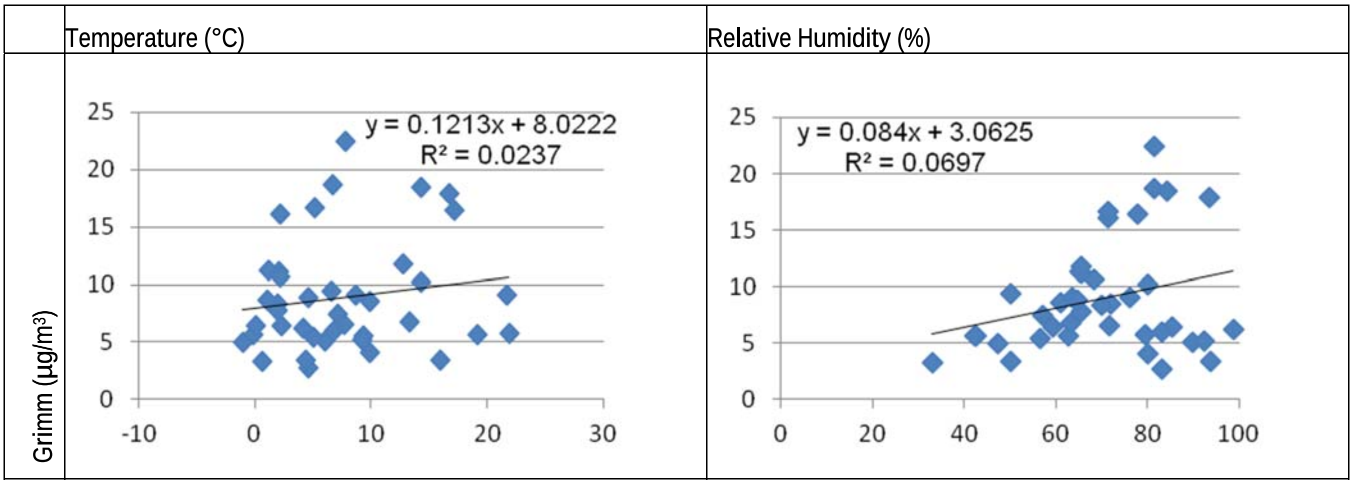

Figure 2.1.1-1. Grimm data vs. temperature and RH.

2.1.2 AirBase CanarIT

Because the AirBase CanarIT was too large for the customized shelters and was adequately sheltered by its own housing, it was attached to a large laboratory stand as shown in Figure 2.1.2-1. This laboratory stand was in turn attached to the railing of the AIRS sampling platform via a C-clamp such that its height matched those of the other sensors. It was oriented so that its main inlet faced the platform as shown in Figure 2.1.2-2.

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[8] U.S. Environmental Protection Agency (EPA). July 2013. QAPP. Raleigh Multi-Pollutant Near-Road Site: Measuring the Impact of Local Traffic on Air Quality. Research Triangle Park, NC.

[9] Alion Science and Technology. 2013. Quality Assurance Project Plan: PM and VOC Sensor Evaluation, QAPP-RM-13-01(1), November 14, 2013. Research Triangle Park, NC.

Figure 2.1.2-1. AirBase CanarIT attached to laboratory stand via bailing wire.

Figure 2.1.2-2. AirBase CanarIT on its laboratory stand perch.

2.1.3 CairPol CairClip $PM_{2.5}$

The CairClip was originally placed on top of the shelter grating with the inlet flush to a hole in the grating. On December 13, 2013, following a review of the data in hand (relatively low concentrations being reported), it was suspended underneath the grating with zip ties, as shown in Figure 2.1.3-1, to maximize airflow. The reason for this being the concern that inadequate fresh air supply (stagnation) might be the cause of a lack of observed day-to-day PM concentration variability with this sensor. The repositioning of the sensor to a fully open nature did not subsequently change its basic performance characteristics and all data captured regardless of positioning were used in the subsequent statistics.

Figure 2.1.3-1. CairClip PM sensor suspended beneath shelter grating.

2.1.4 Carnegie Mellon Speck

Because the Carnegie Mellon Speck's inlet is on its bottom surface, it was simply placed on the grating as shown in Figure 2.1.4-1. The Speck experienced two interruptions in data collection, both of which began while the operator was in the field. This suggests that it failed to restart data collection after a data download was completed. This might be the result of operator error and not necessarily the fault of the device.

Figure 2.1.4-1. Carnegie Mellon Speck oriented in its shelter with the lid up.

2.1.5 Dylos DC1100

The Dylos DC1100 has all of its vents, inlet, and outlet on its backside. Therefore, it was placed on its back with the vents resting directly on the grated floor of the shelter, as pictured in Figure 2.1.5-1. There was one interruption in sampling, the reasons for which remain unknown.

Figure 2.1.5-1. Dylos DC1100 oriented in its shelter with the lid up.

2.1.6 Met One Model 831

The Met One model 831 was positioned upside down so that its inlet protruded beneath the grating of its shelter as shown in Figures 2.1.6-1 and 2.1.6-2. The Met One experienced one interruption in sampling, which began while the operator was in the field. This suggests that it failed to restart data collection after a data download was completed. This might be the result of operator error and not necessarily the fault of the device.

Figure 2.1.6-1. Met One model 831 oriented in its shelter with the lid up.

Figure 2.1.6-2. Met One model 831 oriented in its shelter with the lid down.

2.1.7 RTI MicroPEM

The RTI MicroPEM is an optical particulate matter sensor that uses a size-selective inlet to measure $PM_{2.5}$. Three RTI MicroPEM units were simultaneously tested from July 29 through September 2, 2014 at the AIRS sampling site. On the advice of the manufacturer, they were arranged in the bowl-on-pole shelters as shown in Figure 2.1.7-1. As shown, they are placed on the grating on their side with the opening to the nozzle facing down. Each MicroPEM unit was assigned a number, 1, 2, or 3, based on its position on the sampling platform. The operator was kept blind to the serial number of each unit while it was in the field. There was one interruption in sampling from 8/12/14 to 8/18/14 caused by the tripping of the ground fault circuit interrupter (GFCI) circuit powering the devices.

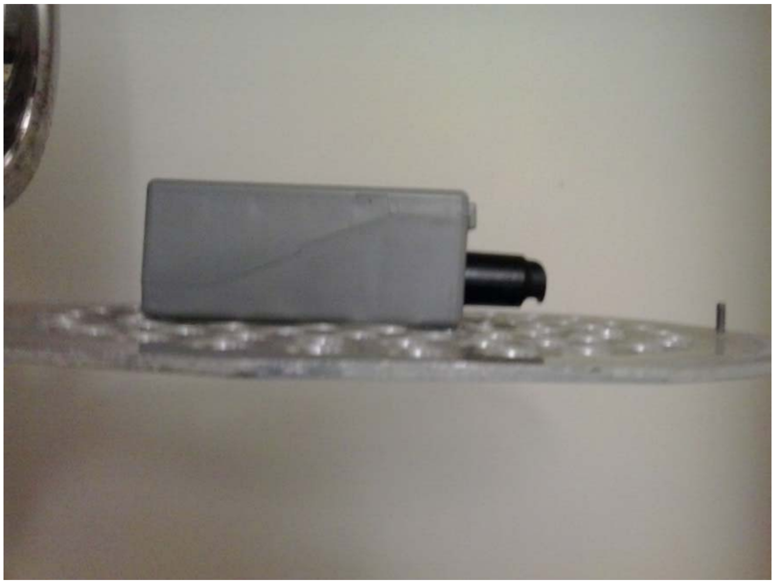

Figure 2.1.7-1. RTI MicroPEM orientation on the plate of a bowl-on-pole shelter.

2.1.8 Sensaris Eco PM

The Sensaris Eco PM was placed on its side so that one of its several ventilation holes would be in contact with the grate. The AIRS platform proved to be too far away from the only WiFi hotspot at the AIRS monitoring site. As such, the Sensaris Eco PM was relocated first to a hi-vol shelter and then to a “bowl on pole” shelter on top of the trailer containing the AIRS WiFi hotspot. This relocation placed it approximately 50 m from the other sensors but still in close proximity (< 10 m) to the collocated Grimm FEM analyzer. Care was taken to place it at approximately the same altitude as the other sensors. The Sensaris Eco PM orientation and location are shown in Figures 2.1.8-1 and 2.1.8-2. The Sensaris Eco PM suffered from many interruptions in overall data collection. Connectivity problems were believed to have influenced overall data collection rates for this device.

Figure 2.1.8-1. Sensaris Eco PM oriented in its shelter with the lid up.

Figure 2.1.8-2. Sensaris Eco PM sampling location (circled above).

2.1.9 Shinyei PMS-SYS-1

The Shinyei PMS-SYS-1 is an optical PM sensor that uses a size-selective inlet to measure $PM_{2.5}$. One unit was tested from July 29 to September 2, 2014 and then again from September 15 to October 17, 2014 at the AIRS sampling site. The first test was performed with the Shinyei sensor attached to the bottom of a bowl-on-pole shelter. The intention was to maximize airflow to the sensor. However, the unit was found to be extremely sensitive to light interference. Whenever the sun was shining, the unit reported nearly 800 μg/m^3. As such, the initial test was discarded and the unit relocated to a Hi-Vol shelter where it would be better protected from sunlight. The position and orientation of the unit in the second test is shown in Figure 2.1.9-1. The unit was attached to the lid of the Hi-Vol shelter via double-sided tape.

Figure 2.1.9-1: Shinyei in a Hi-Vol shelter. Note that the lid to the Hi-Vol shelter was closed during sampling.

3.0 PM Sensor Results and Discussion

3.1 AirBase CanarIT

3.1.1 AirBase Results

The CanarIT (AirBase) is a multi-sensor unit capable of measuring PM (μg/m^3), total VOCs (ppb), and NO_2 (ppb). Several other parameters were measured by the AirBase, but only the unit's PM response is discussed in this report. Data that might have been affected by the presence of an operator's vehicle (general disruption of the local air quality) were removed starting 15 min before the operator's arrival and ending 15 min after departure. Such review was consistently performed across all data collected for all sensors.

As seen in the trace (5-min) data shown in Figure 3.1.1-1, the AirBase did not correlate well with the Grimm. During late November through early December for example, the AirBase indicated a lower PM load, while the Grimm indicated that this is a period of increased PM loading. This lack of correlation is quantified in the 24-hour average data scatter plot shown in Figure 3.1.1-2. In addition, the AirBase showed poor correlation with temperature (Figure 3.1.1-3) and RH (Figure 3.1.1-4) measurements.

Since RH fluctuates constantly over the course of a day, it was important to investigate the 5-min average RH versus the sensor data even if the 24-hour data indicated some correlation. The graph of that data in Figure 3.1.1-5 shows that the outliers were not correlated with RH. A second graph with all AirBase data above 20 µg/m^3 removed (Figure 3.1.1-6) also shows no correlation between the rest of the data and RH.

Given the data detailed above, no basis for any correction factors or removal of outliers can be found. The final scatter plot of Grimm vs. AirBase data is shown below in Figure 3.1.1-7. The scale has been chosen manually to better illustrate the bulk of the data.

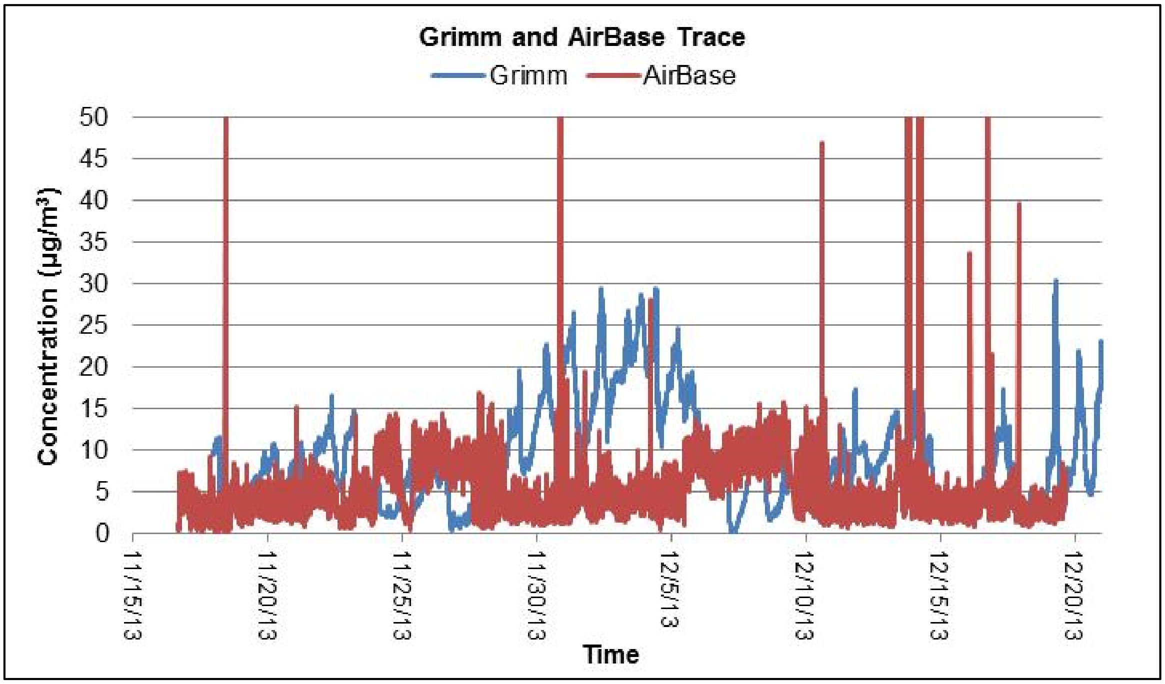

Figure 3.1.1-1. Grimm and AirBase data over time.

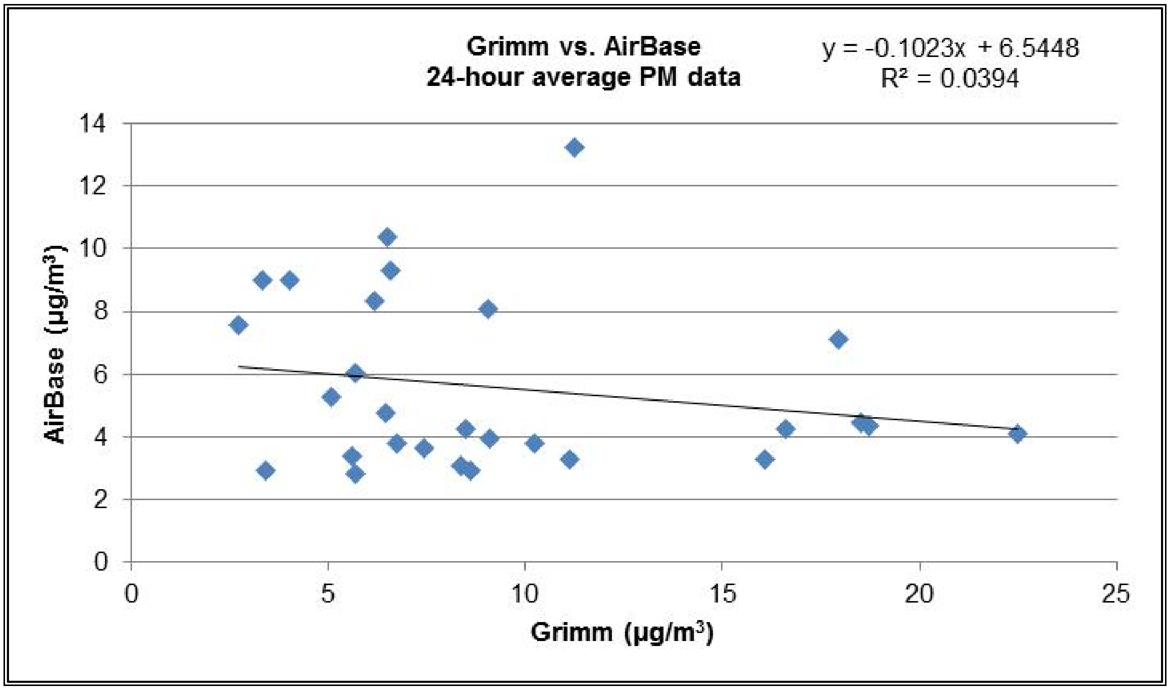

Figure 3.1.1-2. 24-hour time-averaged PM data comparing the Grimm reference sampler with the AirBase CanarIT PM sensor.

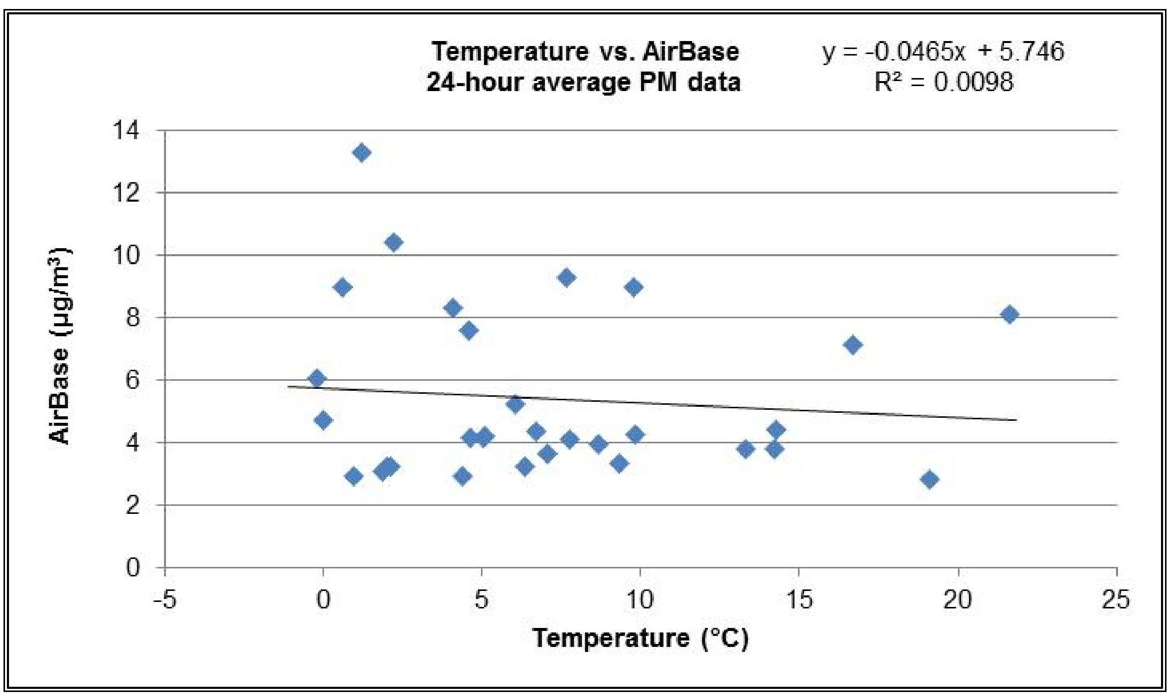

Figure 3.1.1-3. Temperature vs. AirBase 24-hour averaged data.

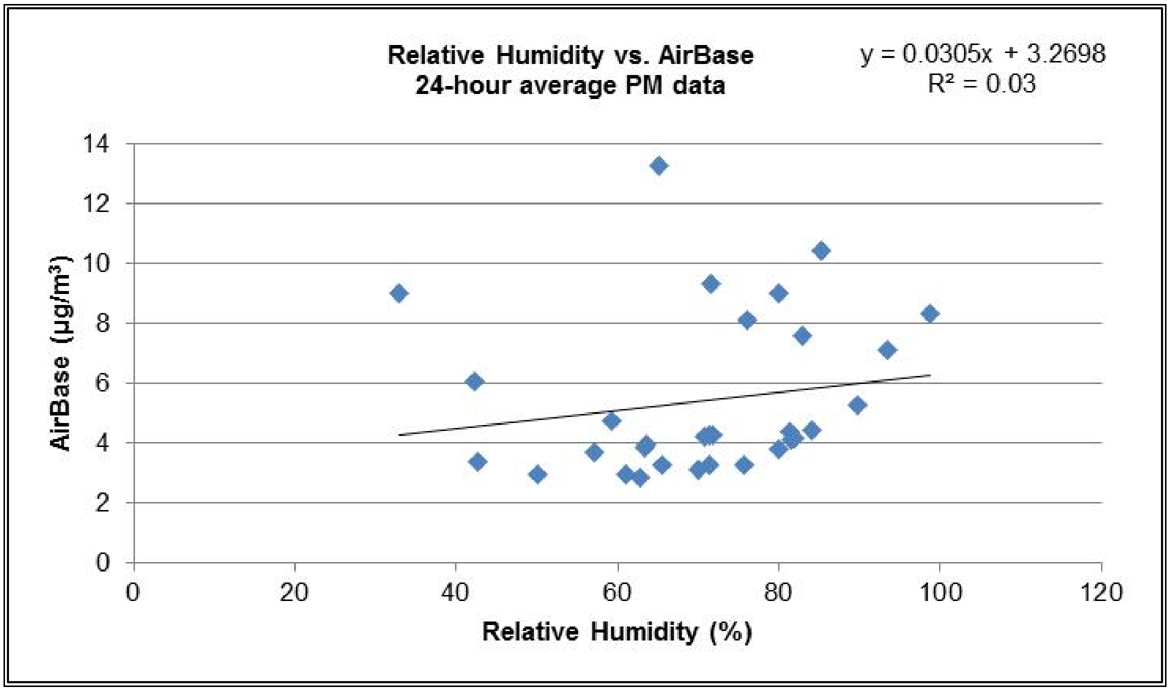

Figure 3.1.1-4. RH vs. AirBase 24-hour averaged data.

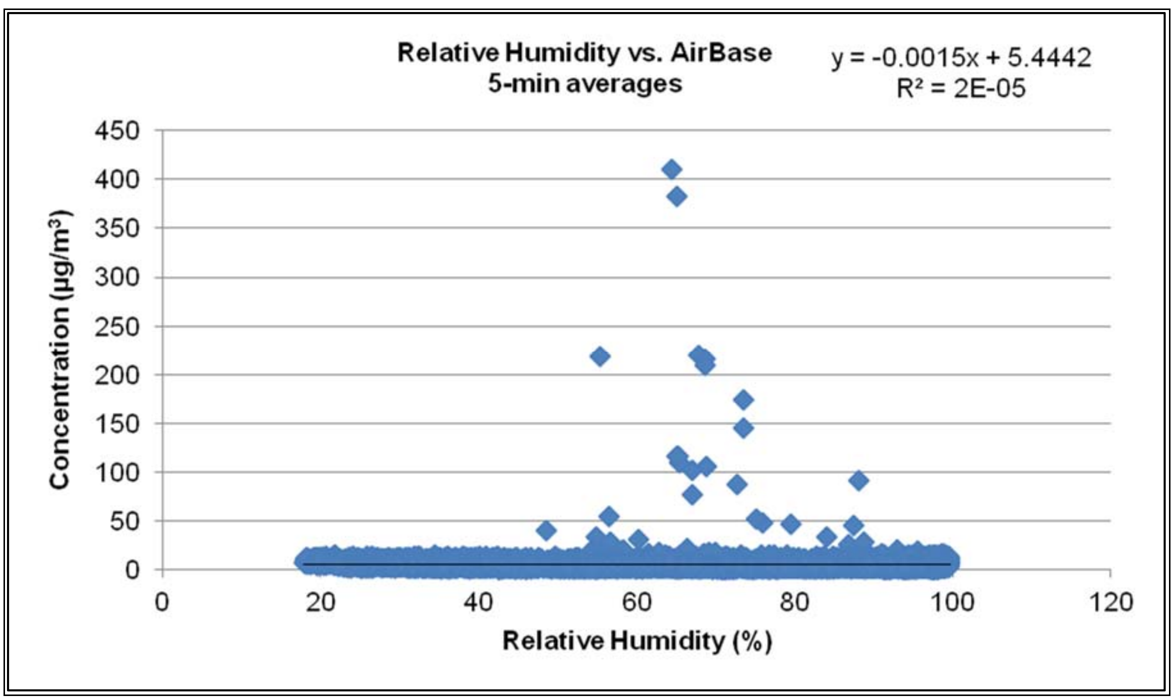

Figure 3.1.1-5. RH vs. AirBase (5-min averages).

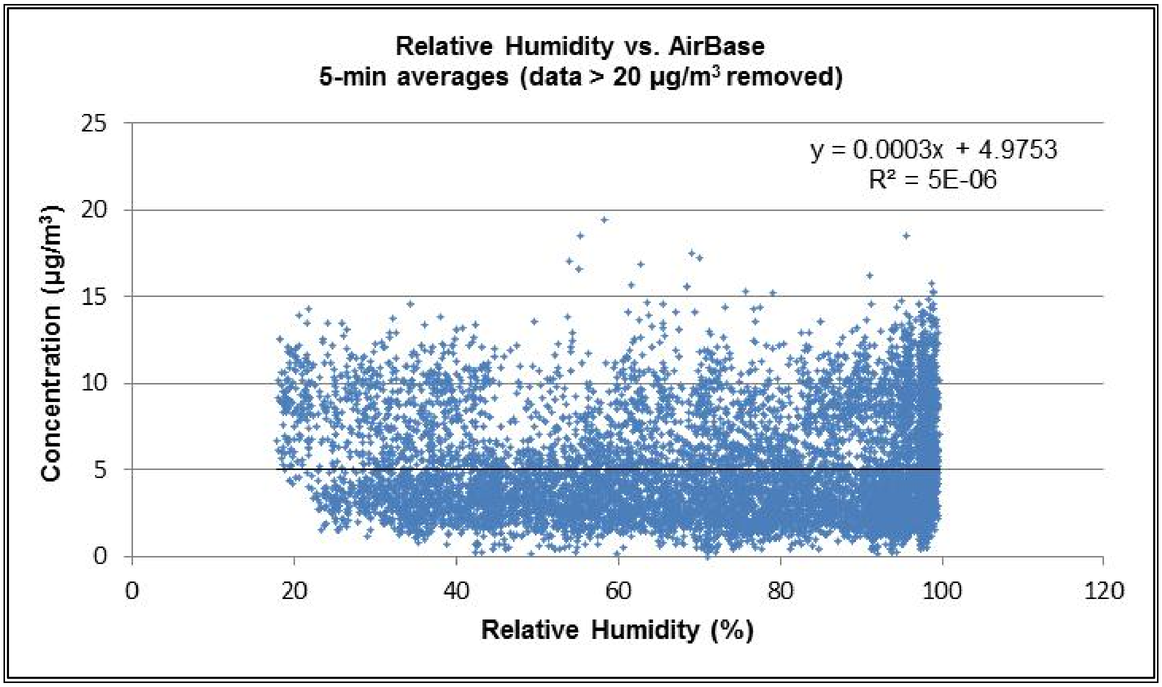

Figure 3.1.1-6. RH vs. AirBase (5-min averages) with data > 20 µg/m^3 removed.

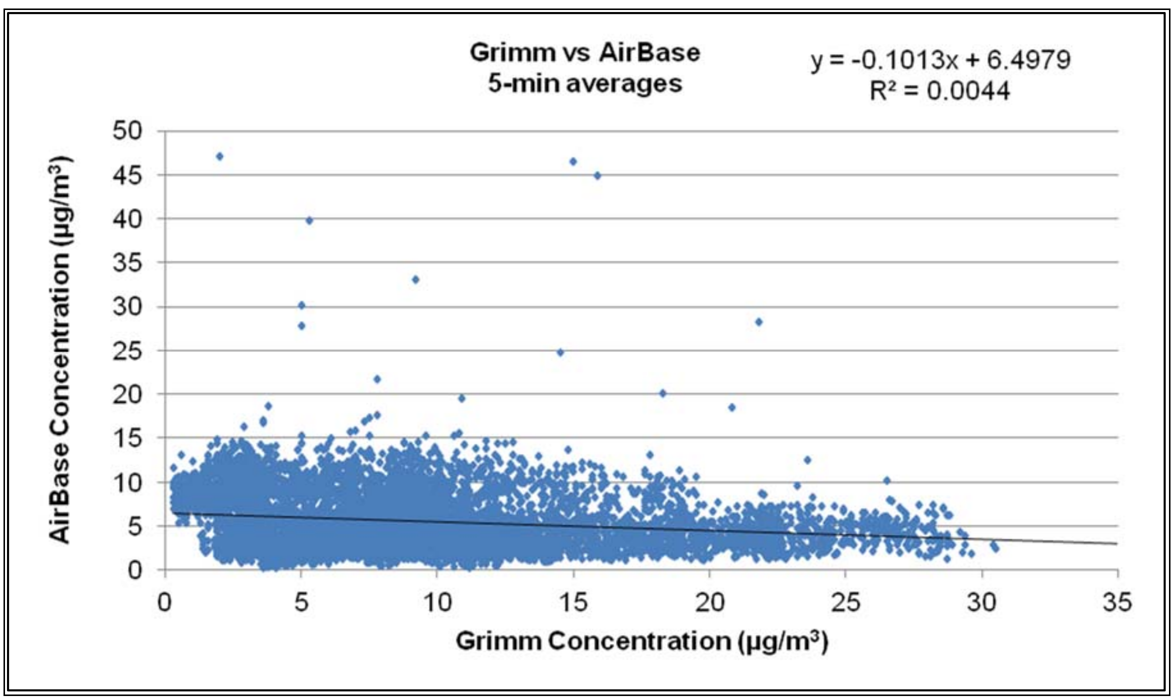

Figure 3.1.1-7. Grimm vs. AirBase (5-min averages).

3.1.2 AirBase Discussion

The AirBase has several features that are useful for remote sampling operations. The unit runs on 12V DC power, which is normally supplied by an AC/DC adapter. With minimal wiring, however, the unit could be modified to work using any number of battery options. The stainless steel housing of the AirBase, which includes a protective cover over all sampling inlets, allows the AirBase to perform outdoors without any additional sheltering.

The AirBase transmits all data to a proprietary server where it can be accessed online. The model tested used a Global System for Mobile Communication (GSM) subscriber identity module (SIM) card and data plan for this purpose. This design decision eases remote operation, as the unit requires fewer in-person operator checks. However, it does add a recurring cost of operation since cellular data plans currently cost approximately $50 per month.

During the evaluation, interruptions in transmission to the server were experienced after every few days of operation. These interruptions required us to cycle power to the AirBase. However, it appeared the AirBase still collected and stored data even when it stopped transmitting. Upon reestablishing a connection to the server, it appeared from the flashing data transmission indicator lights that the AirBase transmitted its backlog of data at a much higher rate than during normal operation, which is supported by the fact that no gaps occurred in the data despite several transmission interruptions.

The trace of the AirBase PM sensor data does not appear to follow that of the Grimm FEM analyzer. Scatter plots show that the AirBase PM data had minimal correlation with the Grimm or with any other factors. No speculation can be provided as to why this lack of agreement was observed.

3.2 CairPol CairClip $PM_{2.5}$

3.2.1 CairClip $PM_{2.5}$ Results

The CairPol CairClip $PM_{2.5}$ sensor is a single sensor unit used for measuring PM in micrograms per cubic meter (µg/m^3). It should be stated that the device tested was a prototype model kindly released by the manufacturer to accommodate our research desire. Data that might have been affected by the presence of an operator disturbing the general air quality were removed starting 15-min before the operator's arrival and ending 15-min after departure.

As seen in the trace (5-min) of the CairClip and Grimm data in Figure 3.2.1-1, the CairClip appears to have substantial sensitivity issues. It recorded 0 µg/m^3 for the vast majority of the sampling time. This was the justification for reconfiguring the device following an initial data review. Reorientation did not appear to improve the response. The 24-hour average data show no correlation between the CairClip and the Grimm (Figure 3.2.1-2), but a strong correlation with temperature (Figure 3.2.1-3) and a possible correlation with RH (Figure 3.2.1-4).

RH was examined first because of a known correlation between RH and the presence of outliers in many optically based PM sensors[10]. The 5-min averaged RH data clearly show that all of the highest points detected occurred at greater than 95% RH (Figure 3.2.1-5). These data points, which are significantly higher than any others, were considered meteorology-impacted outliers. As such, all data at RH greater than 95% were removed.

As shown in Figure 3.2.1-6, the CairClip produced detectable responses only at temperatures above 19.8 °C. Figure 3.2.1-7 is the same graph using only data at temperatures above 19.8 °C. This clearly shows correlation between temperature and the CairClip signal. Figure 3.2.1-8 shows that even with high humidity and low temperature data removed, no clear correlation is observed between the CairClip and the Grimm FEM data.

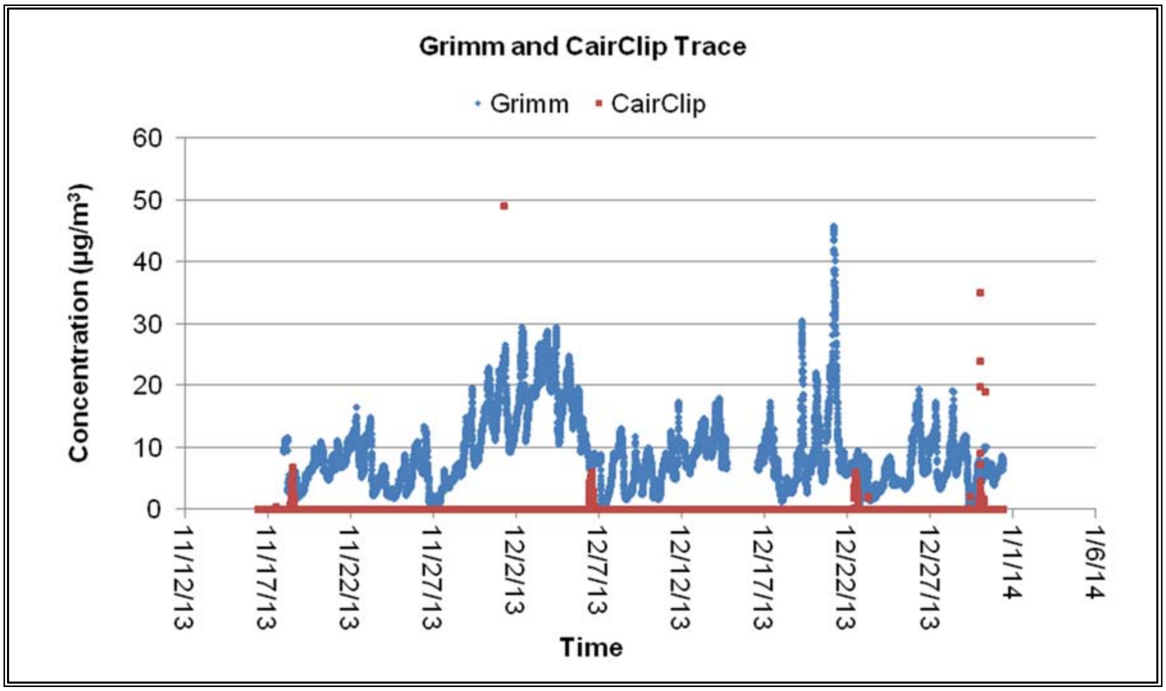

Figure 3.2.1-1. Grimm data and CairClip data over time.

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[10] Chakrabarti, B., Fine, P.M., Delfino, R., and Sioutas, C. 2004. Performance evaluation of the active-flow personal DataRam $PM_{2.5}$ mass monitor (Thermo Andersen pDR-1200) designed for continuous personal exposure measurements. *Atmospheric Environment* 38:3329–3340.

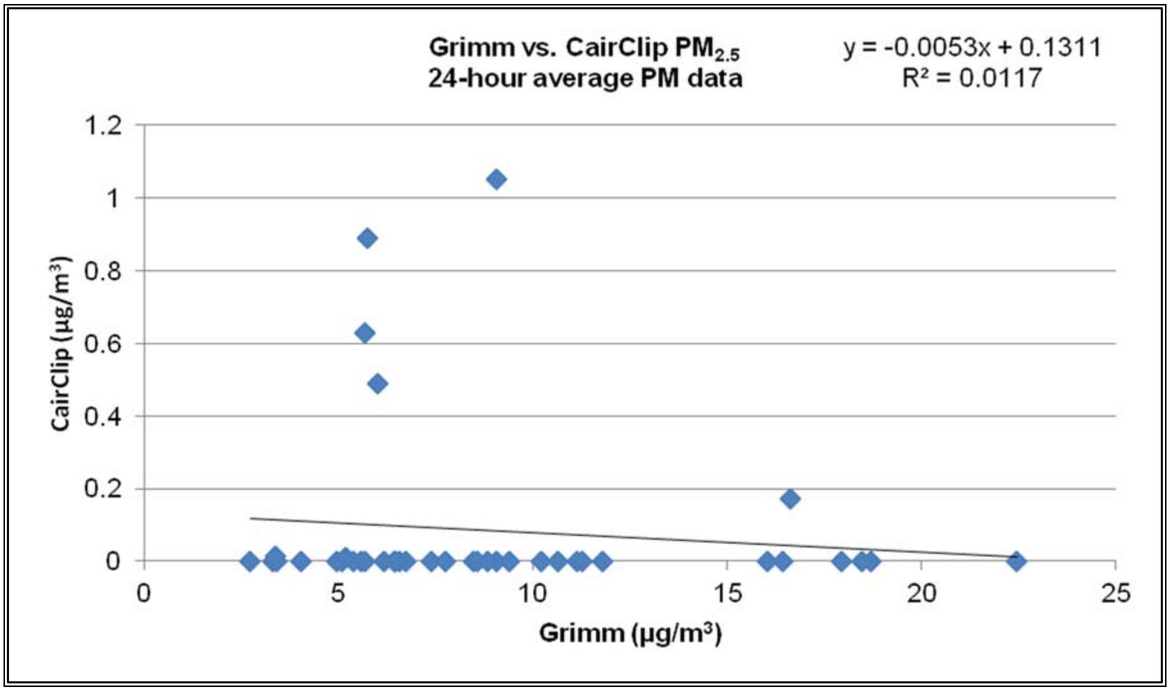

Figure 3.2.1-2. 24-hour time-averaged PM data comparing the Grimm reference sampler with the CairPol CairClip PM sensor.

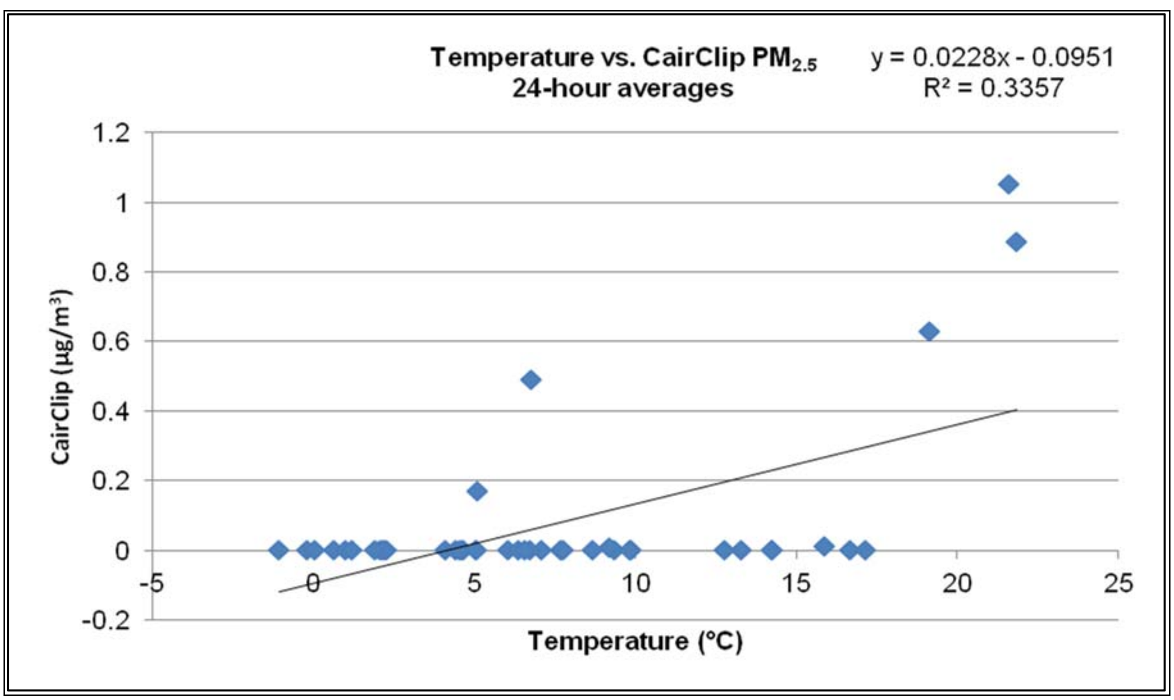

Figure 3.2.1-3. Temperature vs. CairClip 24-hour averaged data.

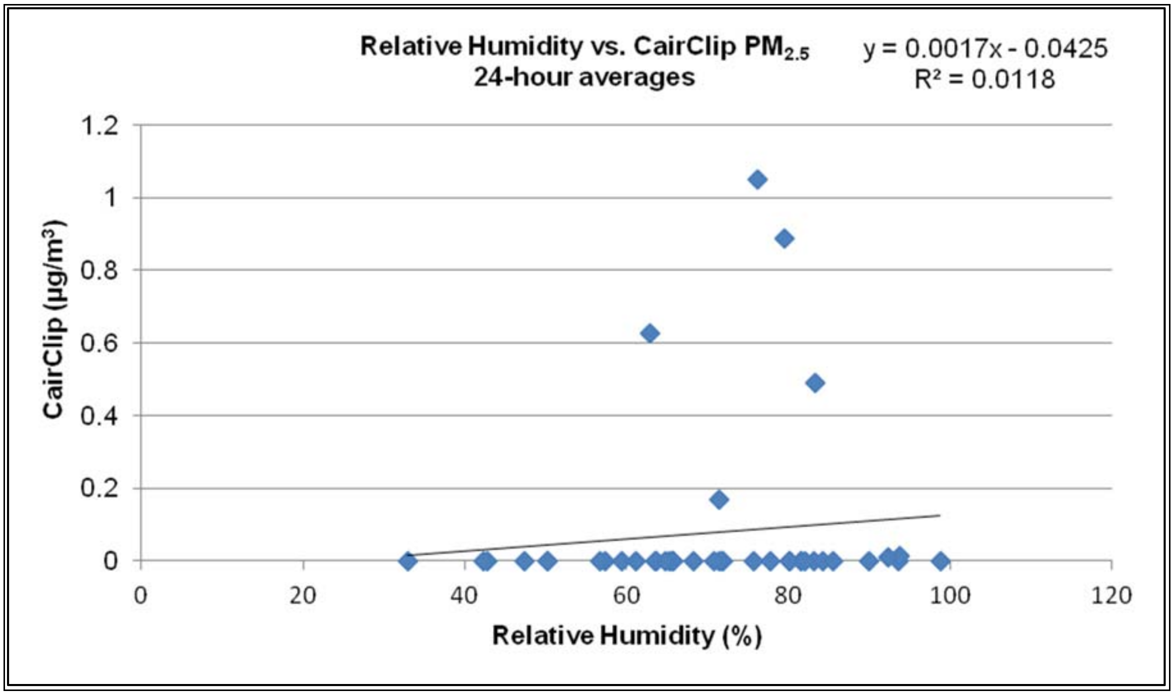

Figure 3.2.1-4. RH vs. CairClip 24-hour averaged data.

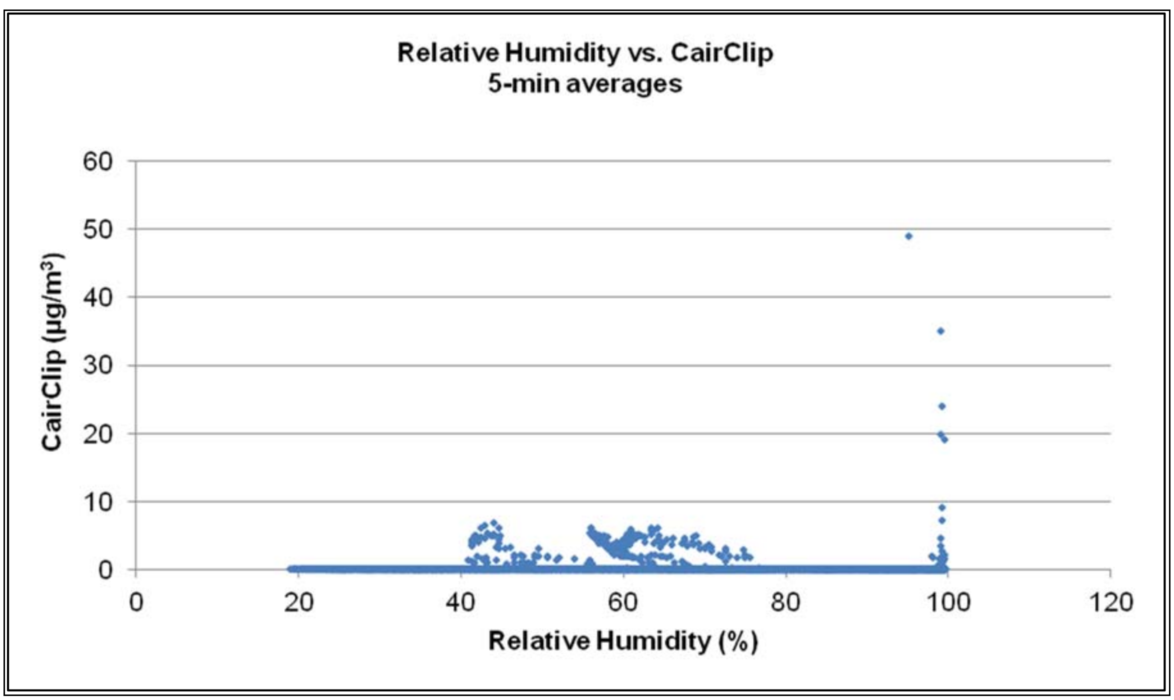

Figure 3.2.1-5. RH vs. CairClip (5-min averages).

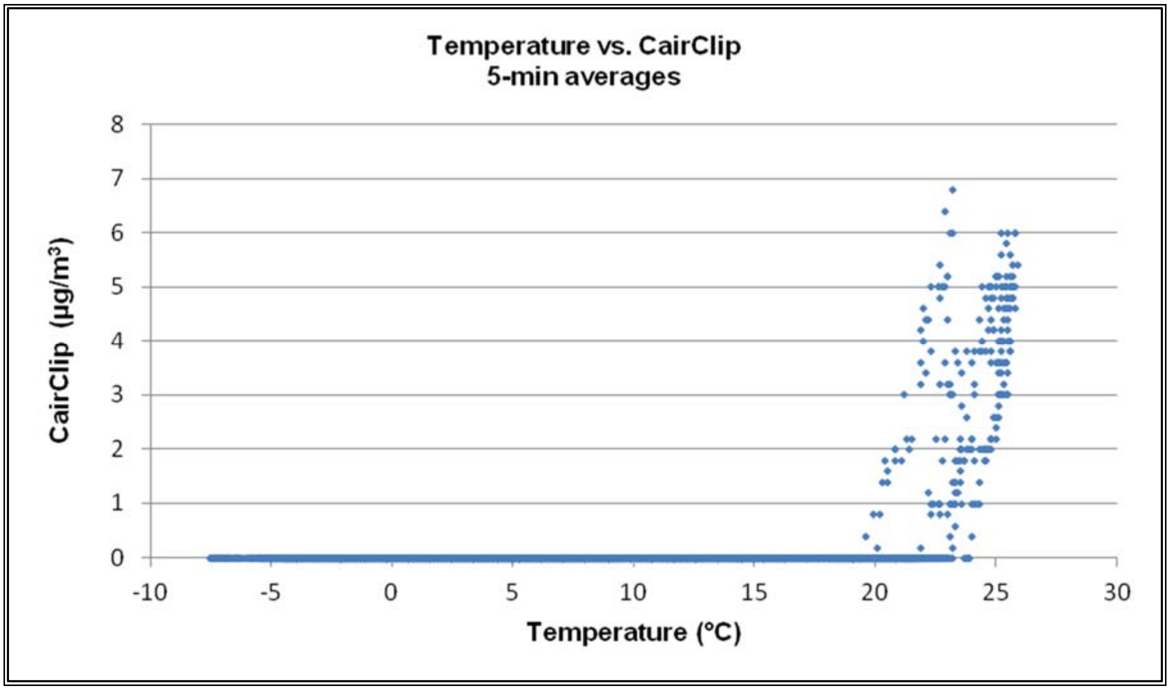

Figure 3.2.1-6. Temperature vs. CairClip (5-min averages). All data taken at humidities > 95% were removed.

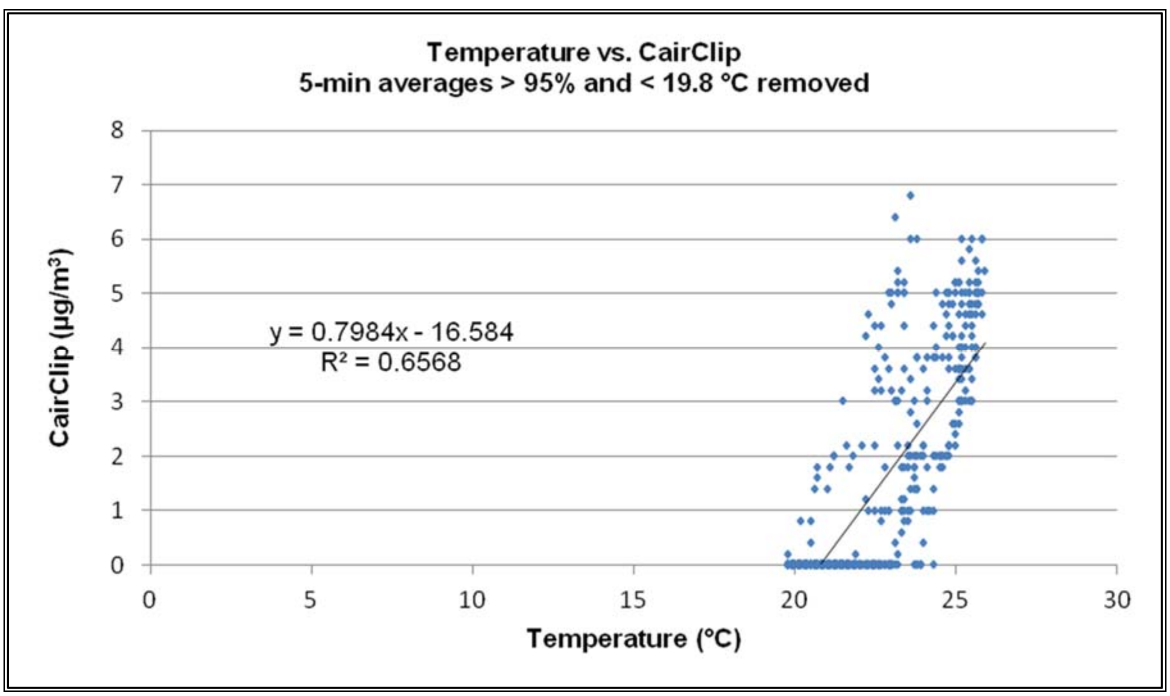

Figure 3.2.1-7. Temperature vs. CairClip (5-min averages). All data taken at humidities > 95% and temperatures < 19.8 °C were removed.

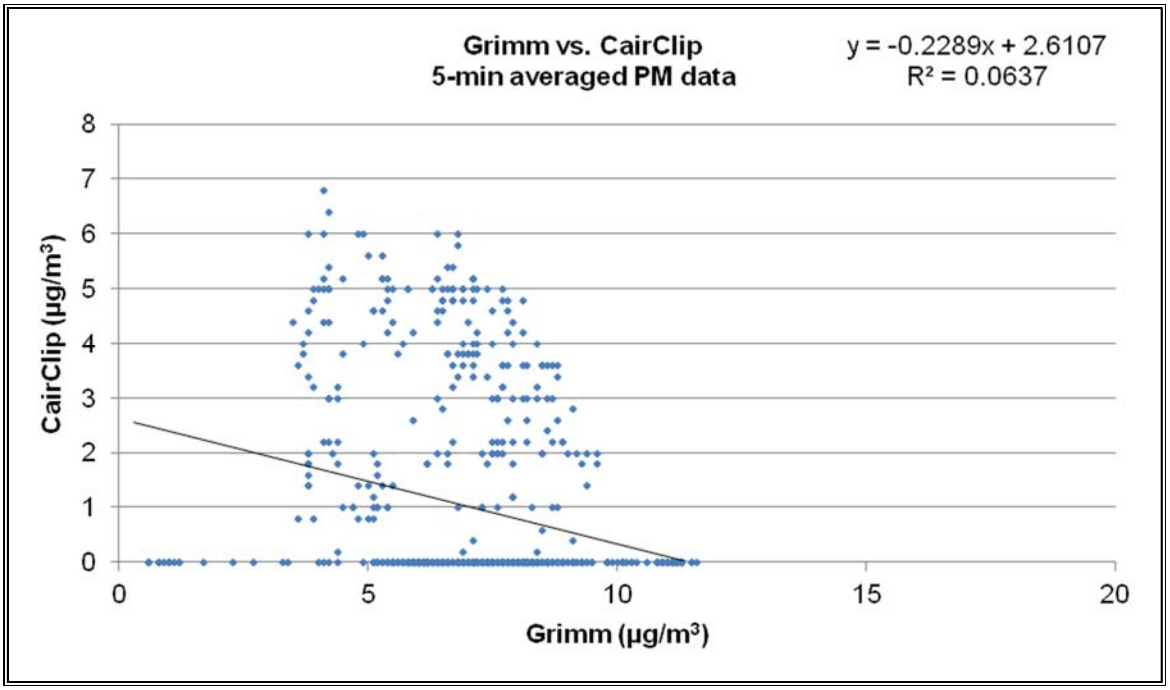

Figure 3.2.1-8. Grimm vs. CairClip (5-min averages).

3.2.2 CairClip $PM_{2.5}$ Discussion

The CairClip sensor operates under battery power for approximately 24 hours at a time, although it can be (and was for this study) operated continuously using a powered mini-USB cable connection. The unit is lightweight and very portable, which makes it viable for mobile applications. Data are collected once per minute and must be downloaded at least every 20 days or data files are at risk of being overwritten. The device maintained excellent uptime throughout the study, in part because of the ease of use of both the software and hardware. Upon opening the software, a warning message in French pertaining to ports intermittently appeared along with an OK button. This warning message popped up repeatedly when clicking on the OK button, but the software opened normally after sufficient clicking of the OK button. The same warning was seen with other models of the CairClip used in other EPA studies and it seems to be a software design issue rather than a fault of the sensor itself. Aside from the inconvenience of clicking OK multiple times, there was no evidence that this function impeded operation of the unit in any way.

Due to the temperature correlations previously discussed, the CairClip PM instrument would not appear to be useful for monitoring below 20 °C. While no correlation with the Grimm reference data was established, only three days out of the entire study featured temperatures above 20 °C reducing the overall database used for comparison. Additional data are required before any conclusions can be drawn regarding the CairClip's performance at higher temperatures.

3.3 Carnegie Mellon Speck

3.3.1 Speck Results

The Carnegie Mellon Speck is an optical PM sensor that measures particle counts once per second. The raw data included many highly defined response peaks (spikes), but the response had reasonable characteristics and did not possess sufficient noise features to be viewed as electronic noise, so those data ‘spikes’ were not removed from the raw data. Even so, Figure 3.3.1-1 shows that spikes in the data completely obscured any correlation that might be present.

The 24-hour averaged data depicted in Figures 3.3.1-2 through 3.3.1-4 suggest a strong correlation with humidity that is likely obscuring any correlation that might be present with temperature and the Grimm. Relative humidity can change rapidly over the course of a day, necessitating a further examination of the correlation between humidity and sensor response at the 5-min averaged time resolution, as shown in Figure 3.3.1-5.

The Speck data showed greatly increased variability at high humidity. Consequently, all data taken at times when RH was greater than 90% were removed. While this removes the largest spikes, at least two large spikes at low humidity remain. Close inspection of the data found nothing to suggest these spikes were related to high humidity or rain events. Figure 3.3.1-6 shows Speck particle counts vs. temperature with the high humidity data removed. Some large outliers remain, suggesting some relationship between the potential range of these outliers and temperature, but causality has not been defined.

Many attempts were made to associate the remaining spikes to a factor that could be corrected for or removed, but these attempts were unsuccessful. Taking the square root or the log of the Speck data was also futile. With no clear method to identify additional outliers, the plot of Speck vs. Grimm data in Figure 3.3.1-7 shows no correlation.

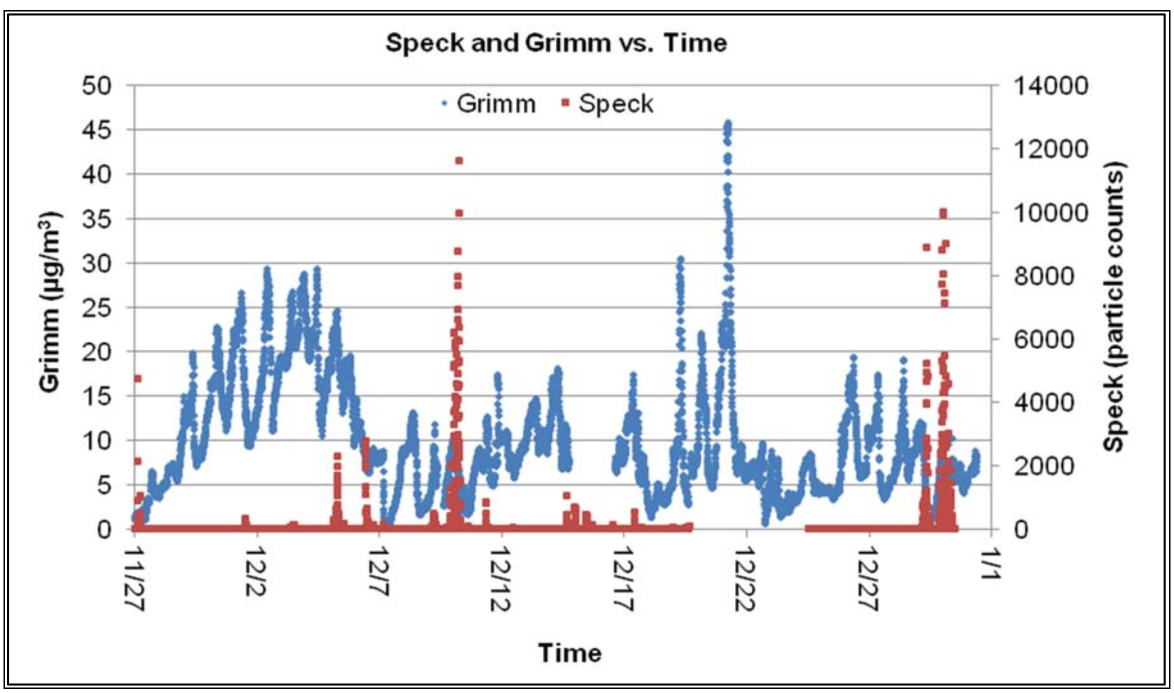

Figure 3.3.1-1. Speck data and Grimm data over time.

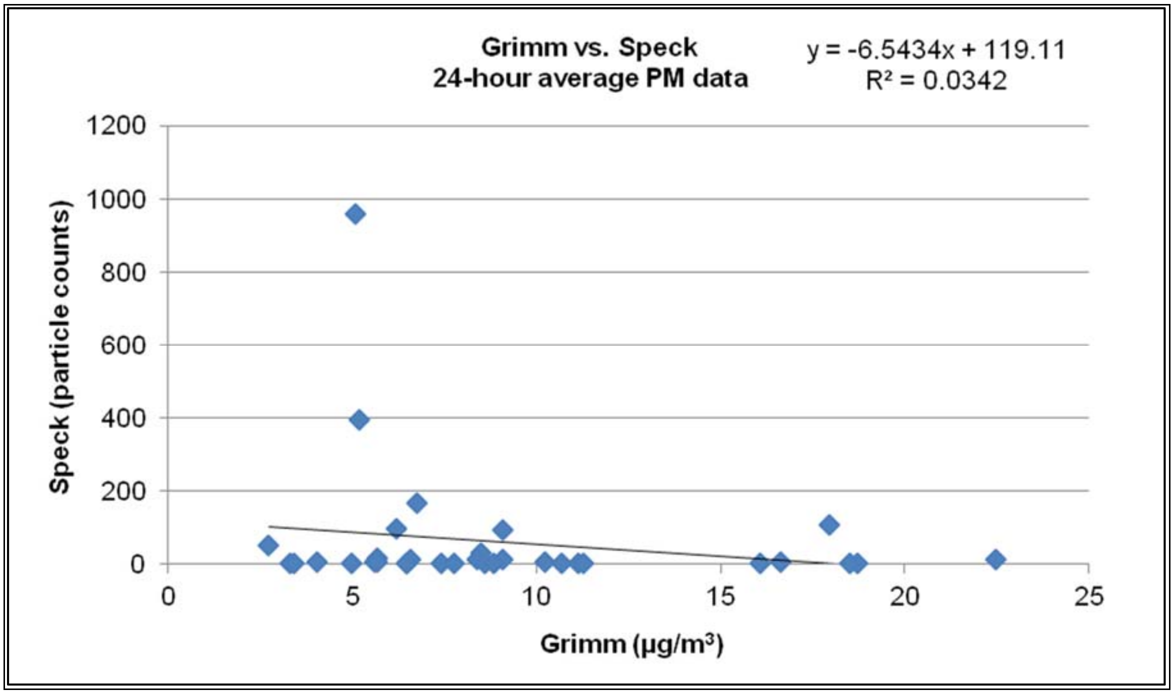

Figure 3.3.1-2. 24-hour time-averaged PM data comparing the Grimm reference sampler with the Speck.

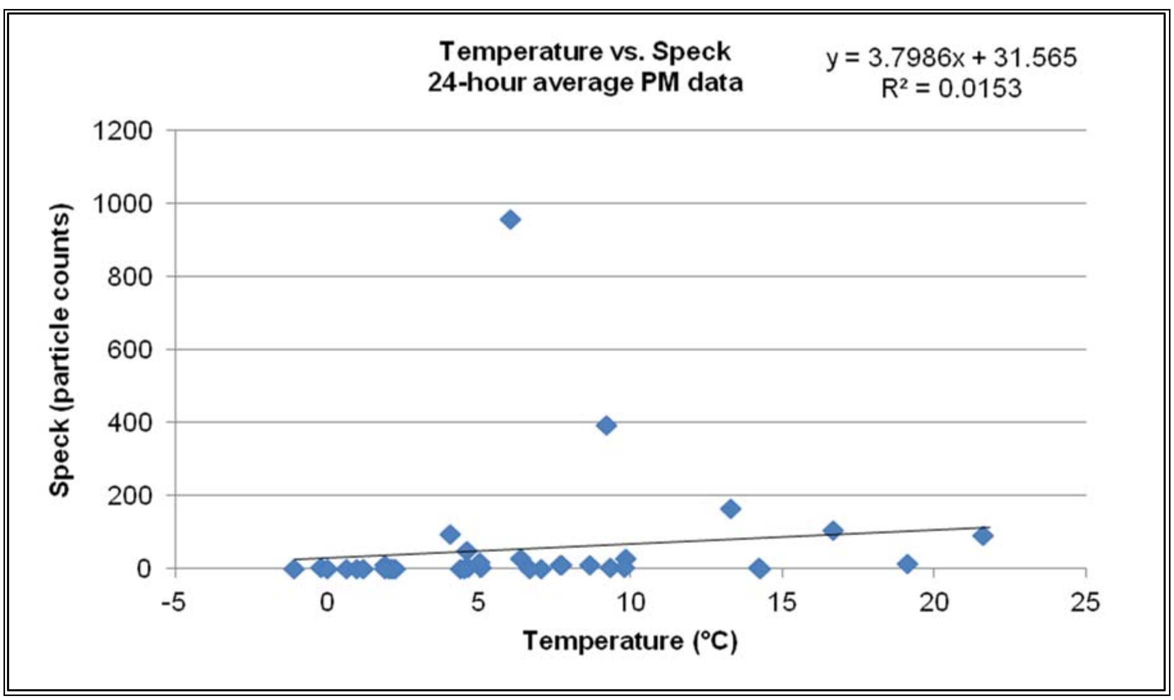

Figure 3.3.1-3. Temperature vs. Speck 24-hour averaged data.

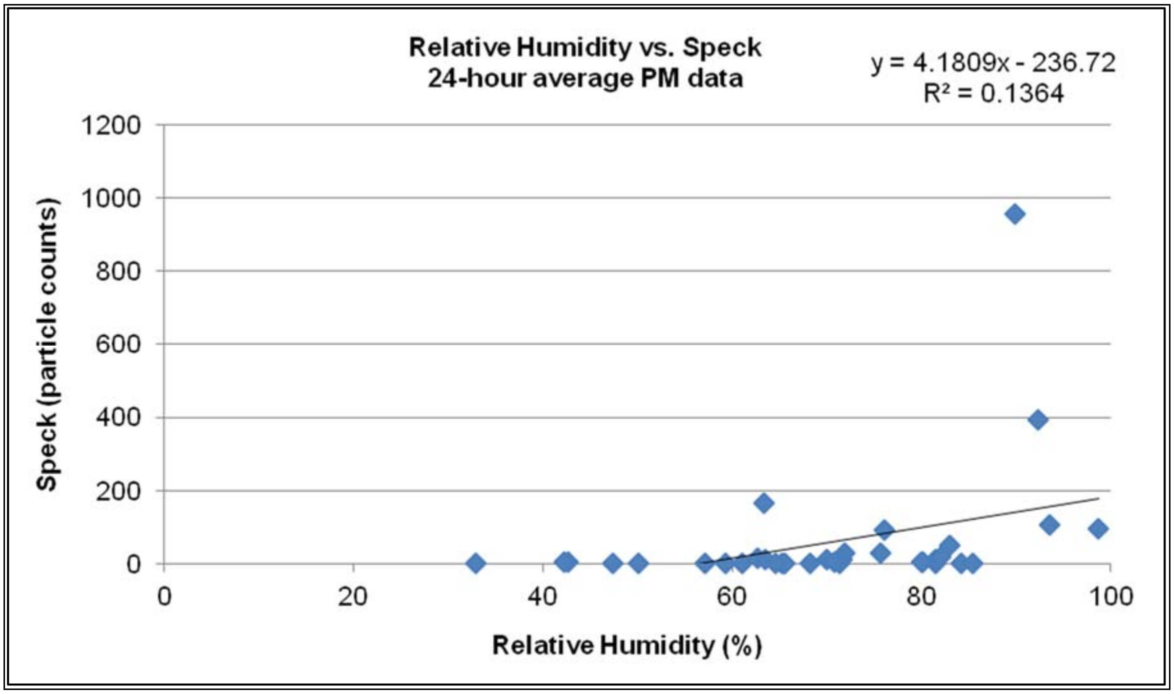

Figure 3.3.1-4. RH vs. Speck 24-hour averaged data.

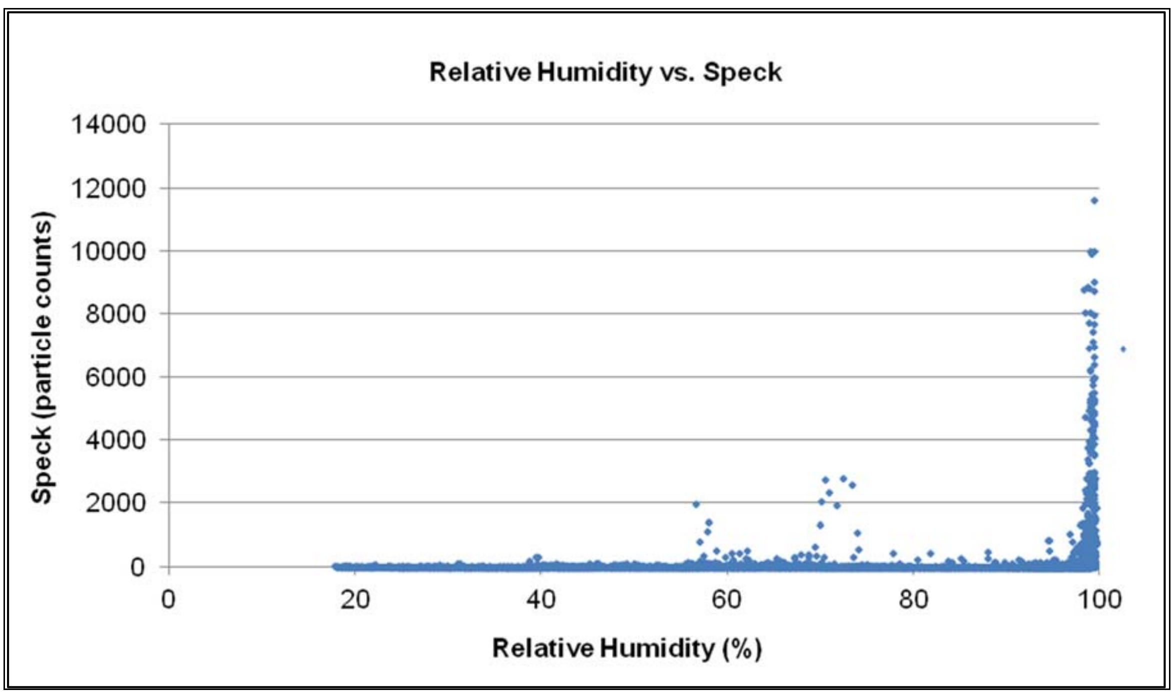

Figure 3.3.1-5. RH vs. Speck (5-min averages).

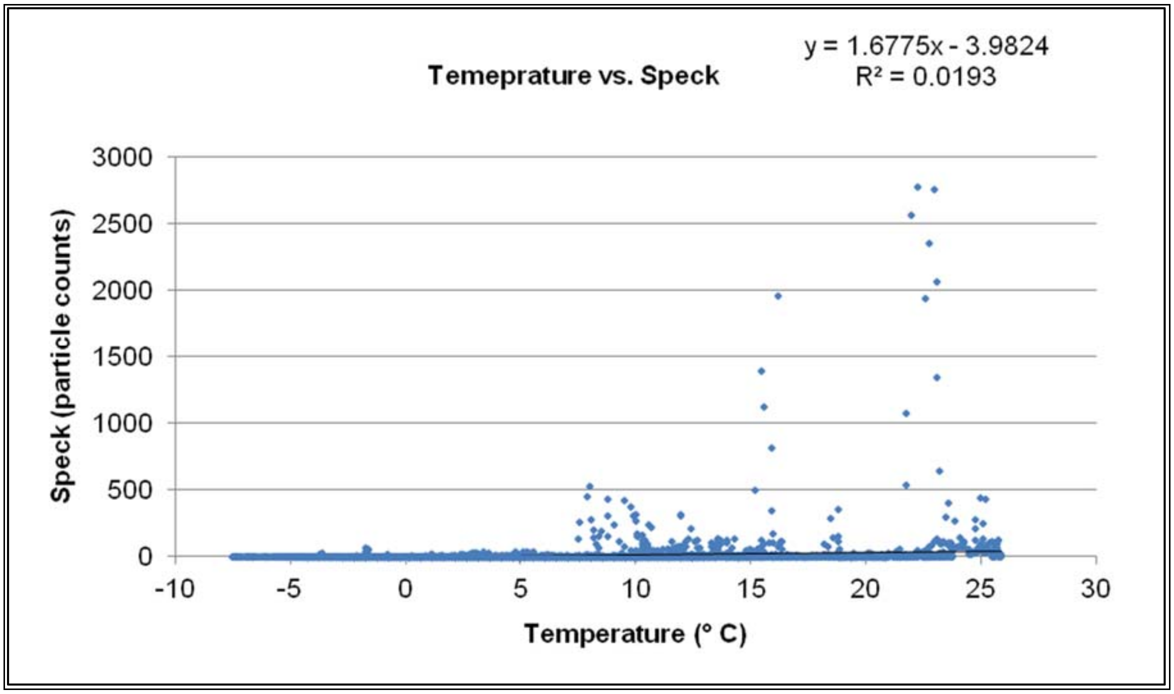

Figure 3.3.1-6. Temperature vs. Speck (5-min averages).

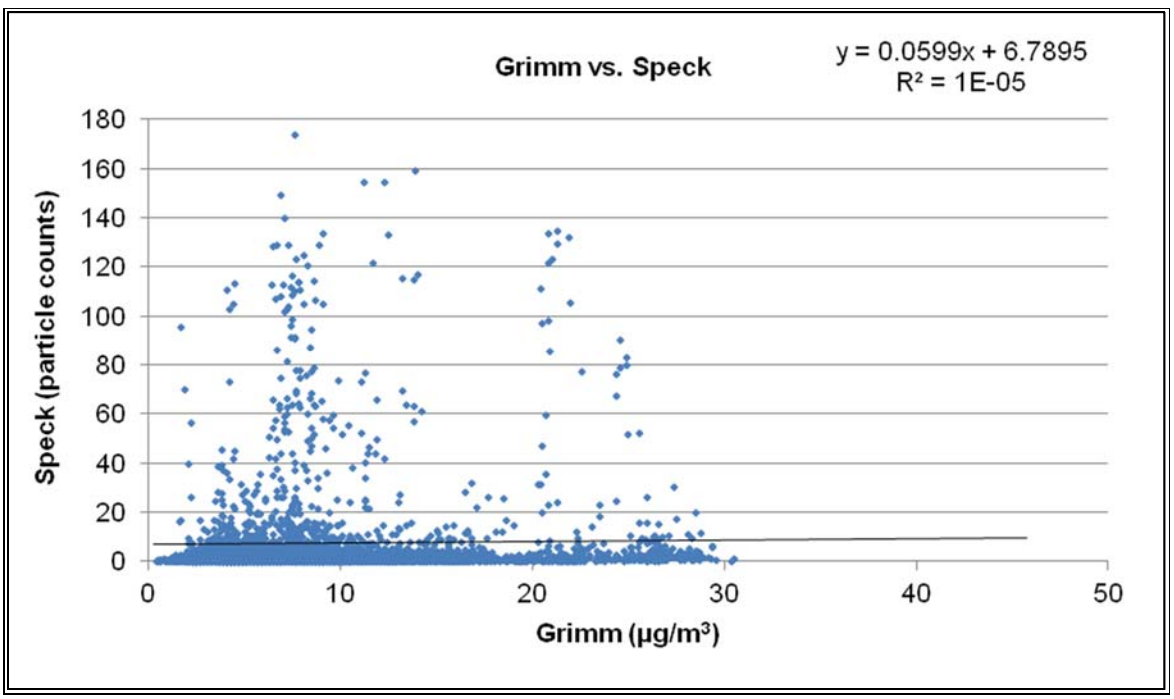

Figure 3.3.1-7. Grimm vs. Speck (5-min averages).

3.3.2 Speck Discussion

The Speck unit does not contain a battery and therefore requires a constant connection to power via a mini-USB cable. Data are preset by the manufacturer to be generated once per second, which causes data to accumulate very quickly. It is important to note that due to the massive file sizes involved, data must be downloaded at least every 10 days, or the files will contain too many lines to import into Microsoft Excel without manipulating the output text file. Finally, it is recommended that Speck Gateway software remain running continuously while the unit is in operation, as it can take several hours to download a backlog of a few days of data.

Data are time stamped in UTC seconds (9 digits), which is the number of seconds since midnight, January 1, 1970, GMT. Data are also time stamped in UTC milliseconds (12 digits) when downloaded. This convention left the raw data for the Speck impossible for operators to scan visually as 9- and 12-digit numbers are not easily mentally converted to dates and times. Thus, making sure the correct data were downloaded required exporting the data to Excel and converting the time stamps into an easily readable format.

The data contained large groupings of very small values interspersed with very large spikes; not all of these spikes could be explained. No correlation could be found with the Grimm FEM analyzer.

It should be mentioned here that based on post-analysis summarization of the Speck data and information on the development of a more advanced Speck that a second round of testing was performed during the early fall of 2014 using the newest version available from the developer. Unfortunately, the device we obtained suffered a mechanical issue, which resulted in its failure, and no updated findings can be shared here. Resource limitations prevent us from conducting a third data collection attempt with this sensor. We encourage readers to review information provided by the manufacturer that indicated the device now reports output in units of ug/m^3 and with a response algorithm developed versus collocated reference monitoring (www.specksensor.org). Based upon the information shared by the manufacturer, the device has been upgraded substantially. Even so, we have no data relative to the upgraded model.

3.4 Dylos DC1100

3.4.1 DC1100 Results

The Dylos DC1100 measures PM in particle counts at two size cutoffs. “Large” particles are defined by the manufacturer as particles 2.5 µm in diameter or larger. “Small” particles are defined by the manufacturer as particles 0.5 µm in diameter or larger. By subtracting the count of large particles from the count of small particles, $PM_{2.5}$ particle counts can be approximated. It is important to note that particles less than 0.5 µm in diameter were not measured. In addition, any conversion factor between particle counts and its conversion to $\mu g/m^3$ would depend on the particle density profile remaining constant. The manufacturer provided no conversion between counts and mass concentration.

For comparison with the Grimm reference data, 5-min averages were calculated for all data from the Dylos DC1100. The 5-min averaged large particle counts were then subtracted from the 5-min averaged small particle counts to yield data defined as 5-min averaged difference. Figure 3.4.1-1 shows that the Grimm and the Dylos data compare well despite using different units on dramatically different scales. This comparison is further explored quantitatively with the DC1100 24-hour averaged data plotted against the Grimm reference data (Figure 3.4.1-2) as well as temperature (Figure 3.4.1-3) and RH (Figure 3.4.1-4). The 24-hour average data suggest a strong correlation with the Grimm reference data. No correlation with temperature was observed while a potential correlation with humidity was evident.

RH fluctuates over the course of a day, necessitating a further look at the correlation between RH and sensor response at a 5-min averaged time resolution (Figure 3.4.1-5). The Dylos signal showed increased variability at high humidity. The upper bound of this variability appears to increase exponentially with RH. The production of artificially high results in the presence of high RH is a well-documented phenomenon with optically based particulate monitors[11]. As such, all data at RH greater than 95% were removed.

A comparison of the 5-min averaged data for the Grimm and the Dylos yielded an R^2 value that was sufficiently high to warrant normalization of the Dylos data. The best-fit line shown in Figure 3.4.1-6 was used to normalize the Dylos data against the Grimm, producing the trace in Figure 3.4.1-7.

[11] Chakrabarti, B., Fine, P.M., Delfino, R., and Sioutas, C. 2004. Performance evaluation of the active-flow personal DataRam $PM_{2.5}$ mass monitor (Thermo Andersen pDR-1200) designed for continuous personal exposure measurements. *Atmospheric Environment* 38:3329–3340.

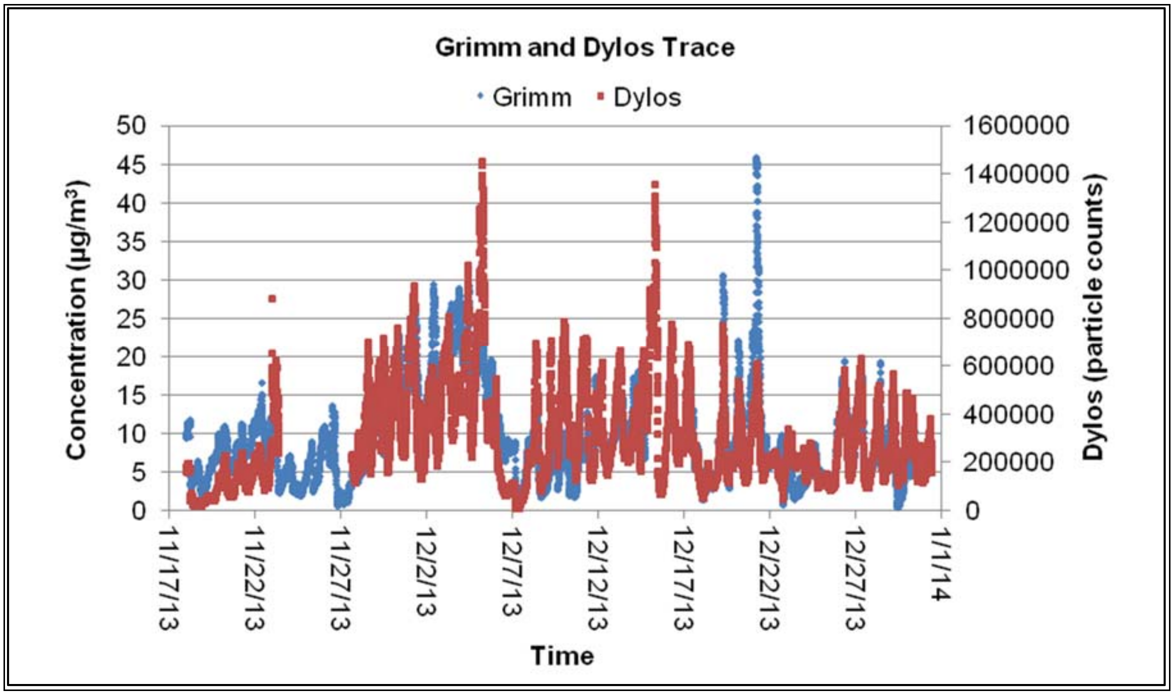

Figure 3.4.1-1. Grimm data and Dylos data over time.

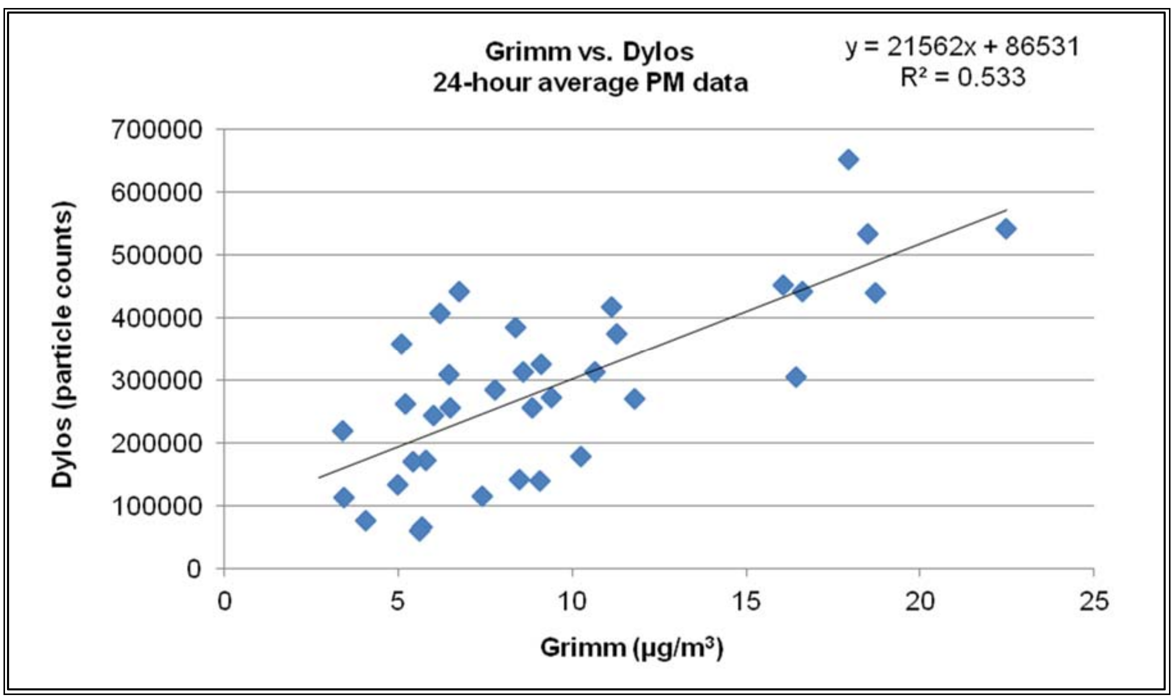

Figure 3.4.1-2. 24-hour time-averaged PM data comparing the Grimm reference sampler with the Dylos DC1100 PM sensor.

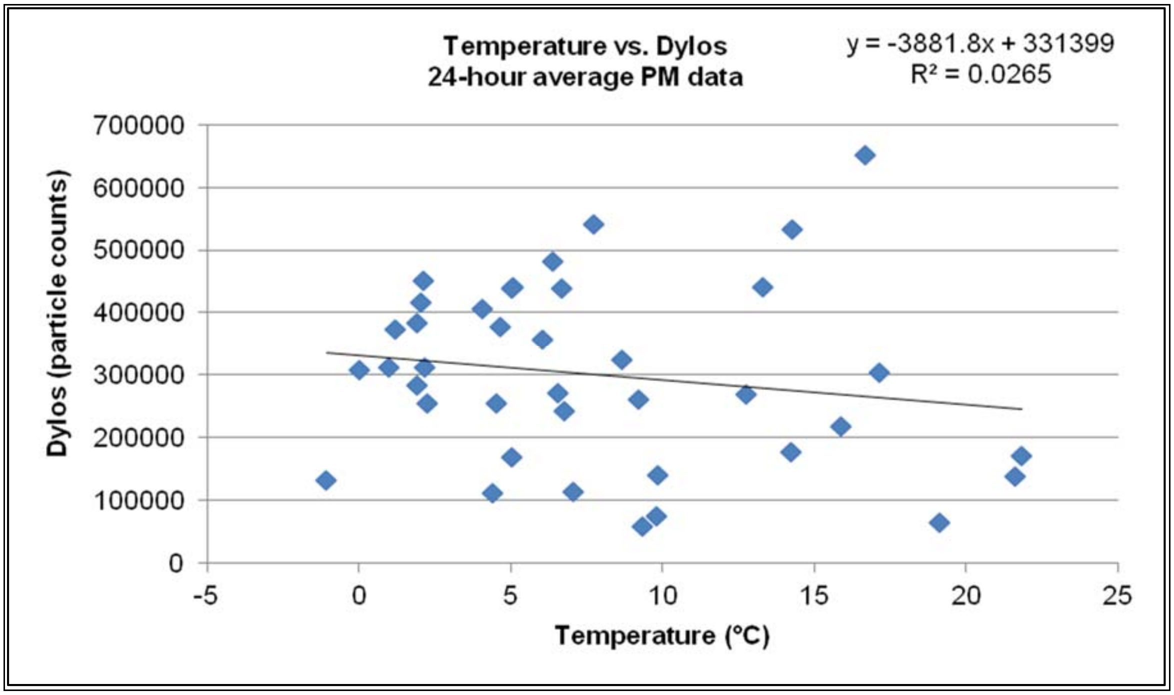

Figure 3.4.1-3. Temperature vs. Dylos 24-hour averaged data.

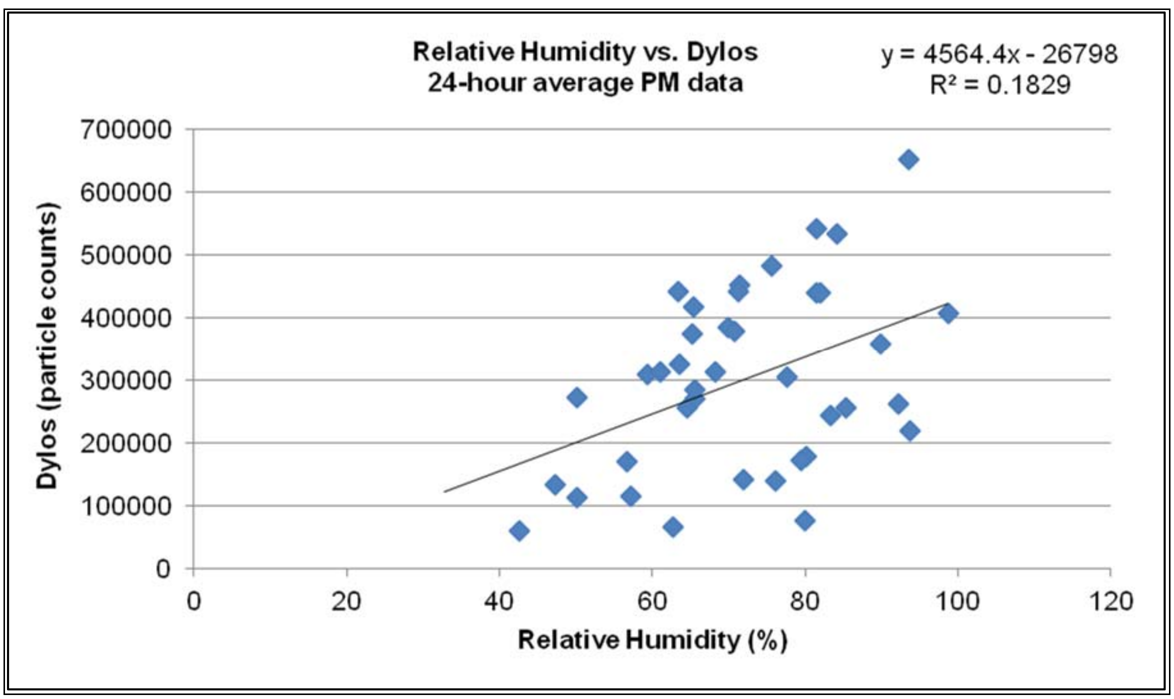

Figure 3.4.1-4. RH vs. Dylos 24-hour averaged data.

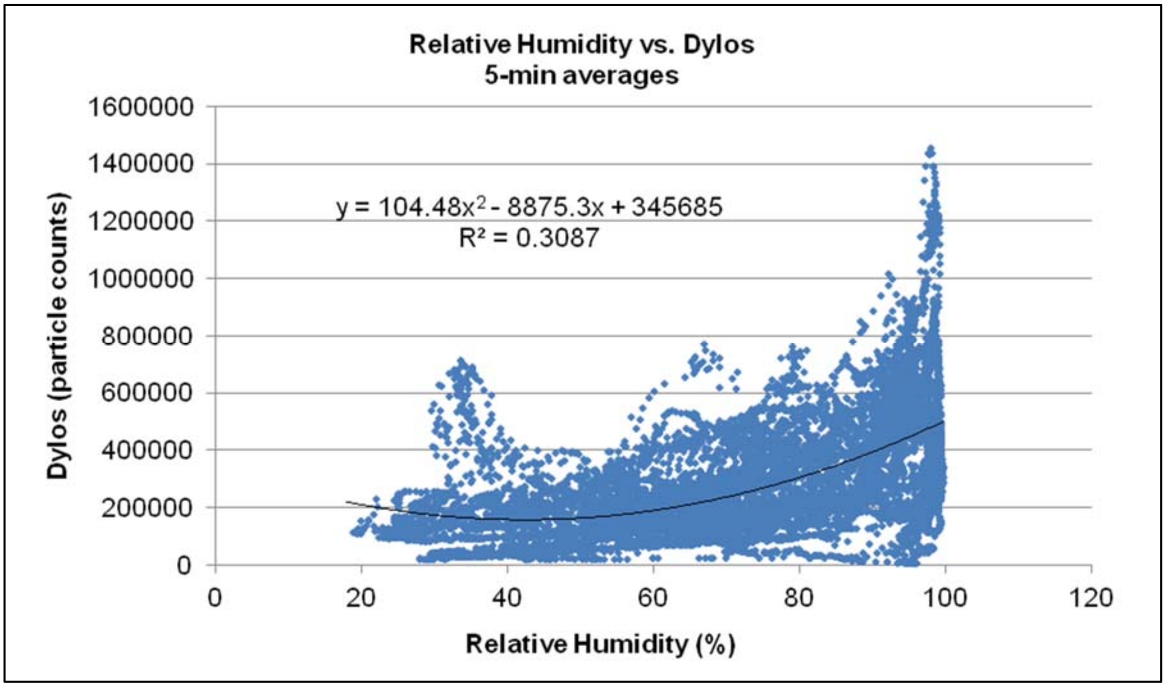

Figure 3.4.1-5. RH vs. Dylos (5-min averages).

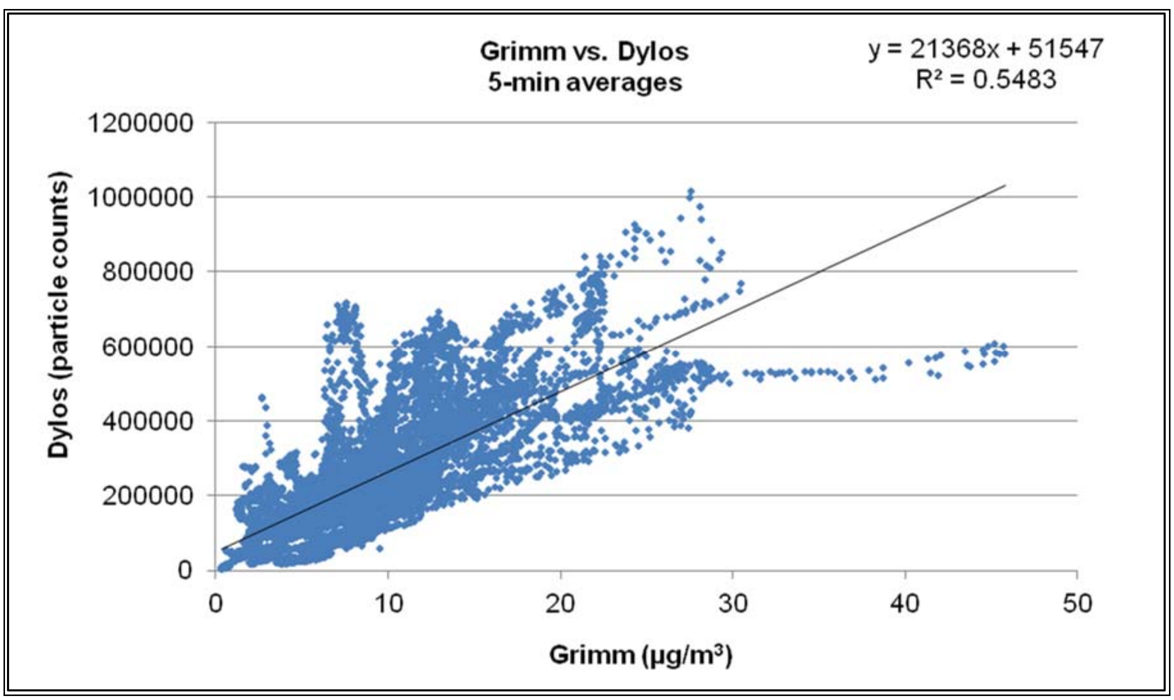

Figure 3.4.1-6. Grimm vs. Dylos (5-min averages).

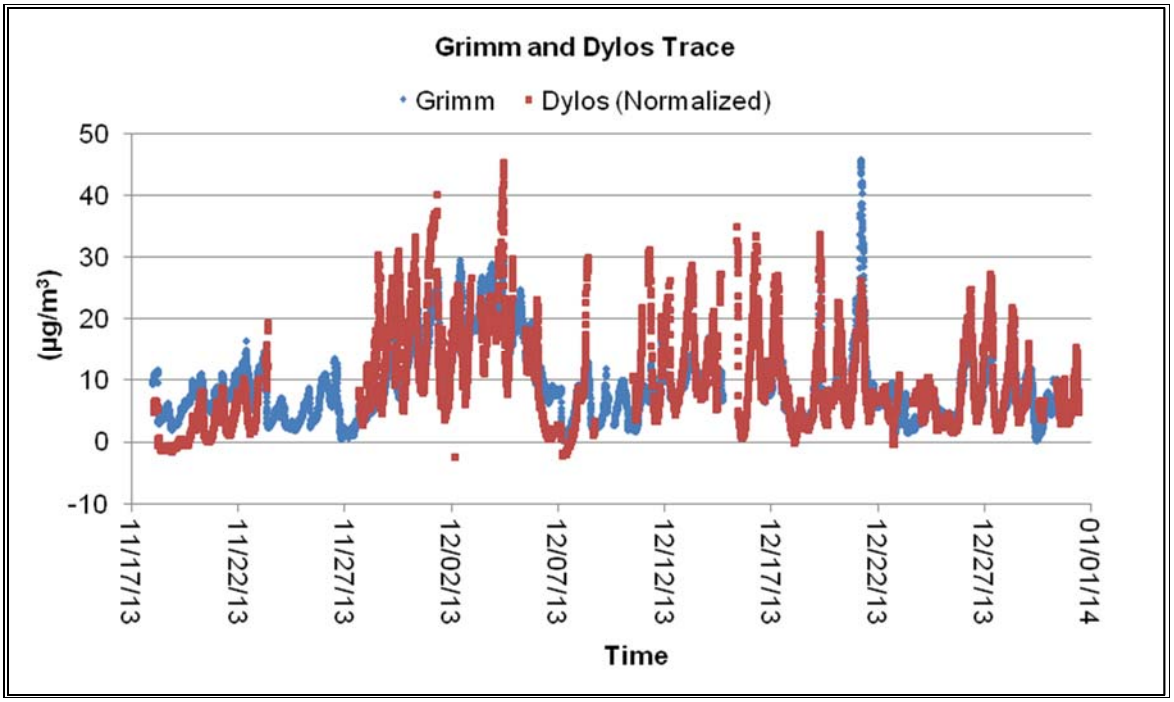

Figure 3.4.1-7. Grimm and normalized Dylos data (5-min averages) against time.

3.4.2 DC1100 Discussion

The Dylos DC1100 does not contain a battery and must be connected to AC power to operate. In addition, only data recorded directly to a computer via the Dylos Logger software contains time stamps. Consequently, the Dylos should be considered for stationary applications only. When preparing to operate a Dylos DC1100, it is important to note that an RS-232 connection to a computer is required.

Raw data are produced once per minute. Visual inspection of the raw data showed it to be smooth and devoid of fast time resolution spikes, which indicate no obvious malfunctions, electrical noise, or other errors occurred during its operation. The device showed no correlation with temperature and minimal correlation with humidity. Removing data taken at 95% RH and above was sufficient to bring the R^2 value to 0.55 when compared with the Grimm reference monitor. Analysis of the differences between the normalized Dylos data and the Grimm data compared to temperature and humidity suggested that further removing data above 90% RH while removing data obtained at temperatures below 0 °C might yield a further improvement in R^2. However, this represented removal of a large volume of data while only increasing R^2 to 0.6.

A closer look at the data reveals discrepancies between the Dylos (normalized) and the Grimm FEM data (Figure 3.4.1-8). On the afternoons of November 28, November 29, and December 1, 2013, the Dylos showed significant and protracted spikes in particulates, whereas the Grimm indicated only very modest increases. The three spikes appear to correlate with a sudden increase in temperature and a drop in humidity, but this pattern was not consistently repeated in the rest of the data. These spikes might be related to meteorological phenomena that were not tracked in this experiment, but which feature sudden temperature and humidity changes. It is also possible that these spikes indicate a localized combustion event (e.g., idling diesel engine) that produced large numbers of low-density particles affecting the device. Even so, we have no record of such an event occurring and it is only speculation as to one possible explanation.

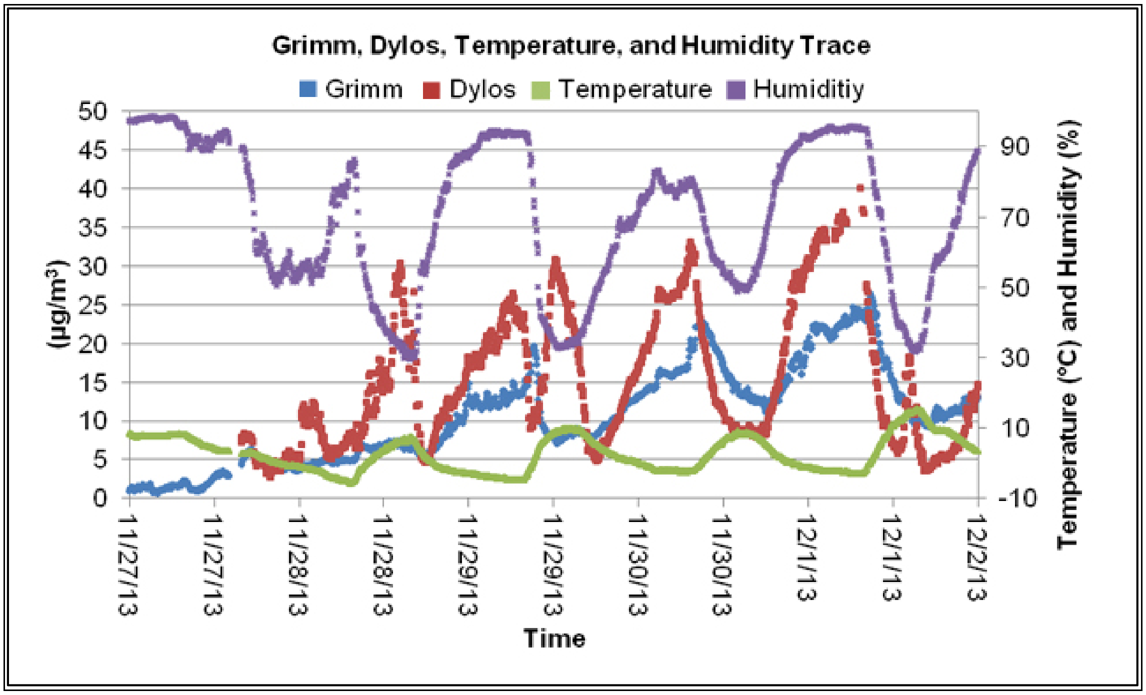

Figure 3.4.1-8. Dylos, Grimm, Temperature, and RH from November 27 to December 2, 2013.

3.5 Met One Model 831

3.5.1 Met One Model 831 Results

The Met One Model 831 is an optical PM sensor that uses a proprietary algorithm to calculate particle density in micrograms per cubic meter (µg/m^3) from particle counts at four different size fractions (PM_1, $PM_{2.5}$, PM_4, and PM_{10}).

Early attempts to interpret the Met One data focused on the $PM_{2.5}$ channel as it was hypothesized that data from this channel would provide the best match with the Grimm $PM_{2.5}$ data. The $PM_{2.5}$ channel was found to contain many outliers in the form of sharp spikes on an order of magnitude or greater than the adjacent data. Many attempts were made to identify and remove outliers from the $PM_{2.5}$ data prior to calculating 5-min averages. Despite these efforts, 5-min averages of raw PM_1 data were found to have a coefficient of determination relative to the Grimm reference data more than three times greater than the $PM_{2.5}$ with the Grimm. Figure 3.5.1-1 clearly shows that compared to the PM_1 channel (which had no outliers removed), the $PM_{2.5}$ channel (which had many outliers removed) displayed significantly more spikes. For these reasons, only data for the PM_1 channel are reported in the remainder of this section as a best-case scenario.

Figure 3.5.1-2 shows that the responses from the Grimm and the Met One compare well. This comparison is further illustrated using Met One 24-hour averaged data plotted against the Grimm reference data (Figure 3.5.1-3) as well as temperature (Figure 3.5.1-4) and RH (Figure 3.5.1-5). The 24-hour averaged data suggests a correlation with the Grimm reference data, no correlation with temperature, and a strong correlation with humidity.

As RH naturally fluctuated over the course of any given day, further investigation into the correlation between humidity and sensor response at the 5-min averaged time resolution was necessary. These results are shown in Figure 3.5.1-6. The Met One signal showed increased variability at high humidity. The upper bound of this variability appears to increase exponentially with rising relative humidity. As a result, all data taken at times when the relative humidity was greater than 90% were removed.

The 5-min averaged data scatter plot comparing the Grimm to the Met One yielded an R^2 value sufficient to warrant its normalization to examine potential improvement. The best-fit line of Figure 3.5.1-7 was used to normalize the Met One data against the Grimm, producing the trace in Figure 3.5.1-8.

The spike seen on December 4, 2013 straddles data that were removed because they were taken at greater than 90% RH. It is possible there was an unrecorded drizzle or light rain event during this time that might have caused the spike. Consequently, all data collected between 04:00 and 14:00 on December 4, 2013, were removed. The scatter plot of the Met One data vs. the Grimm was remade in Figure 3.5.1-9 and renormalized in Figure 3.5.1-10.

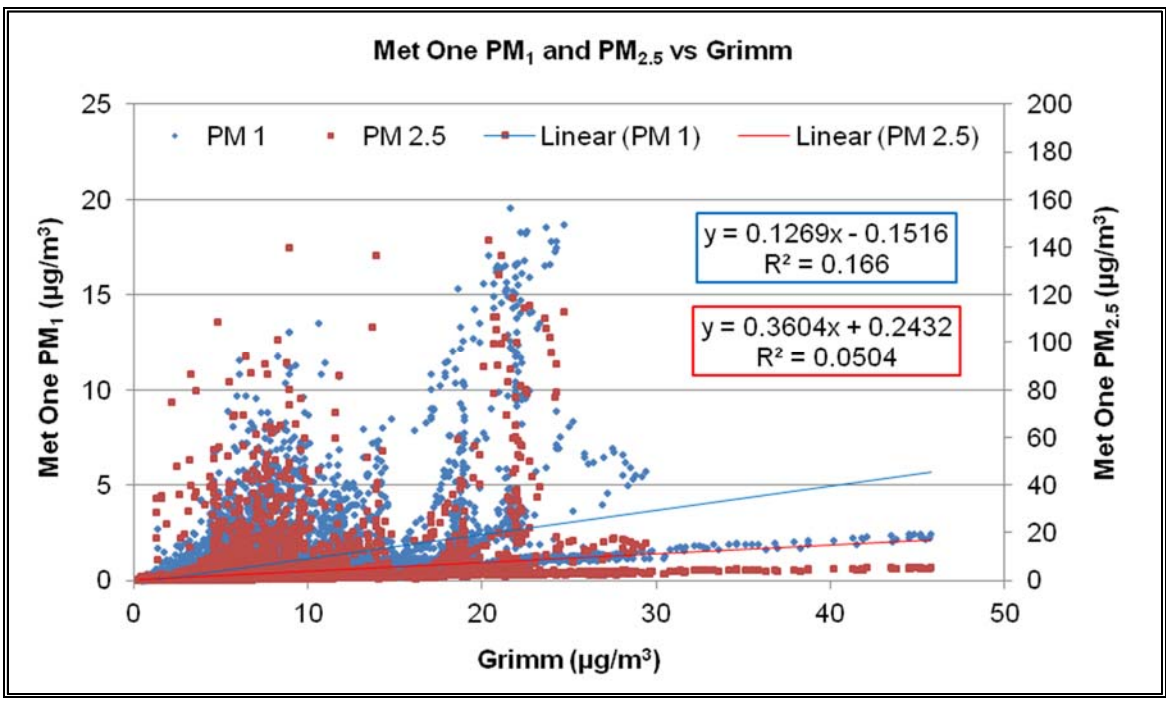

Figure 3.5.1-1. Grimm vs. Met One Model 831 PM_1 and $PM_{2.5}$ (5-min averages).

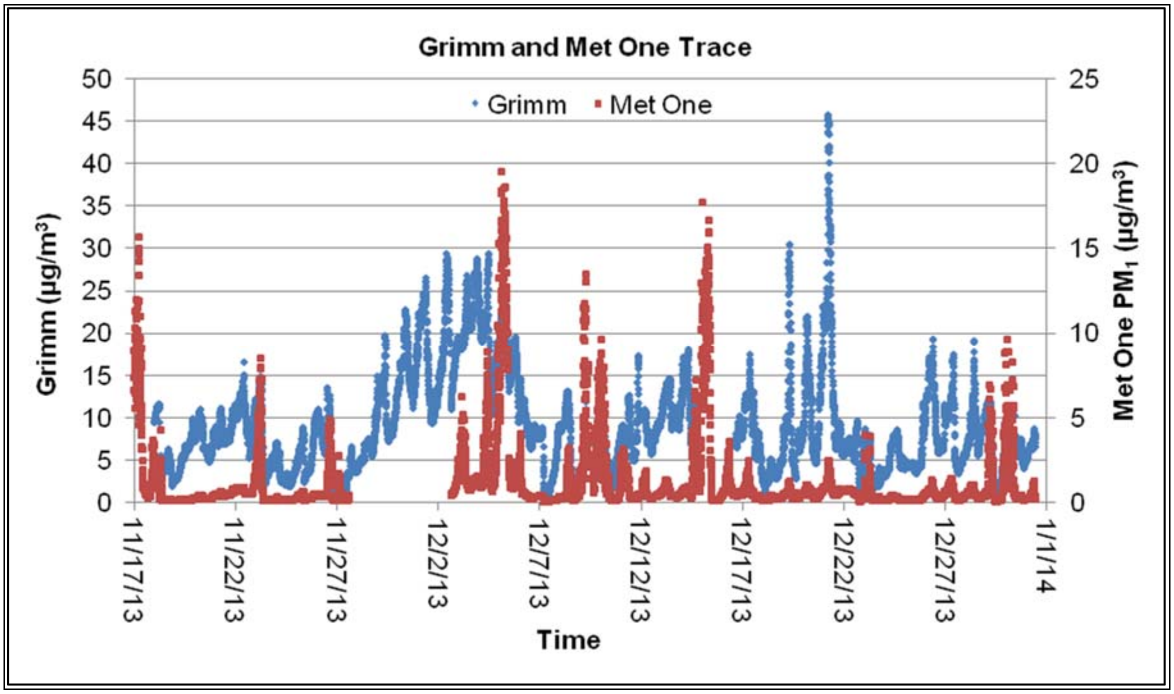

Figure 3.5.1-2. Grimm data and Met One Model 831 data over time.

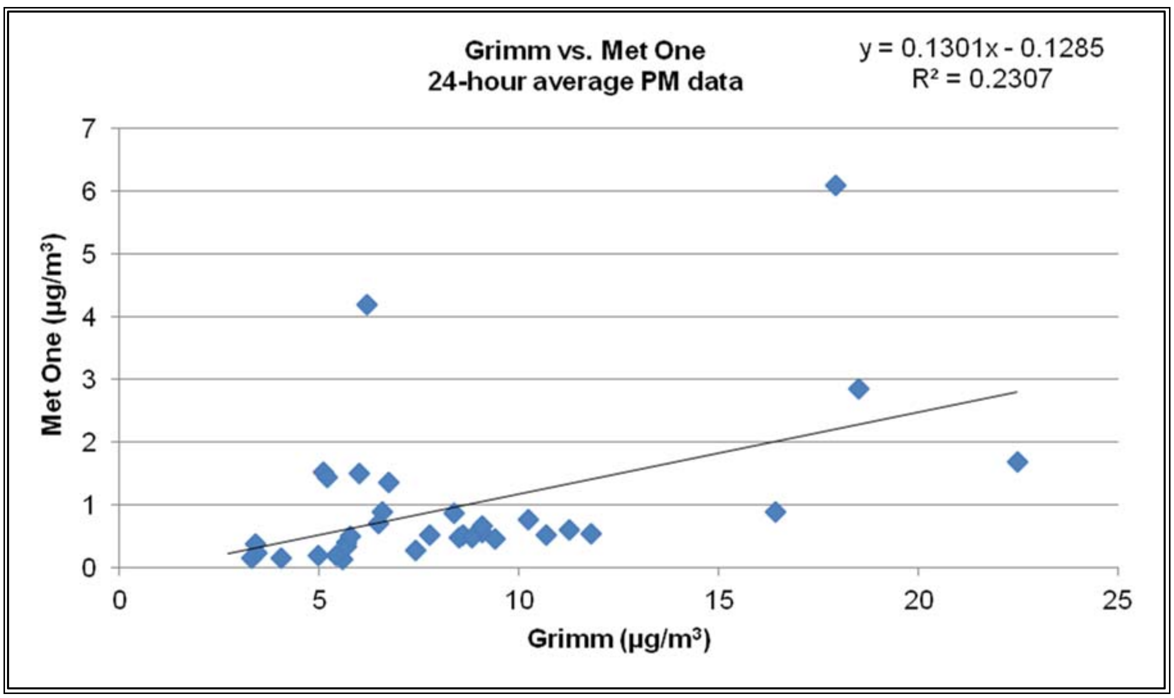

Figure 3.5.1-3. 24-hour time-averaged PM data comparing the Grimm reference sampler with the Met One Model 831 PM sensor.

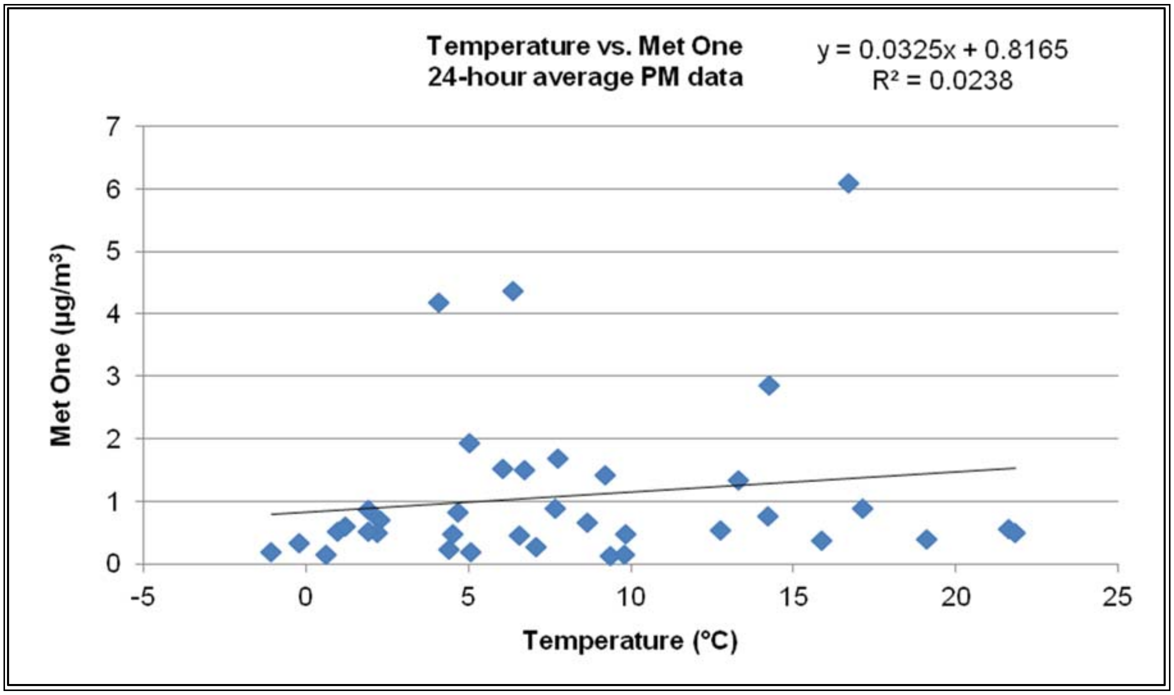

Figure 3.5.1-4. Temperature vs. Met One Model 831 24-hour averaged data.

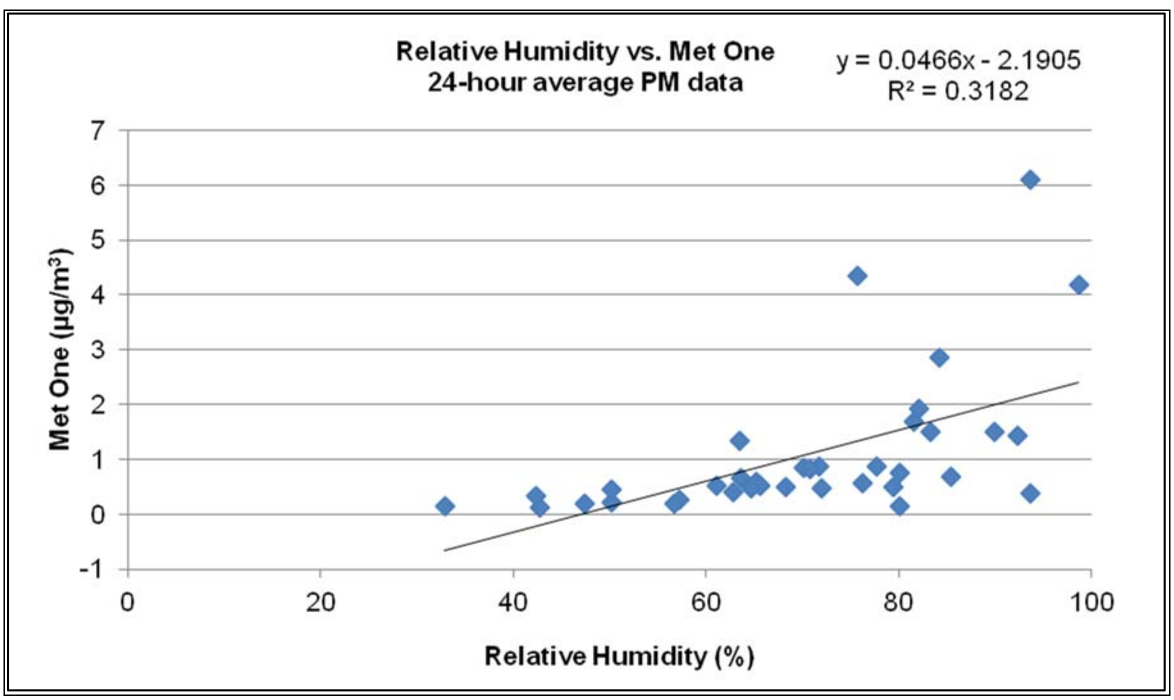

Figure 3.5.1-5. RH vs. Met One Model 831 24-hour averaged data.

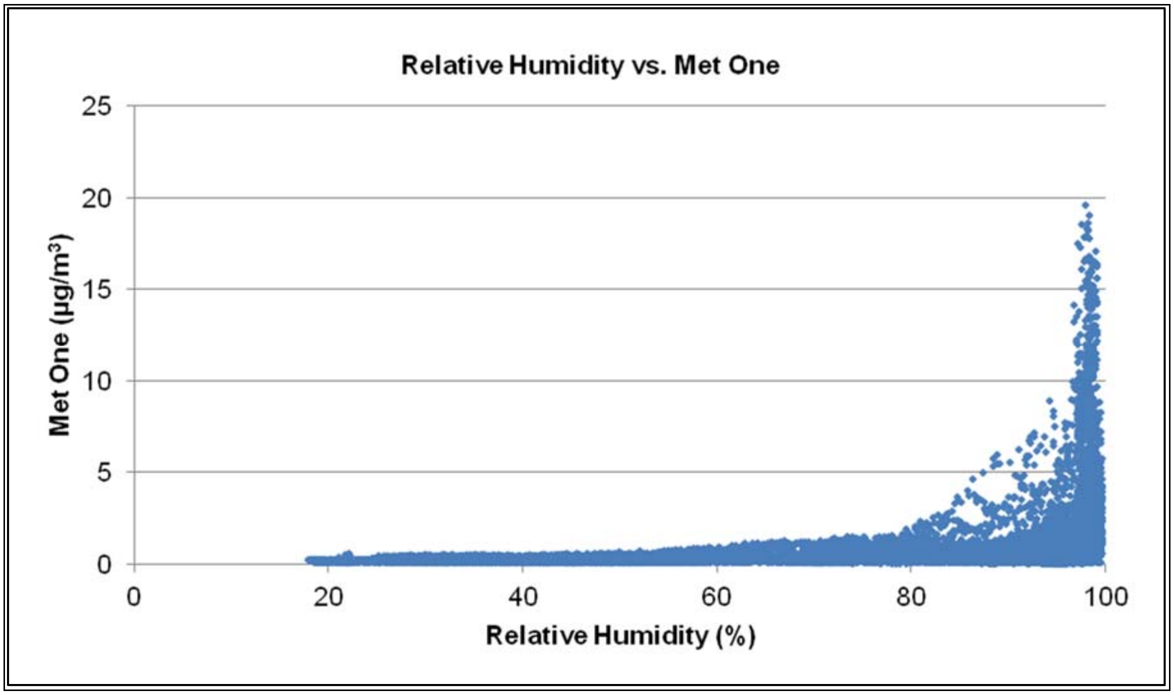

Figure 3.5.1-6. RH vs. Met One Model 831 (5-min averages).

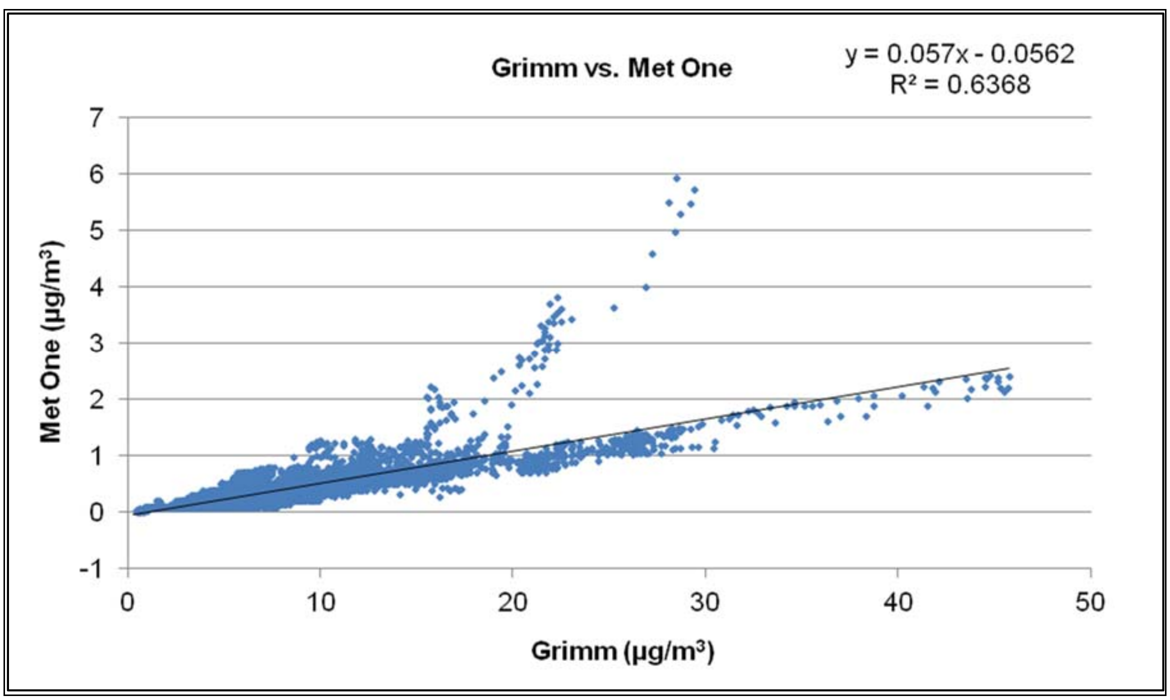

Figure 3.5.1-7. Grimm vs. Met One Model 831 (5-min averages).

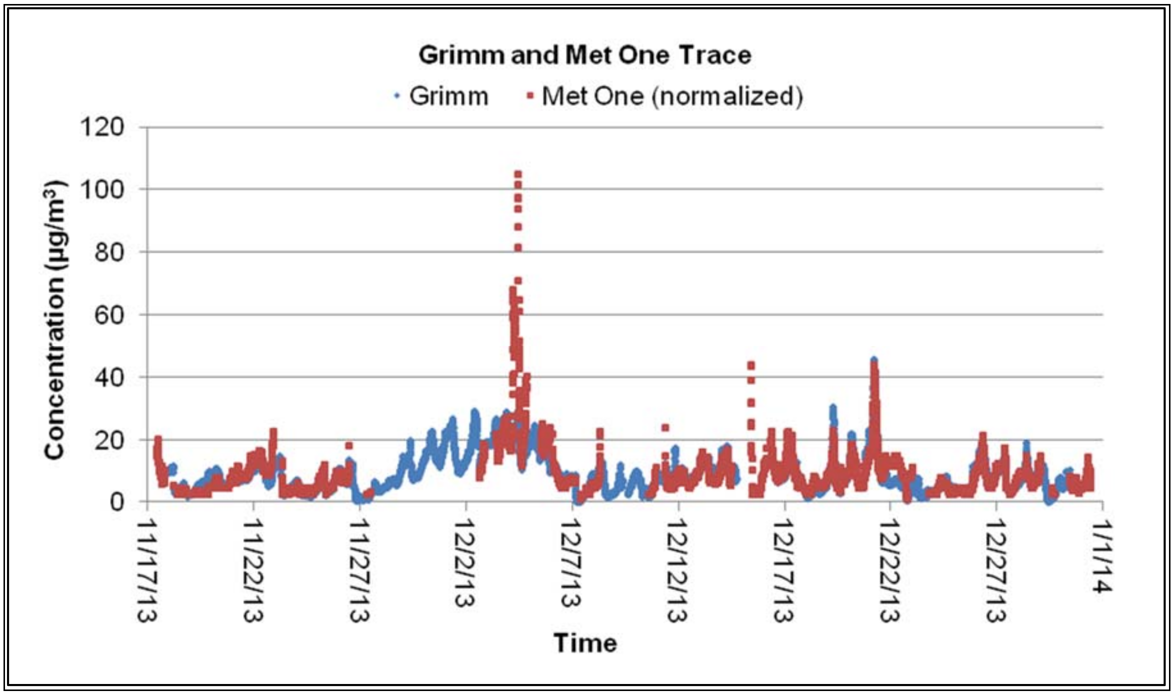

Figure 3.5.1-8. Grimm and normalized Met One Model 831 data (5-min averages) against time.

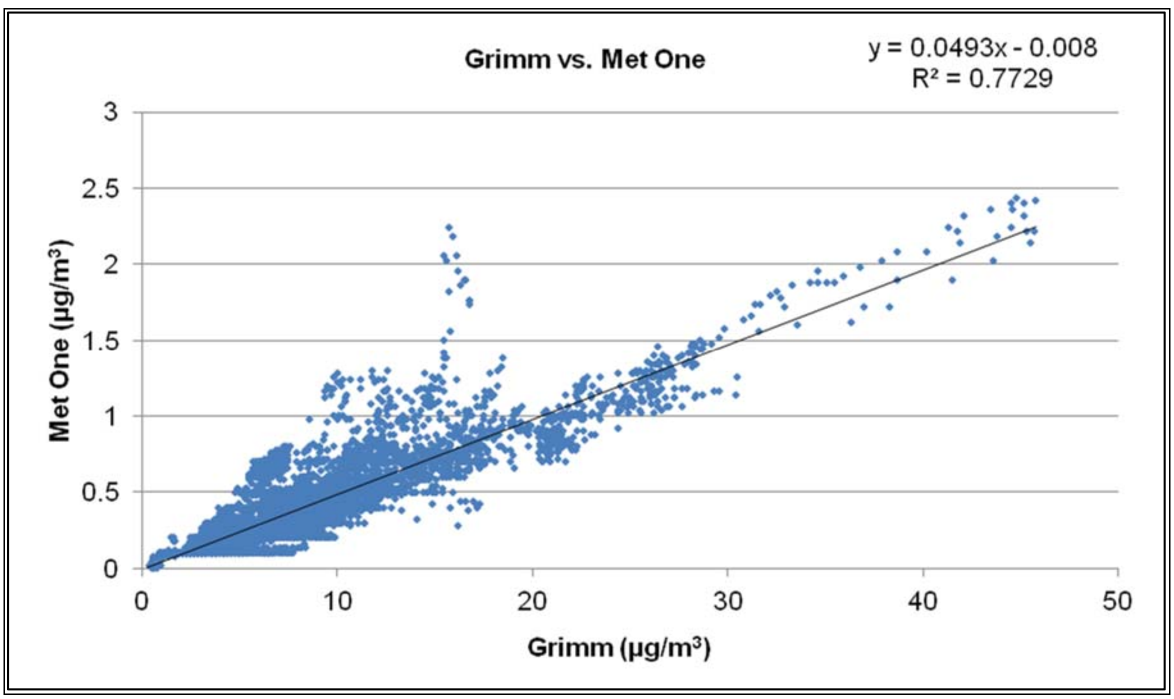

Figure 3.5.1-9. Grimm and Met One Model 831 data (5-min averages) with data from 04:00 to 14:00 on December 4 removed.

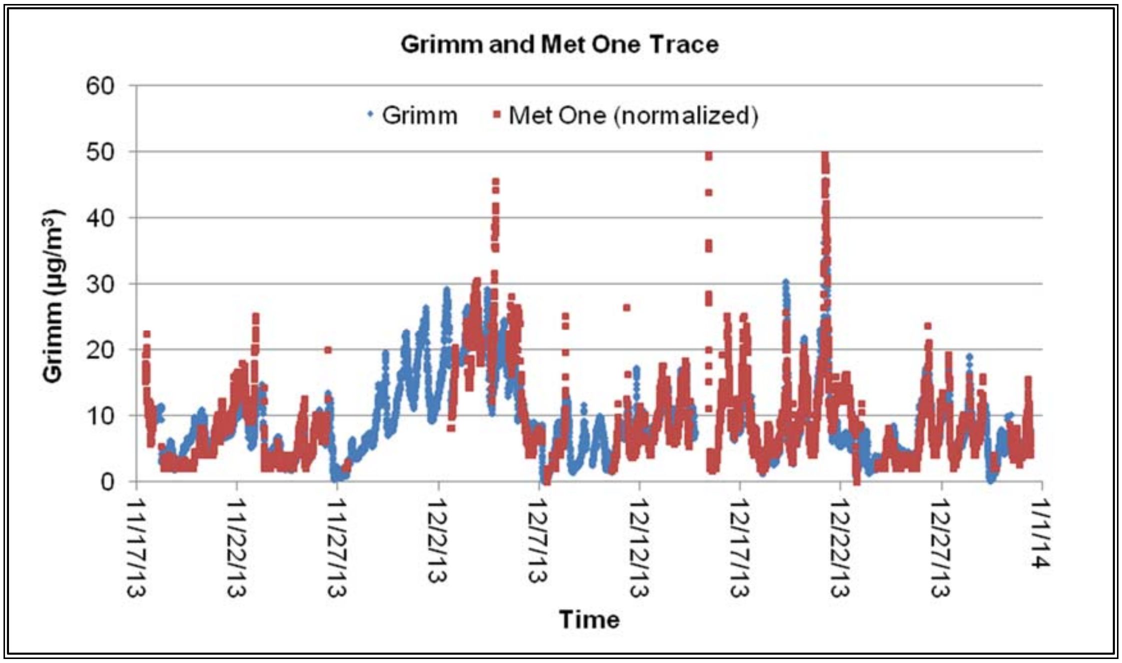

Figure 3.5.1-10. Grimm and renormalized Met One Model 831 data against time (5-min averages).

3.5.2 Met One Model 831 Discussion

While the Met One Model 831 does contain a battery, the operational duration of that battery was not tested as part of this study and remains unverified. The device was easy to operate and ran smoothly with only one section of missing data (11/27/13 through 12/2/13). Because this gap spans exactly from one operator visit to the next, the failure was likely a result of operator error. The Met One does require flow checks and zero checks, but neither required any adjustment during the evaluation. The only caveat is that flow rate checks and zero checks require an unusually tiny hex key making it difficult to use and hard to replace if misplaced or lost.

Raw data are produced once per minute. The $PM_{2.5}$ and larger channels featured many abnormally high spikes, while the PM_1 channel was comparatively smooth. Further analysis showed that the PM_1 channel matched the reference analyzer to a far greater degree than the others. As such, this report focused on the PM_1 channel only.

The device showed no correlation with temperature but a significant correlation with RH. Removal of data taken at RH greater than 90% improved the coefficient of determination between the Met One and the Grimm to 0.64. Several outlier spikes remained, however. Closer examination of these spikes reveals they were immediately before or after time periods associated with high humidity. Even so, they are not present in the majority of such periods. In addition, there are multiple periods of high humidity in which the Met One data is devoid of spikes and matches the Grimm data extremely well. It is possible that light mist or drizzle might have influenced the Met One response but with rainfall accumulation too small to be adequately measured.

3.6 RTI MicroPEM

3.6.1 MicroPEM Results

The RTI MicroPEM is an optical particulate matter (nephelometer) sensor that uses a size-selective inlet to measure $PM_{2.5}$. The device as originally received produced data of poor quality during the November to December 2013 testing. This included many outliers. One of the more obvious and prevalent features of these was a frequent negative spike to approximately -600 µg/m^3. Subsequent discussions with RTI International on the findings indicated a recent upgrade on the device was available that should resolve the issues we were observing (poor peak trends versus the Grimm, high degree of temperature and RH influence in concentration response). Based upon this information, the MicroPEM was upgraded to meet the latest component configuration and then a new round of testing was performed. It is data from that round of testing that we report.

It should be clearly stated here that the MicroPEM is not designated by RTI as a device intended for 24-hr outdoor monitoring. Therefore, the evaluation performed involves factors beyond its general scope of use (personal and/or indoor monitoring). Even so, the evaluation performed here should be viewed as one that should provide practical guidelines on the use of this device, which the authors of this report consider as one of the more advanced $PM_{2.5}$ sensors relative to its potential for meeting a variety of monitoring needs. We protected the device from stray light as much as practically possible by operating it within the aluminum shelters previously mentioned.

Raw data was inspected visually for large outliers. Less than ten outliers were found and were removed manually. These outliers were highly fluctuating positive and negative signal responses, which appeared to be possibly electrical noise in nature. Data was then compiled into 5-minute block averages. Traces of each MicroPEM response over time overlaid with a trace of the Grimm over time are shown in Figure 3.6.1-1, Figure 3.6.1-2, and Figure 3.6.1-3.

All three MicroPEMs appear to track the Grimm well. There are, however, frequent spikes during which the MicroPEM signal greatly exceeds the Grimm's signal. Most of these spikes occur in all three MicroPEM units simultaneously and as previously mentioned may have been related to a common electrical spike at the site. This suggests they are systemic to the design. All three units were re-zeroed on 8/12/14 and 8/25/14. All three units show significant baseline shifts at these times. Based upon our observations, a more frequent zeroing frequency (e.g. every 24 hrs) might have provided benefit to the comparison performed here. Temperature and humidity are examined as possible confounding factors for MicroPEM 1 in Figure 3.6.1-4 and Figure 3.6.1-5.

Figure 3.6.1-4 demonstrates that there is no correlation between the performance of MicroPEM 1 and temperature. This is in sharp contrast to the experiments conducted in the winter of 2013-2014 during which strong correlations were reported. Figure 3.6.1-5 demonstrates that relative humidity has no effect on the MicroPEM's signal below 90% RH. There is a significant cluster of aberrantly high data points when RH > 94%.

All data with RH > 94% was removed. The remaining data was compiled into one-hour rolling averages to smooth it. Finally, the data was divided into three cohorts (7/29/14 to 8/12/14, 8/12/14 to 8/25/14 and 8/25/14 to 9/1/14) in order to account for the significant baseline shifts, which occurred when the MicroPEMs were re-zeroed. Figures 3.6.1-6, 3.6.1-7, and 3.6.1-8 are scatterplots of this data for each unit vs the Grimm. Table 3.6.1 compiles the R^2 figures for each unit and cohort.

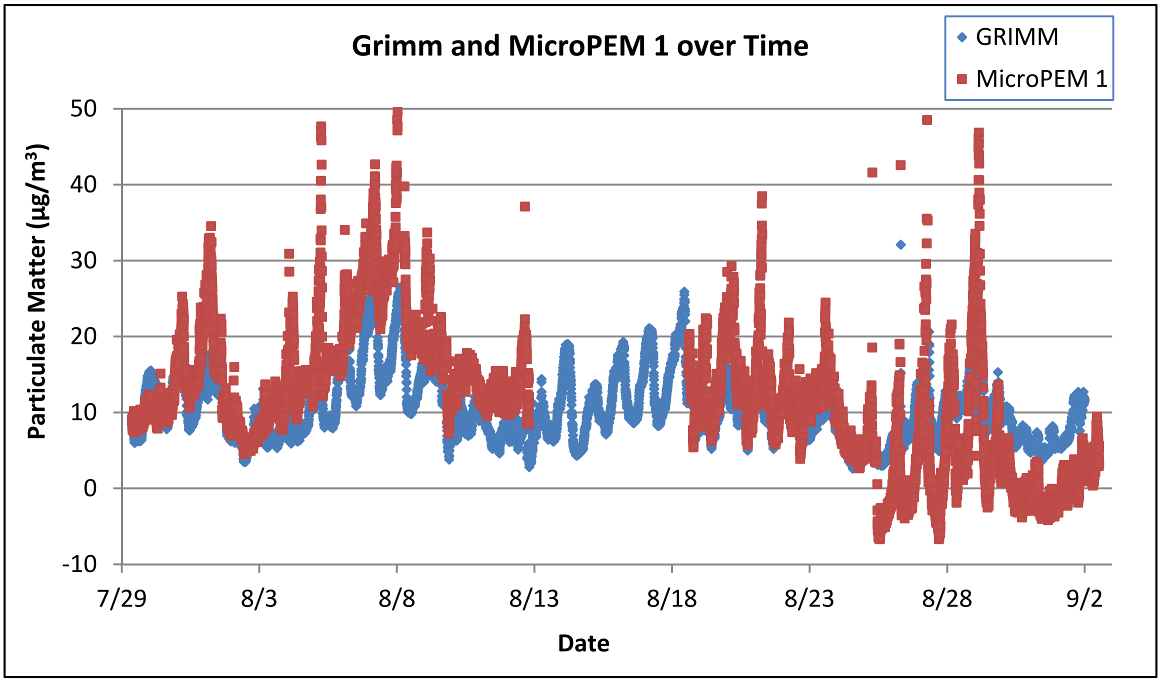

Figure 3.6.1-1. A trace of MicroPEM unit 1 and the Grimm over time.

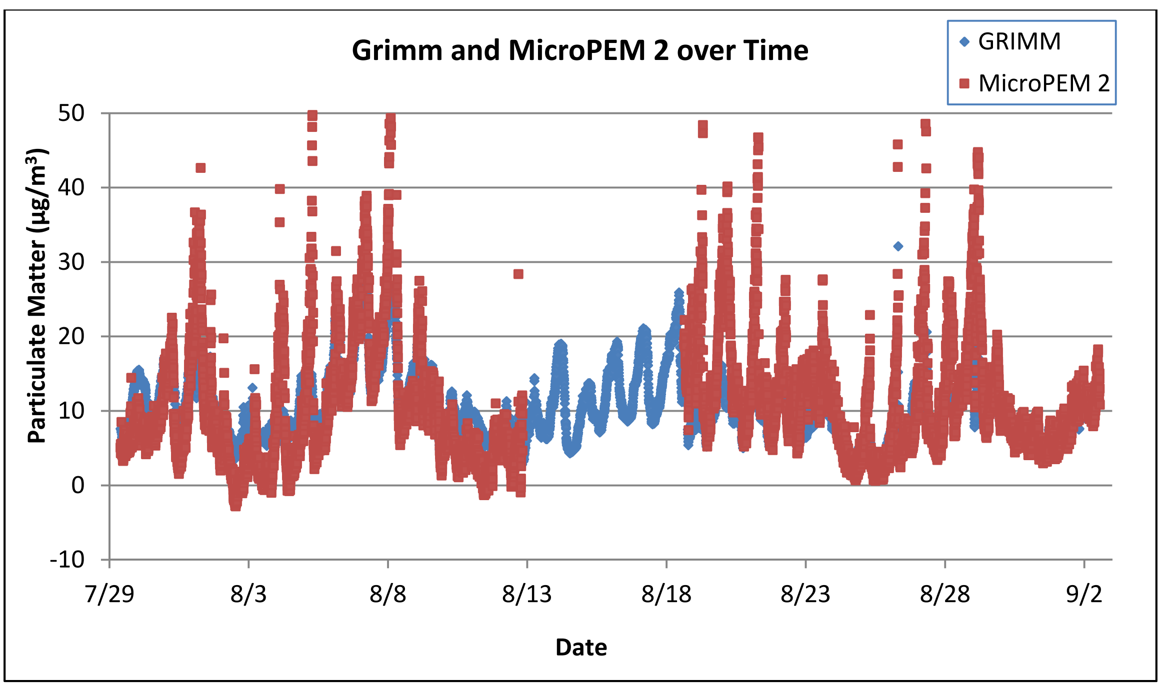

Figure 3.6.1-2. A trace of MicroPEM unit 2 and the Grimm over time.

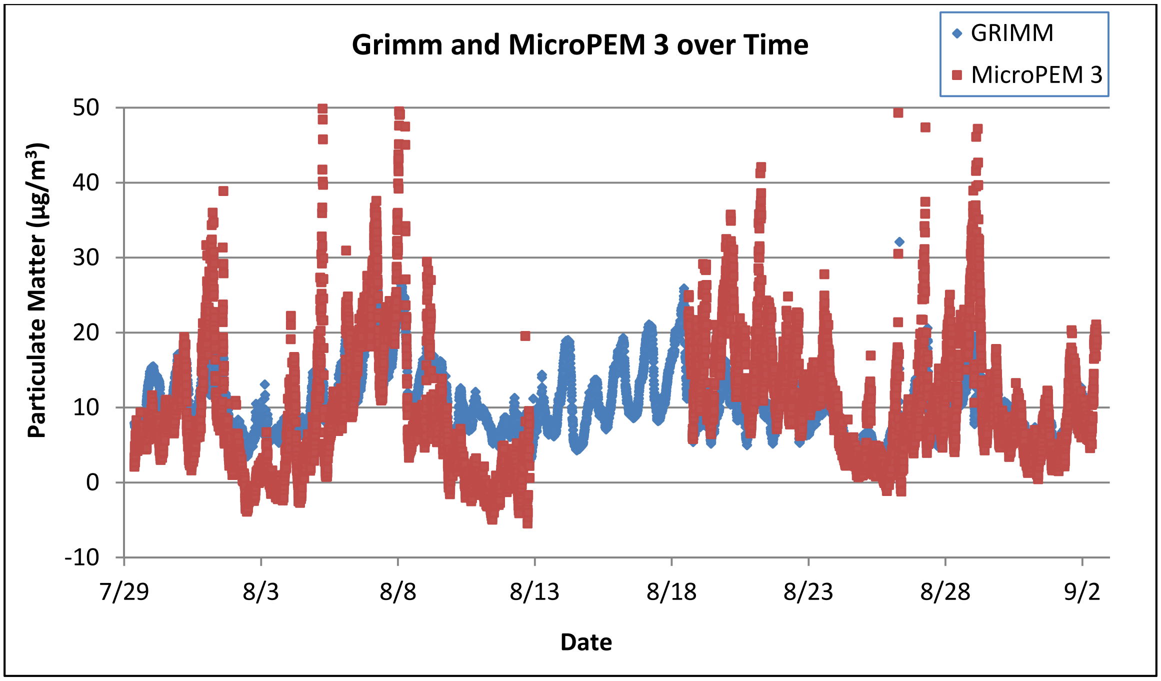

Figure 3.6.1-3. A trace of MicroPEM unit 3 and the Grimm over time.

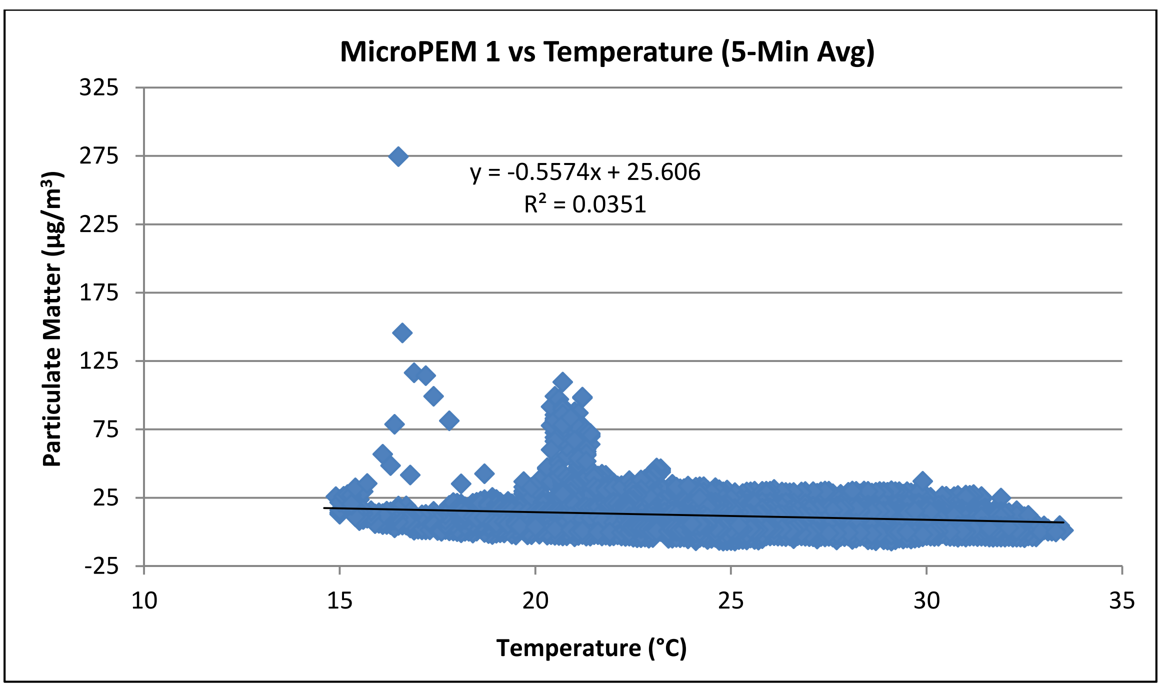

Figure 3.6.1-4. Scatterplot of MicroPEM 1 vs Temperature.

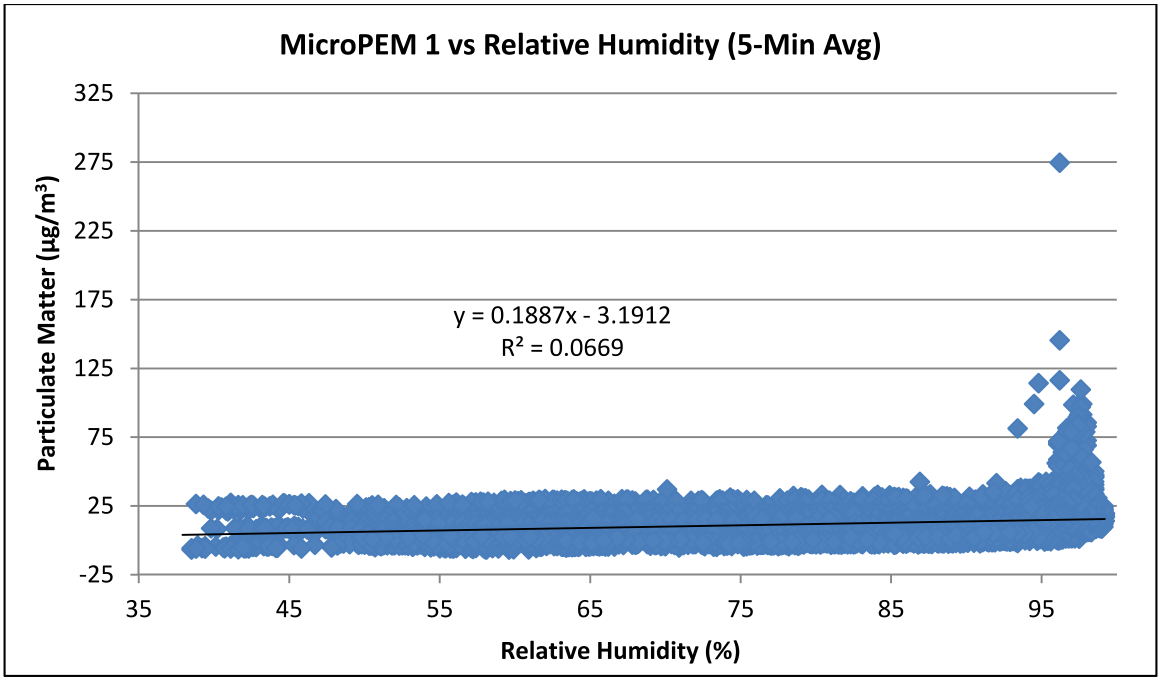

Figure 3.6.1-5. Scatterplot of MicroPEM 1 vs Relative Humidity

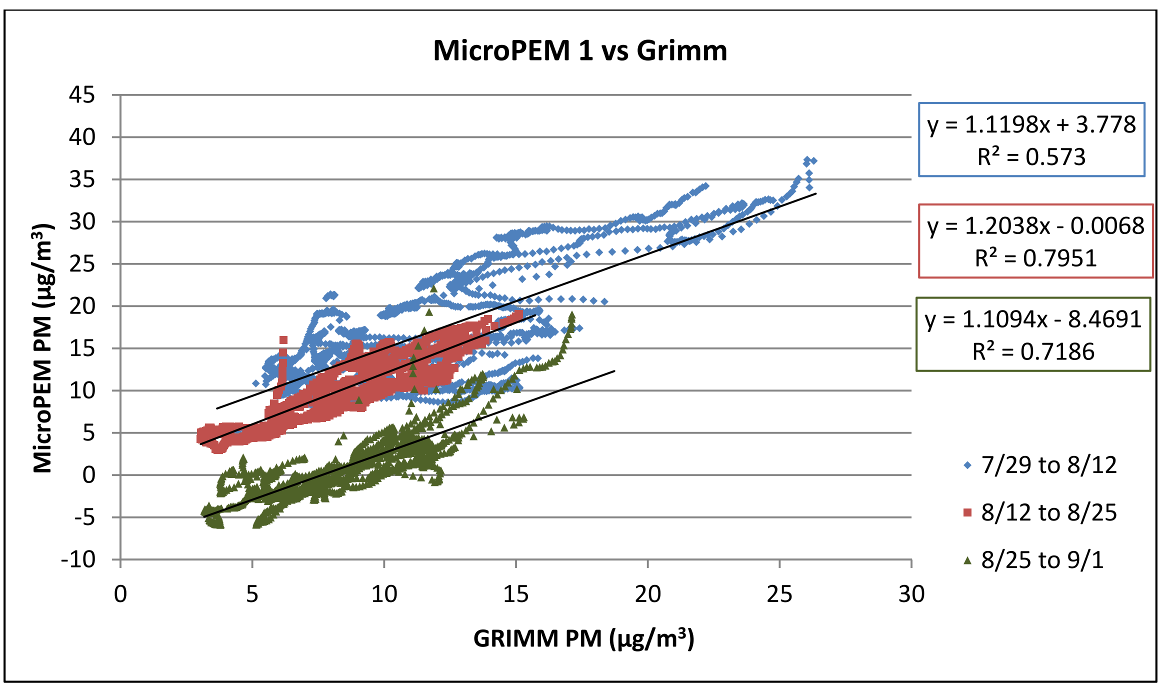

Figure 3.6.1-6. Scatterplot of MicroPEM 1 vs the Grimm. The data has been divided into three time periods following zeroing of the unit.

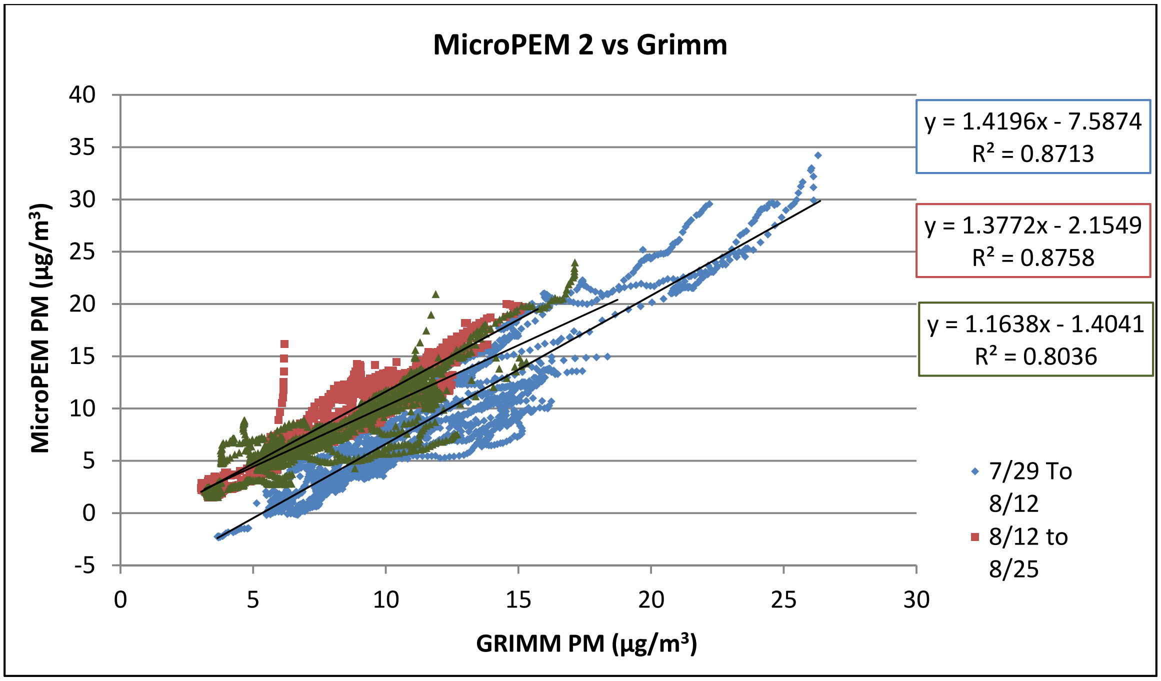

Figure 3.6.1-7. Scatterplot of MicroPEM 2 vs the Grimm. The data has been divided into three time periods following zeroing of the unit.

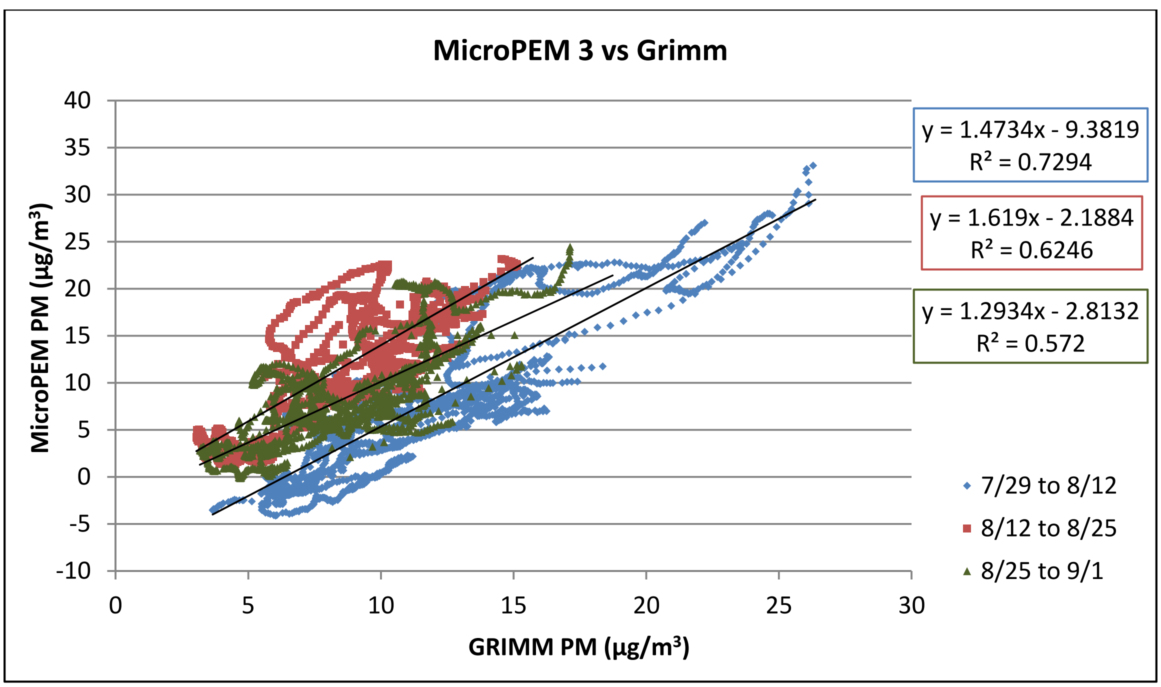

Figure 3.6.1-8. Scatterplot of MicroPEM 3 vs the Grimm. The data has been divided into three time periods following zeroing of the unit.

	MicroPEM 1	MicroPEM 2	MicroPEM 3	All Units
7/29 to 8/12	0.61	0.88	0.76	
8/12 to 8/25	0.80	0.87	0.62	
8/25 to 9/1	0.59	0.78	0.54	
Average	0.67	0.84	0.64	0.72
Std. Dev.	0.11	0.06	0.11	0.13

Table 3.6.1. R^2 values for all cohorts of all MicroPEMs versus the Grimm

3.6.2 MicroPEM Discussion

The MicroPEM is a relatively simple unit to use, although it does require signficantly more maintainence than any of the other sensors. Filters must be changed multiple times a week depending on particulate loading, and the nephelometer should be zeroed frequently (daily if possible) to take full advantage of its capabilities. The flow rate requires calibrating/auditing at regular (e.g., twice weekly) intervals.

The MicroPEM is capable of running on either AC power on on battery power, although using AC power is recommended. Despite running on AC power, a functioning coin cell battery must be in place to record accurate time stamps. If the coin cell has run down, the device is capable of running on AA batteries instead; however, the operators found that the lifespan of a set of AA batteries in the absence of a coin cell battery was a few days at best. In the event the device has no battery power but is running on AC power, time stamps will revert to a “default” time and begin counting from there. In all instances of running on default time, the amount of time recorded on default time corresponded almost exactly with the amount of time missing from the accurate time stamps. This allowed operators to use the default time stamped data with less than 5-min uncertainty of when the data were taken. Finally, the software delivers the same battery warning regardless of which battery system has failed.

An interesting effect that stands out in the operation of this device is the difficulty in properly zeroing the instrument. Since each of the three units was re-zeroed three times, there are a total of 9 zeroing events to evaluate. The degree of error of each zeroing is equal to the Y intercept of the scatterplot between the unit and the Grimm. In only one of the nine zeroings was the zero set too low, resulting in a positive baseline shift error. In seven of the nine, the zero was set too high resulting in a negative baseline shift error. In three instances, this error was greater than 5 $\mu g/m^3$. A zeroing which is set too high might be the result of particles slipping into the system past the zero air filter. The variability in the observed severity of this error suggests an operator error component rather than simple equipment failure. It is likely that the seal between the zero air filter assembly and the MicroPEM inlet was to blame. The gasketed cup which connects the MicroPEM inlet to the zero air filter is not much deeper than the opening of the MicroPEM inlet. Slight errors in seating this cup may result in outside air, laden with particles, leaking into the MicroPEM during zeroing. This would cause the observed abnormally high zeroes. The problem may be solved by fabricating a deeper cup to more easily provide a seal between the MicroPEM and the zero air filter. Figure 3.6.1-9 illustrates how the zero air filter attaches to the MicroPEM; Figure 3.6.1-10 demonstrates the relatively shallow nature of the gasketed cup compared to the inlet of the MicroPEM.

Finally, a look at the response factors for each of our scatterplots shows that the MicroPEM is between 10% and 60% more sensitive to PM load than the Grimm. Some of this excessive response is in the form of spikes that form in rapidly changing high humidity conditions.

Figure 3.6.1-9. RTI MicroPEM with zero air filter attached.

Figure 3.6.1-10. RTI MicroPEM inlet alongside the gasketed cup which serves as an attachment point for the zero air filter.

3.7 Sensaris Eco PM

3.7.1 Sensaris Eco PM Results

The Sensaris Eco PM produces data in 1-second and 30-second averages for PM_1 and PM_2. The data were highly discontinuous and large portions were missing. These problems were so great as to make a comparison of the trace of the Eco PM sensor and the Grimm reference sampler of no value. The 24-hour averages were similarly inappropriate because of this sporadic data. All four channels are plotted against time in Figure 3.7.1-1. It should be recognized that this device was "prototype" and kindly provided by Sensaris and therefore the results observed here may not reflect the ability of the developer's final version.

Most of the data recorded on both PM_2 channels was 0.00μg/m^3; therefore, the remainder of the analysis effort focused on the PM_1 30-second averaged data. The Eco PM sensor and the Grimm sampler are compared in a scatter plot in Figure 3.7.1.-2. The R^2 value of 0.3153 suggests some correlation, but there are other significant factors at work. Relative humidity and temperature were both checked as potential confounding factors in Figures 3.7.1-3 and 3.7.1-4, respectively. There is no clear evidence of a trend with humidity. The temperature graph (Figure 3.7.1.4) shows an R^2 of 0.3133, indicating a possible correlation. However, the Grimm displays higher measurements at the same points where the Eco PM measurements are higher, suggesting that the correlation with temperature might be coincidental. Thus, more data are required before a case can be made for a temperature correction factor.

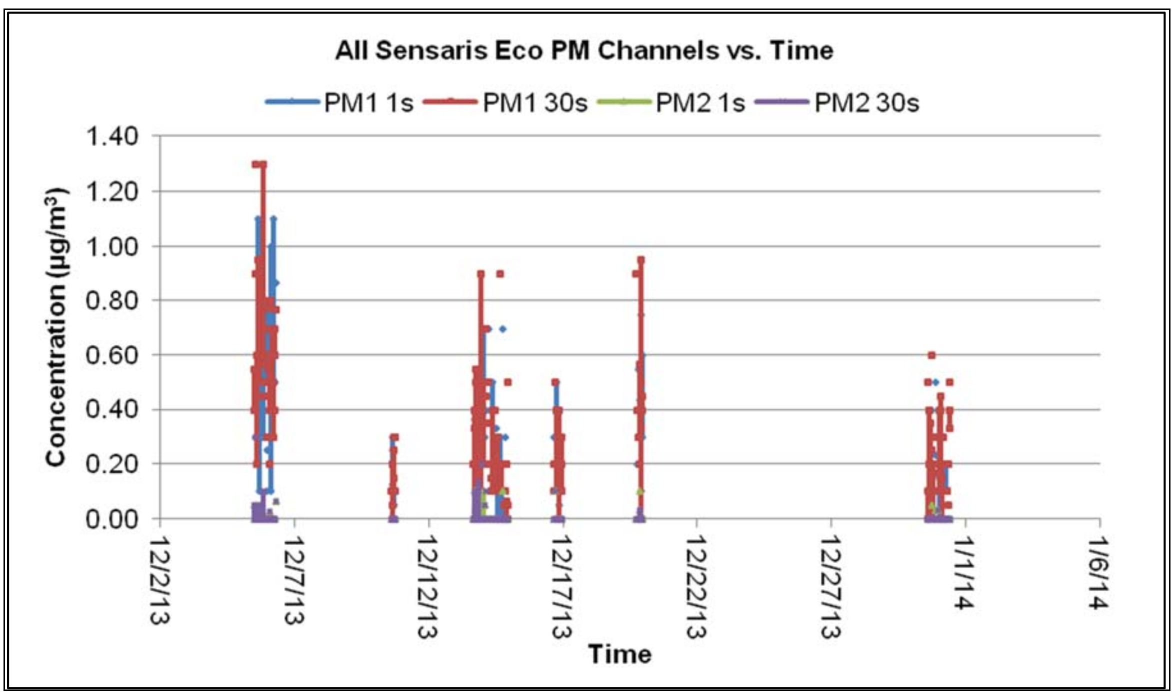

Figure 3.7.1-1. Sensaris Eco PM concentration measurements over time.

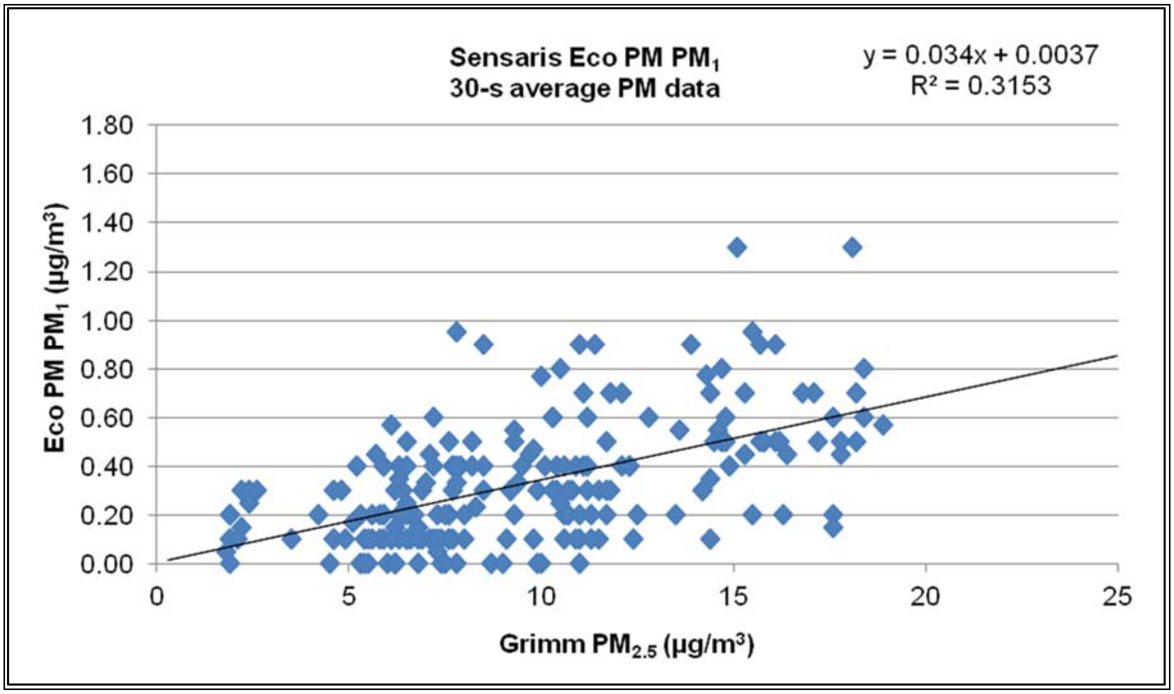

Figure 3.7.1-2. 30-s time-averaged PM data comparing the Grimm reference sampler with the Eco PM sensor.

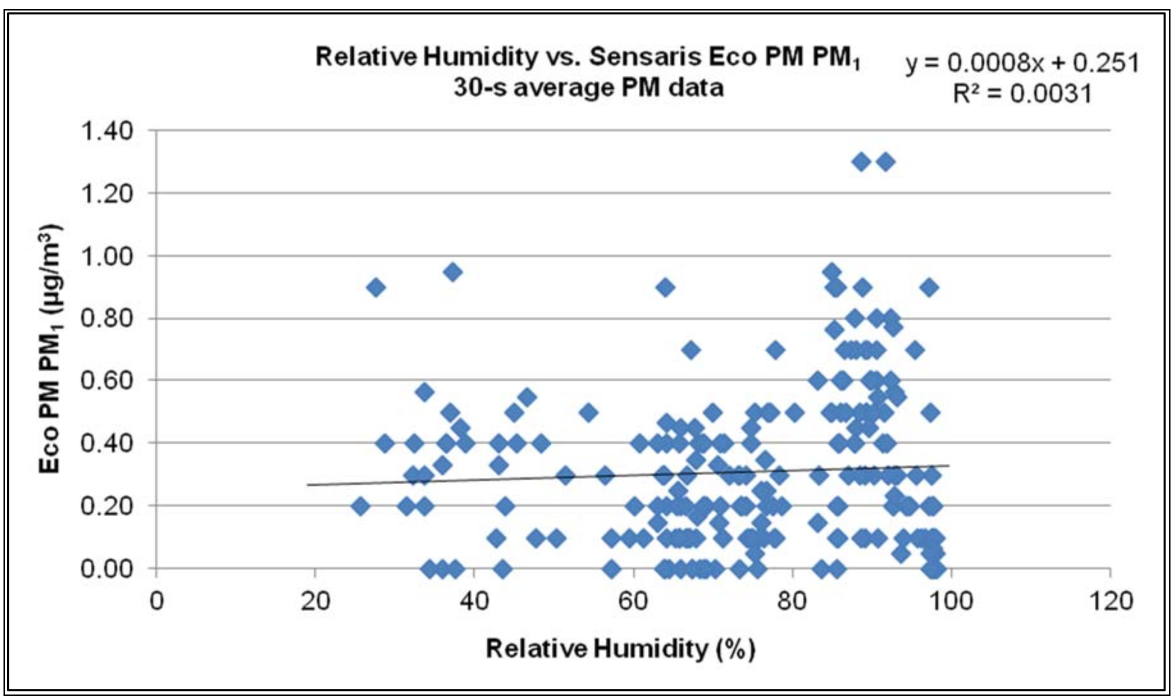

Figure 3.7.1-3. RH vs. Eco PM (30-s averages).

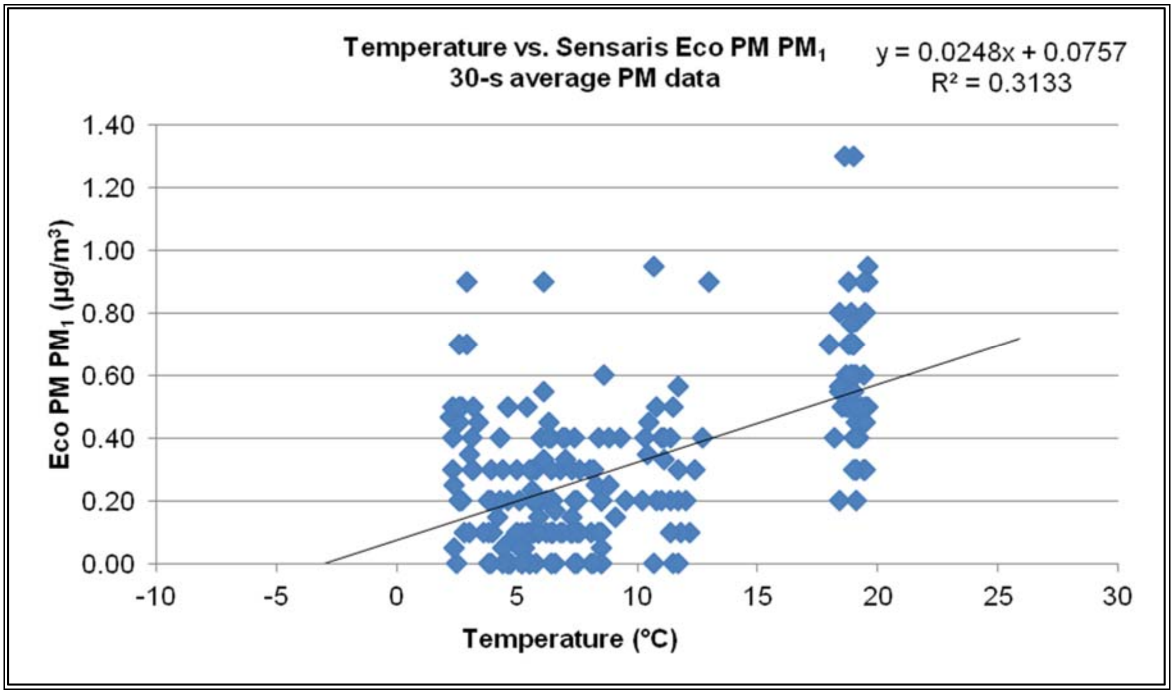

Figure 3.7.1-4. Temperature vs. Eco PM (30-s averages).

3.7.2 Sensaris Eco PM Discussion

The Sensaris Eco PM must communicate with an android device via Bluetooth, which in turn must have WiFi access. Data are transmitted to Sensdots.com and are not stored locally. An attempt was made by the vendor to provide a version of the software that would allow local storage of data, but this new version did not work after a full day's experimentation and troubleshooting. Time and budgetary restrictions prevented further attempts at troubleshooting.

Perhaps the single-most interesting problem encountered in the entire study occurred while initially configuring the Eco PM sensor. Early testing attempts were made at a coffee shop near the EPA-RTP office in order to take advantage of available WiFi. These efforts met with no success. During the troubleshooting process, we were informed that the Eco PM, upon activation of its Bluetooth antenna, immediately attempts to pair with the first Bluetooth-capable iOS device it detects. Therefore, the first discovered iOS device was unrelated to this study (likely located in a bystander's pocket), used the wrong operating system, and did not have the Android app required to operate the Eco PM. As a result, the pairing can be a problem and can only be deactivated by powering down the Eco PM. It is, therefore, mandatory that there be no iOS devices within Bluetooth range while the Eco PM is initializing. This particular feature in the system might limit urban applications of the Eco PM.

The Eco PM also struggled to maintain uptime. Despite all attempts to correct the issue by ensuring all transmitters and receivers were close to one another and shutting off sleep/hibernation modes for all devices involved, the Eco PM was frequently found to have ceased recording within 24 hours of being reset. In addition, recorded data were highly discontinuous. At no point were data points recorded within 5 consecutive minutes. Only 328 data points were recorded, and they were so spread out that this became 239 5-min “averages.” Many of these averages are only a single data point.

The Sensaris Eco PM supposedly reports PM_1 and PM_2 data at two different averaging times; however, the data reported for PM_1 is consistently greater than the data reported for PM_2. This should not be possible since all of PM_1 data should be contained within PM_2. All of the channels recorded very low values. The 1.3 μg/m^3 recorded on the PM_1 channel 30-second averaging time was the largest concentration recorded.

3.8 Shinyei PMS-SYS-1

3.8.1 Shinyei PMS-SYS-1 Results

The Shinyei was set to collect 5-minute average data. The trace data from the Shinyei compared to the Grimm FEM data is shown in Figure 3.8.1-1.

The Shinyei appears to track the Grimm, but with significant deviations. Figure 3.8.1-2 shows that these deviations are significant enough to cause the coefficient of determination (r^2) between the Shinyei and the Grimm to be extremely poor.

Temperature and relative humidity were explored as possible sources of these deviations in Figures 3.8.1-3 and 3.8.1-4. Temperature was found to have no correlation, while relative humidity had no correlation below 95%. Above 95% RH there was a significant cluster of aberrantly high data points.

Data in which RH > 95% was removed, but significant spikes remained. Daily rainfall totals from NOAA were found to correlate highly with the remaining spikes. Rainfall data from the OAQPS Triple Oaks near road monitoring station (35º51’54.53”N, 78º49’10.80”W) was gathered to provide a more nuanced view of the rainfall data. All data collected within one hour of detected rainfall was removed. Significant spikes remained, however.

It was discovered that many of these spikes occurred several hours before rain was detected. A detailed evaluation of the wind data recorded at the Triple Oaks site found that the Shinyei was much more likely to report particulate concentrations higher than the Grimm FEM analyzer when the one hour average wind speed was greater than 1.7 m/s. In addition, when the wind speed was greater than 1.7 m/s, there was a positive correlation ($r^2 = 0.3144$) between the difference between the Shinyei and the Grimm and wind speed. At wind speeds less than 1.7 m/s there was no correlation. This is detailed in Figure 3.8.1-5. Data was removed that contained 1-hr average wind speed greater than 1.7 m/s.

Figure 3.8.1-6 is a trace of the Shinyei data with high humidity, high wind, and rain removed alongside the Grimm data over time. Figure 3.8.1-7 is a scatterplot of the Shinyei vs the Grimm.

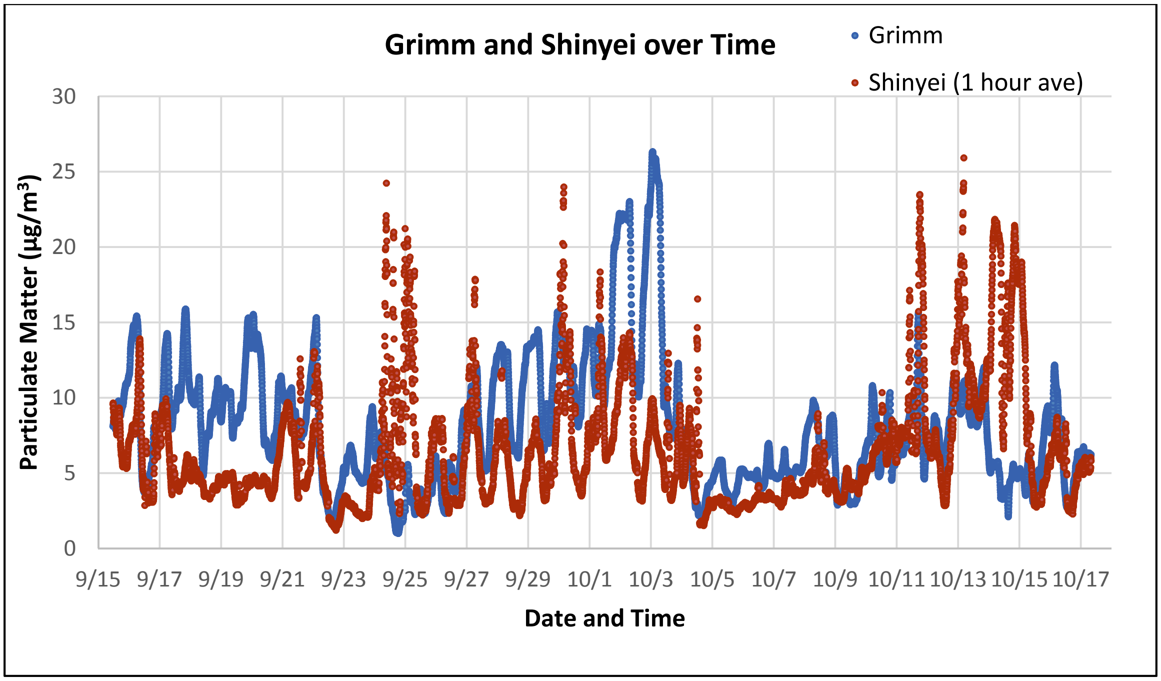

Figure 3.8.1-1: A trace of the Shinyei and the Grimm over time.

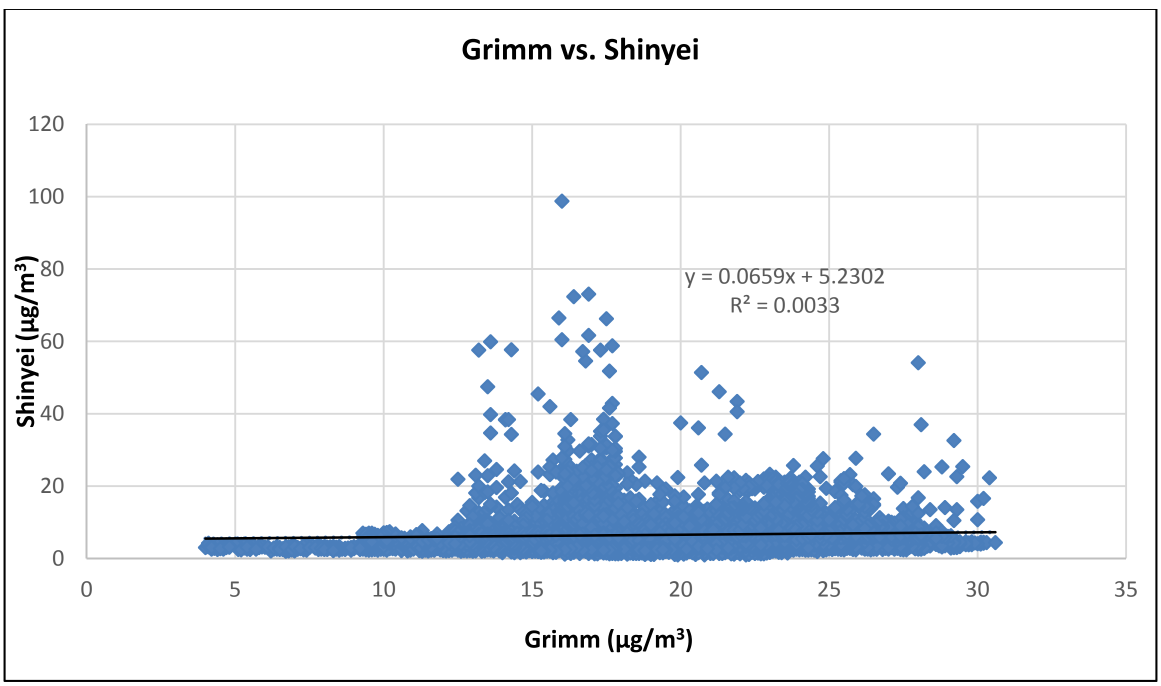

Figure 3.8.1-2: Grimm vs. Shinyei (5-min averages).

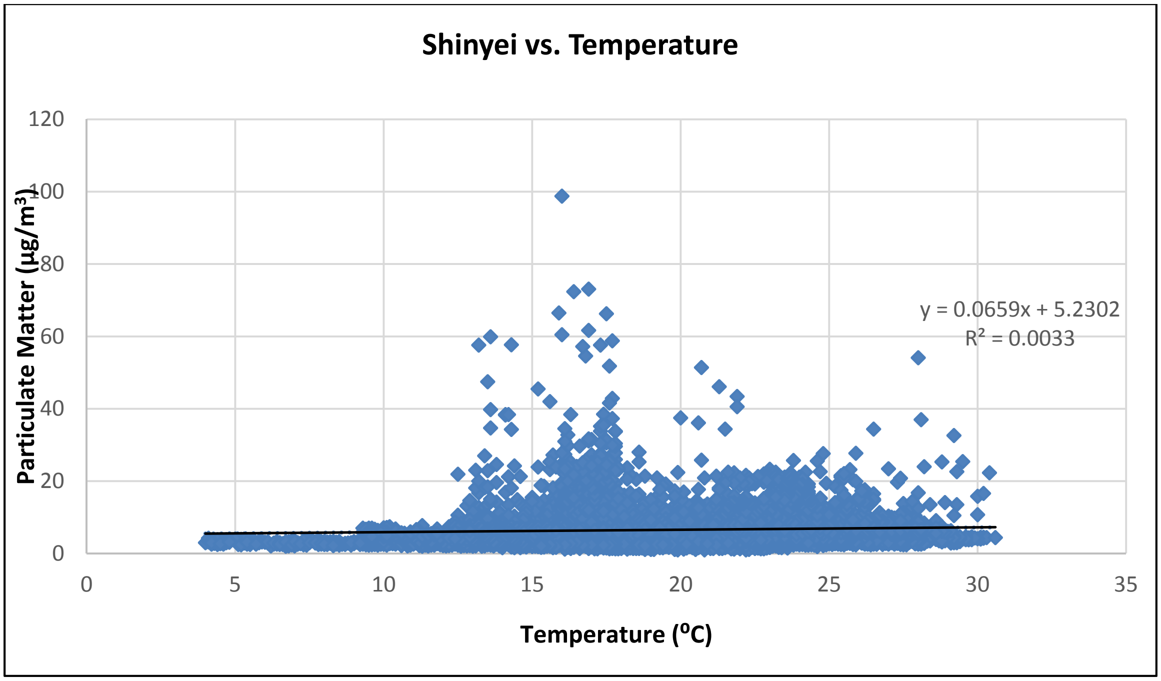

Figure 3.8.1-3: Scatterplot of the Shinyei vs Temperature.

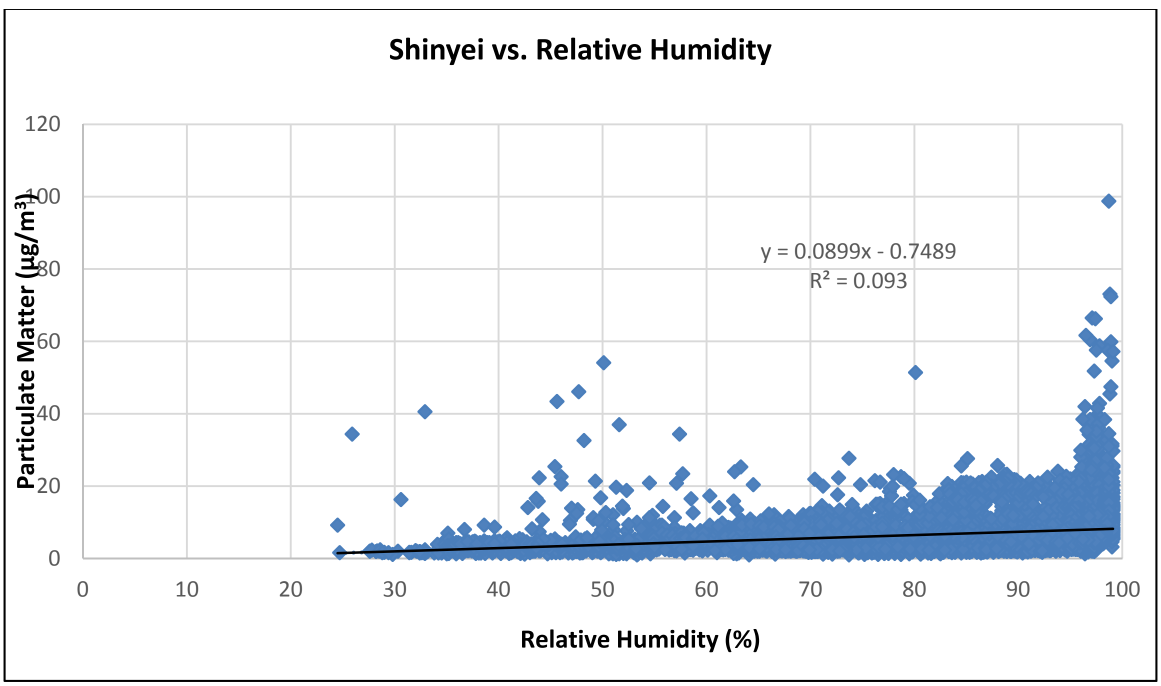

Figure 3.8.1-4: Scatterplot of the Shinyei vs Relative Humidity.

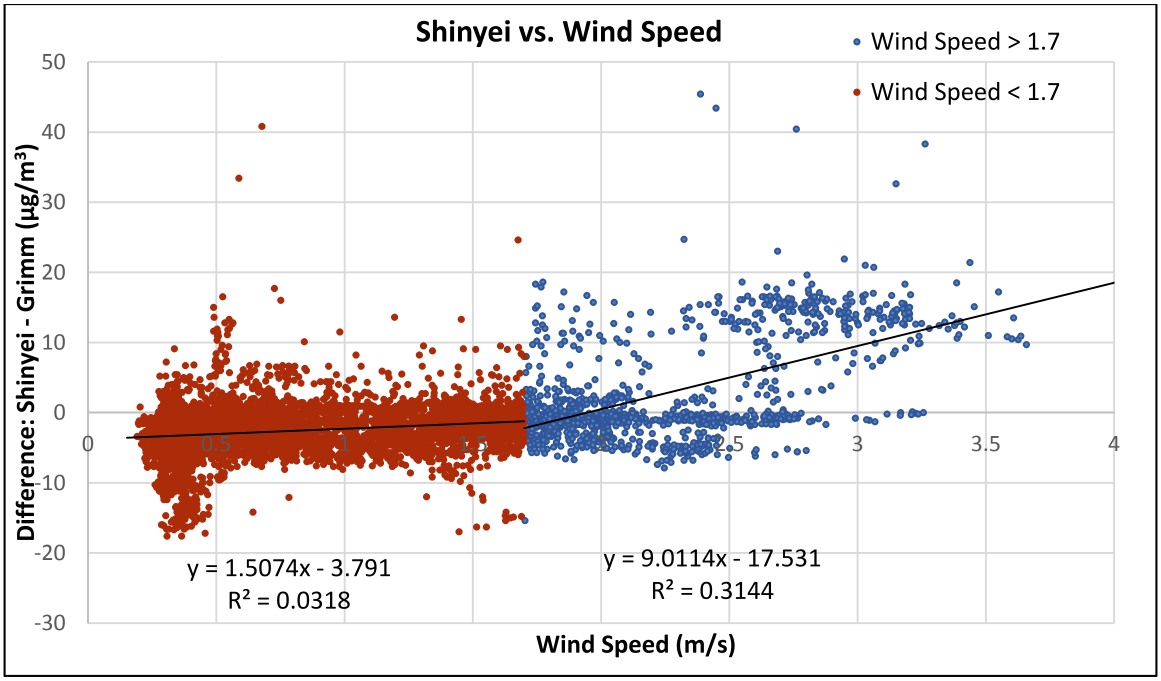

Figure 3.8.1-5: Scatterplot of the Shinyei vs Wind Speed. The graph is broken into two parts to illustrate the change in correlation at 1.7m/s wind speed.

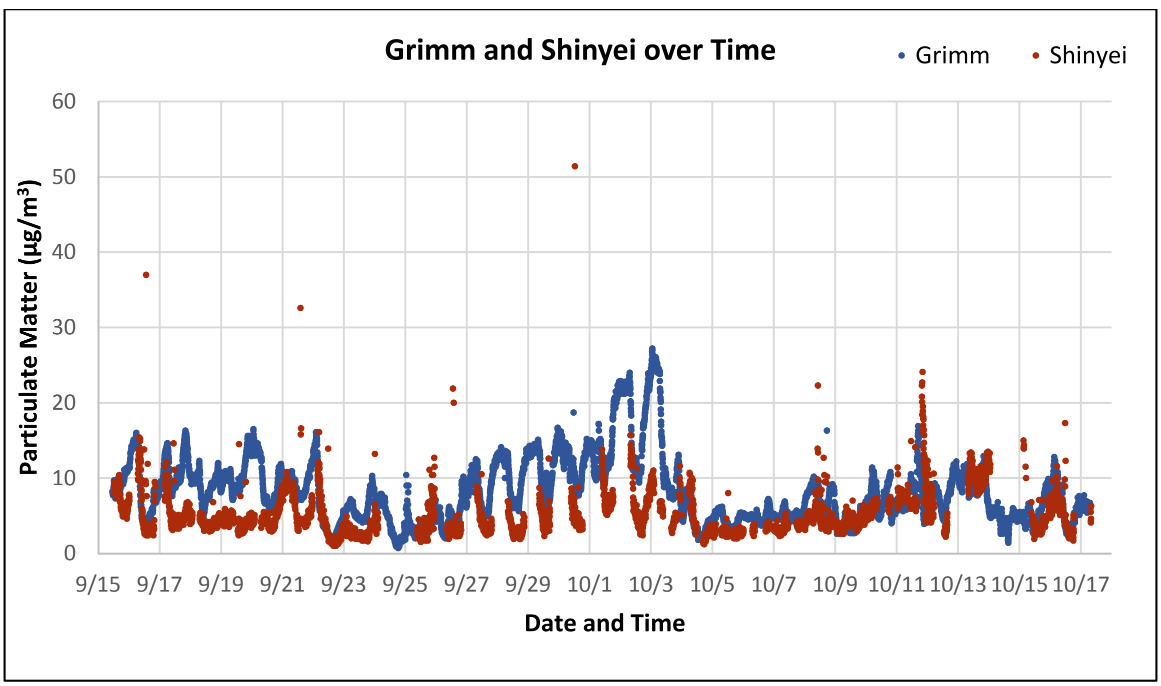

Figure 3.8.1-6: A trace of the Shinyei and the Grimm over time. Data affected by high humidty (>95%), winds (> 1.7m/s in a one-hour average), or within one hour of measure rainfall has been removed.

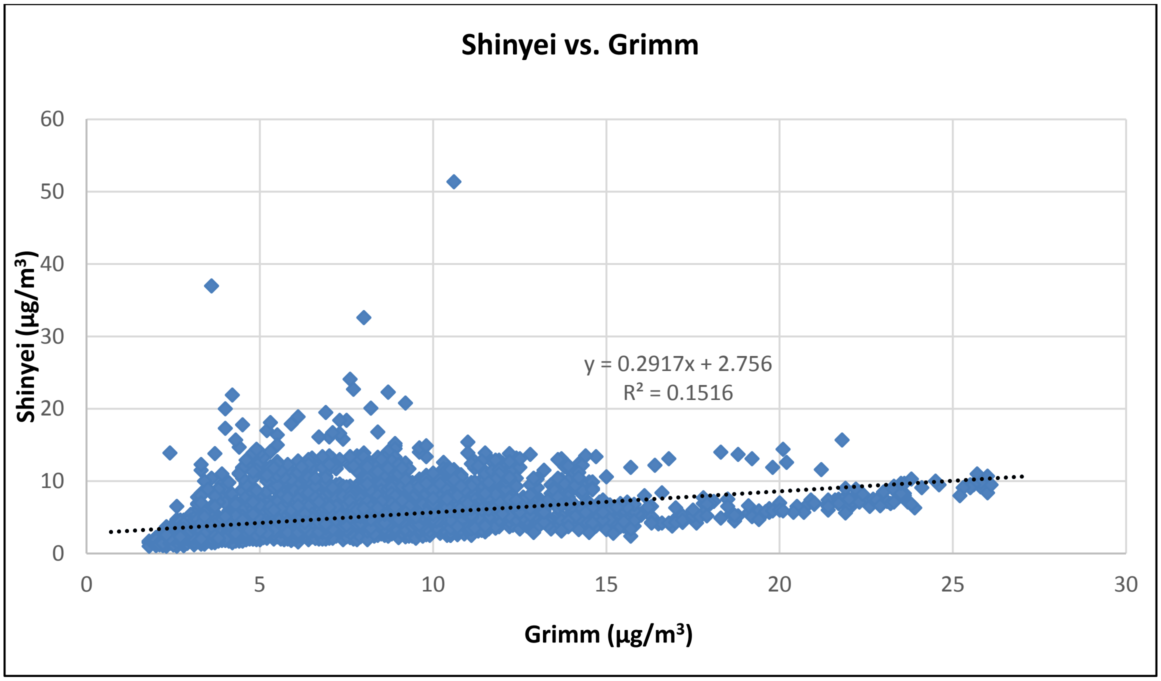

Figure 3.8.1-7: Scatterplot of the fully processed Shinyei data vs the Grimm.

3.7.2 Shinyei PMS-SYS-1 Discussion

The Shinyei is unusually sensitive to light and wind, therefore the device would need to be housed in a well-designed enclosure to improve sensor performance. The need for an enclosure is compounded by the fact that most of the circuitry for the device is in the form of a plain circuit board with no housing whatsoever. It is up to the end user to not only house the unit in such a way that it will be well shielded from light, moisture and wind while preventing air stagnation, but also to protect the circuitry from electrical shorts.

The Shinyei is incapable of recording data without a constant connection to a computer via Ethernet crossover cable. As a result, the mobility of this device can be limited. In addition, Ethernet crossover cables can be difficult to acquire but can be made with an *Ethernet cable crimper*. The requirement of a specialized cable or a specialized tool to make the cable may be challenging for citizen science user groups/applications.

Finally, even after accounting for light intrusion, humidity, rain, and wind speed, the coefficient of determination was poor for quantitative measurements ($r^2 = 0.1516$).

3.9 General Discussion

The performance of all PM sensors tested is summarized in Table 3.9-1. The terms used in the table are defined as follows:

- R^2: coefficient of determination of the final scatter plot of 5-min averaged data against the Grimm FEM data. This column determines the linearity of the sensor.

- Response: slope of the best-fit line of the final scatter plot of 5-min averaged data against the Grimm FEM data. This column can be used as a calibration factor for the sensor. Calculated by either particle counts or µg/m^3 (sensor reporting units), as appropriate, divided by µg/m^3 (reference analyzer reporting units).
- RH limit: the highest relative humidity at which the sensor can produce reliable data.
- Temp Effects: if a direct relationship exists between temperature and the sensor's signal, the R^2 of that relationship is displayed.
- Time Resolution: the measure of how frequently the sensor produces a PM data point.
- Uptime: qualitative assessment by the operator about the frequency of data loss.
- Ease of Installation: qualitative assessment by the operator about the level of effort required to bring the sensor to operational status in the field.
- Ease of Operation: qualitative assessment by the operator about the level of effort required to operate the sensor, take data, and process the data.
- Mobility: qualitative assessment by the operator about the level of infrastructure required to operate the sensor in the field using the current ROP. Other procedures might have different requirements.

It should be recognized that uptime, ease of installation, ease operation, and mobility descriptors provide here are somewhat arbitrary as no definitive criteria exist for their quantitation. As reported here, they define what we observed when trained technical staff attempted to operate the device in an outdoor environment. As examples, uptime rating was highly dependent upon the ability of the device to maintain data collection operations for an extended period of time. An excellent rating would indicate near flawless data collection capability. Ease of installation was influenced by how quickly the device could be placed outdoors as provided directly from the manufacturer. A poor rating is indicative of the need to work well beyond the primary directions provided by the manufacturer to establish basic data collection operations. Ease of operations was defined as how easy it was to start, complete and recover data collections. A fair rating was indicative of the fact that such operations were eventually completed but with some effort needed to make this a repetitive process. Lastly, mobility was defined as how easy it would be to move the device from one location to another. A poor rating would equate to a sensor that had to be hard wired to a computer, an AC/DC power supply, or other features (e.g., weather shielding, WiFi hotspot) that would limit the ease of movement with respect to successful data collections.

Sensor	R^2	Response	RH Limit	Major temp effects	Time resolution	Uptime	Ease of installation	Ease of operation	Mobility
AirBase CanarIT ($\mu g/m^3$)	0.004	-0.101	100%	None	20 s	Excellent	Good	Excellent	Very good
CairClip PM ($\mu g/m^3$)	0.064	-0.229	95%	0.657	1 min	Excellent	Good	Very good	Excellent
Carnegie Mellon Speck (particle counts)	0	0.06	90%	None	1 s	Very good	Good	Fair	Good
Dylos DC1100 (particle counts)	0.548	21368	95%	None	1 min	Very good	Good	Good	Poor
Met One 831 ($\mu g/m^3$)	0.773	0.049	90%	None	1 min	Excellent	Good	Good	Good
RTI MicroPEM ($\mu g/m^3$)	0.720	1.35 ± 0.12	95%	0.588	10 s	Very good	Good	Fair	Fair
Sensaris Eco PM ($\mu g/m^3$)	0.315	0.034	100%	0.313	Unknown	Bad	Poor	Bad	Poor
Shinyei PMS-SYS-1 ($\mu g/m^3$)	0.152	0.292	95%	None	1 s	Good	Fair	Good	Fair

Table 3.9-1. Summary of PM Sensor Performance and Ease of Use Features

A summary of each sensor and ease of use is reported below:

AirBase CanarIT: Once the AirBase CanarIT has been set up, all it requires is power and the occasional reboot when it loses connection to the server. Even in the event connection is lost, the sensor continues recording and saving data for transmission once connection has been reestablished. The requirement that it be furnished with a GSM SIM card and data plan adds a recurring expense to operations.

CairPol CairClip $PM_{2.5}$: The prototype CairClip sensor does not appear to function at temperatures below 19 °C. As a result, there is very limited data with which to draw any further conclusions. The operator urges further testing in a warmer environment. The long battery life, simple software, and simple operation contribute to its high scores in uptime, ease of use, and mobility.

Carnegie Mellon Speck: The 1-second time resolution causes file sizes to get large and cumbersome very quickly. As a result, download times are very long. While the use of UTC seconds for time stamps likely saves memory, it also inhibits the ability of the operator to verify correct operation in the field.

Dylos DC1100: The low mobility score is because the Dylos DC1100 does not record time stamps internally. It must therefore be connected to a computer at all times via RS-232 to collect meaningful data.

Met One Model 831: All calculations were performed on the PM_1 size fraction. Larger size fractions are highly prone to outliers and do not match Grimm FEM data nearly as well even after concerted efforts have been made to remove those outliers.

RTI MicroPEM: The MicroPEM is a comparatively high-maintenance instrument. Time stamps sometimes malfunction when battery power is low, even if the device is operating on external power.

Sensaris Eco PM: The sensor to tablet via Bluetooth to website via WiFi method of data recovery is a highly questionable design decision. The Bluetooth connection clearly has problems, and it is possible the WiFi connection does as well. Data are apparently not stored at any point until it reaches the server. As such, dropped packets at any point in the process will result in lost data. This sensor required a substantially greater level of effort than any of the other PM sensors at every stage of the project and yielded the least amount of data. Given the small volume of data collected, the quantitative measurements reported above should be considered highly suspect. The mobility score is low because it requires a location that has WiFi and no iOS devices present.

Shinyei PMS SYS-1: This sensor required extensive waterproofing in preparation for field placement and modest electrical knowledge in making the necessary signal/power connections. It was observed to be extremely light sensitive and extraordinary precautions had to be performed to collect data useable for the evaluation.

4.0 Study Limitations

It must be recognized that the scope of this low cost sensor performance evaluation was limited with respect to a number of primary parameters:

- The resources of the U.S. EPA to conduct the extensive field tests defined herein, and
- The scope of the performance testing that could be performed while being extensive was not meant to fully compare the devices versus FEM standards.

4.1 Resource Limitations

4.1.1 Intra-sensor Performance Characteristics

Resource limitations routinely permitted for only a single sensor of a given manufacturer to be examined. Therefore, this report provides very limited findings on intra-sensor performance characteristics. As with any examination of data precision, a sufficient amount of information from multiple instruments is necessary to truly assess the ability of a monitoring device to accurately measure the challenge concentration and to do so in a repeatable manner. Likewise, it has been our experience that low cost sensors sometimes fail without any obvious warning and therefore the findings being reported here may reflect comparisons not truly representative of the device’s normal performance characteristics. We can only assume that the devices operating here were functioning properly based upon their normal operating guidelines and lack of fault indicators (if such warnings were available). If a fault warning was observed, all such data collection periods were parsed from the resulting analyses. When possible, a substitute device was obtained and testing continued with the replacement.

4.1.2 Test Conditions

Resources also prevented the U.S. EPA from examining the sensors under a wide variety of environmental and interfering agent conditions. While the research effort was initially anticipated to begin in the late summer of 2013 and then continuing into the early winter of that same year, a government-wide furlough during 2013 along with availability of FEM comparison data due to previously scheduled instrument maintenance outside of our planned monitoring dates, curtailed such plans. Ultimately, the field effort associated with nearly all the sensors was condensed to just a two month period (November to December 2013). This limited the variability of temperature extremes one would have liked to have available relative to challenging the sensors.

It also resulted in the sensors being challenged to more extremes with respect to cold temperature conditions, which many of the sensors were clearly not built to function without significant modifications. It should be clearly stated here that with the exception of the AirBase CanarIT device, none of the other sensors tested were manufactured to meet environmental conditions associated with outdoor monitoring and our tests results need to be considered possibly worst-case scenarios relative to their performance. Even so, we weather protected devices to safeguard their operation, provided modest warming to their enclosures, protected them from stray light and excessive wind, and provided ancillary power supplies as needed. We anticipate citizens attempting to use low cost PM sensors in outdoor circumstances regardless of what manufacturers have suggested as operating conditions, and the tests conducted here attempted to mimic the anticipated use patterns of citizens.

Data findings associated with the MicroPEM and Speck were limited to the summer/fall of 2014 following a repeat of testing for these devices once it was established they had undergone a significant upgrade in both hardware and software relative to the initial round of testing. New testing was subsequently performed to ensure that the data reported here provided the most positive conditions for performance challenge with respect to the manufacturer's latest design specifications.

4.1.3 Sensor Make and Models

This work represented a limited examination of low cost PM sensors costing under $2500 per unit. Other more expensive devices are commercially available but were considered outside the scope of what most citizen scientists might be willing to purchase relative to cost. Based on an extensive market survey prior to initiating this effort, other low cost devices often having the same sensing system (light scattering sensor) but housed in a different packaging by another manufacturer did exist. Our eventual study design was defined by trying to select a cross section of many of those available while trying to ensure various features specific to each of the units offered interesting aspects not redundant in the others. Even so, it must be recognized that even the same sensing system engineered differently by various manufacturers could offer significantly different performance characteristics. Therefore, the summary analysis provided here does not in any way try to 'define' low cost PM sensor capabilities. It does not serve as the primary guide one might use in selecting a sensor for various applications. The summary of the evaluation activity is solely intended to provide the reader with an understanding of EPA's experiences with the various sensors and how well their data compared with that from a collocated FEM under the conditions of this field study.

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