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Evaluation of Elm and Speck Sensors

Office of Research and Development
National Exposure Research Laboratory

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Ron Williams
National Exposure Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, NC, USA 27711

Amanda Kaufman
ORISE Participant
Oak Ridge Institute for Science and Education
Oak Ridge, TN, USA 37831

Tim Hanley, Joann Rice
Office of Air Quality Planning & Standards
U.S. Environmental Protection Agency
Research Triangle Park, NC, USA 27711

Sam Garvey
CSS Dynamac
Research Triangle Park, NC 27711

Disclaimer

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Acronyms and Abbreviations

AC/DC	alternating current/direct current
ACE	Air Climate & Energy
AIRS	Ambient Air Innovation Research Site
°C	degrees Celsius
CAPS	Cavity Attenuated Phase Shift
FEM	Federal Equivalent Method
FRM	Federal Reference Method
hr	hour
m	meter
mb	millibar
min	minute
NAAQS	national ambient air quality standards
NERL	National Exposure Research Laboratory
NO_2	nitrogen dioxide
O_3	ozone
OAQPS	Office of Air Quality Planning and Standards
ORD	Office of Research and Development
PM	particulate matter
ppb	parts per billion
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
RTP	Research Triangle Park
s	second
SD	secure digital
SIM	subscriber identity module
VOC	volatile organic compound

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. The US EPA has been evaluating emerging PM sensor technologies that might provide benefit to citizen scientists and the scientific community-at-large. Such technologies are rapidly expanding, and new versions of sensor devices previously examined by the US EPA are released by manufacturers. The results described here represent an examination of two such examples involving the Creative Labs Speck and the PerkinElmer Elm sensors.

Study Objectives

The US EPA's Air Climate & Energy (ACE) research program is engaged in an ongoing effort to discover and evaluate a wide array of emerging technologies. In particular, it is conducting world-wide market surveys of low cost PM sensors (<$2,500.00). Such a price point represents the upper limit of cost that community groups and citizen scientists often see as the maximum affordable expenditure regarding any capital investment they might make with respect to acquiring low-cost sensors for their own use. The US EPA is conducting collocated field evaluations of select sensors in direct comparison with FEM instrumentation. Selection is based upon the unique features of the device that might provide technical insight into technologies not previously examined, its commercialization and availability to the general public. Direct requests from US EPA stakeholders (Regional offices, State air quality officials, etc.) desiring to gain knowledge on specific sensors is also a factor in conducting this research. The devices examined in this report reflect sensors previously examined in earlier efforts that have undergone significant revision by the manufacturers. Likewise, the devices represented sensors either being widely used in citizen science efforts or which were releasing data in a very public format. Therefore there was a high degree of interest in their performance characteristics by a wide range of air quality officials. The Creative Labs Speck and the PerkinElmer Elm sensors were obtained and sited in the established PM sensor test platform on the US EPA's RTP, NC campus (AIRS). Data collections representing approximately a 45 day evaluation period were conducted. The collocated $PM_{2.5}$ FEM instrumentation with 5-minute (min) time resolution provided the means to investigate both short duration and daily (24-hour [hr]) comparisons between the test devices and the FEM response. Potential data confounders such as temperature and relative humidity (RH) were obtained to aid in the investigation. The relationship between FEM response and the various sensors was established using regression formulas.

Study Approach

A single Speck PM sensor was obtained from Creative Labs and following review of its updated software and data output characteristics (in comparison to the unit previously examined[1]), quality assurance protocols were developed. Also, a copy of the PerkinElmer Elm pod was obtained. Operating procedures were developed to acquire its data stream[2]. The Elm is a multi-sensor pod device, capable of reporting on multiple air quality pollutants. The unit obtained for this effort provided for ozone (O_3), nitrogen dioxide (NO_2), and PM_{10} estimates.

The necessary infrastructure to conduct the short-term evaluations was established. The Elm is weatherized and capable of direct placement in the open environment (i.e., rain). It also provides automated data transmission and processing via the manufacturer's software. The Speck does not have these innate features. Therefore, weather shielding as well as data collection/processing procedures were developed using previously established means for deploying this device.[1]

For approximately one and a half months during the winter of 2015, these collocated low cost sensors were sited on a monitor test platform with a Grimm Model EDM180 $PM_{2.5}$ (EQPM-0311-195) FEM on the US EPA's RTP, NC campus. Comparison research on FEM monitors, capable of providing high degree confidence estimates of ozone or nitrogen dioxide, was also accomplished at the test site. Both sensor and comparison monitors, along with ancillary meteorological sensors (RH, temperature), operated continuously during this time. The only exception was data recovery, flow checks/calibration, and general servicing as required by the various manufacturers. Once the monitoring period was completed, data from the comparison monitors and sensors was compared to determine how these variables influence low cost sensor performance.

Sensor Performance Results

Discreet statistical evaluation of sensor performance (Speck and Elm) was established with respect to collocated data associated with the Grimm FEM, as well as the comparison monitors for nitrogen dioxide and ozone (Elm). Resulting regression characteristics were optimized with respect to data normalization and influence of confounders under some circumstances. This was an effort to account for observed sensor limitations with respect to environmental operating conditions such as RH.

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[1] Williams, R., A. Kaufman, T. Hanley, J. Rice, AND S. Garvey. Evaluation of Field-deployed Low Cost PM Sensors. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-14/464 (NTIS PB 2015-102104), 2014.

[2] Williams, R., A. Kaufman, AND S. Garvey. PerkinElmer Elm. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-15/125 (NTIS PB2015-105136), 2015.

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*: Both of the units required basic electrical connections using step-down transformed power, as they do not possess internal power sources.
- *Data collection/transmission/storage/recovery:* The Elm has the ability to transmit data directly to the manufacturer's website where it can be viewed online. We did not activate that option with the device and instead collected data using the internal data storage card in the Elm. We often find internal data storage cards provide significant benefit as compared to WiFi or cellular options, and they do not hinder the comparison in any way. Speck data was collected via a laptop using a direct cable connection between the two devices. Both the Elm and Speck raw data had to be processed via manufacturer's software. This was accomplished via internet connections where EPA collected data were transmitted to the manufacturer's proprietary analysis packages. Processed data in the final format provided by the manufacturer were then transmitted back automatically to EPA and used in the resulting analyses without modification.
- *Data Schemes:* Data schemas (output) by the two manufacturers varied. Therefore, all processed data were recovered and then integrated into an EPA-developed database to allow for comparisons to be made between sensor data and reference monitoring data. All data was defined by time/date stamps (1 minute integration periods) and represented the primary means by which comparisons were established. Previous efforts concerning such data clearly indicated that longer averaging times resulted in improved regression between reference data and sensor data, and 5 minute integration periods represented the primary means of comparison.
- *Installation and WiFi considerations*: Sensors were not operated using wireless data transmission either due to EPA decision, or the inability of the device (Speck) to operate in that manner.

Conclusions

This marks the second formal evaluation we have performed on the Speck, and no significant improvement in agreement with the reference monitor was observed ($r^2 < 0.1$), when fairly short time intervals (5 minute averages) are compared. RH in excess of 95% was shown to have a dramatic impact upon PM concentration estimates. The device showed a marked and significant response (positive bias) with respect to increasing temperature conditions. While no statistical modeling was performed on one specific area of the data, it suggests that some of the poor regression effects might be associated with the device providing poor agreement with the reference monitor when lower ambient concentrations were encountered ($PM_{2.5} < \sim 10$ µg/m^3). Model 2 of the Speck evaluated here had significantly improved output features in comparison to the original model previously evaluated, relative to its onboard display panel. Likewise, Creative Labs output processing software associated with the current model offered some advantages with respect to features end users might appreciate.

We previously evaluated the CanairIT sensor pod.[1,3] The Elm appears to have many of the same physical features as the CanairIT device. While the original CanairIt and Elm had some similarities (size, appearance, etc.), differences related to proprietary configurations between the two pods cannot be fully defined here, and are not theorized. In particular, the sensor elements themselves might have changed as well as any algorithm or response factors used in reporting air quality outputs.

Poor agreement ($r^2 < 0.01$) was established here between the Elm and NO_2 monitor comparison. The unit's ozone sensor provided the most agreeable comparisons with our reference measurements ($r^2 > 0.7$) as compared to any sensor making up this pod. There was no general agreement between the Elm and its PM measures with respect to the collocated reference monitor, relative to any discernable pattern. RH events in excess of ~ 90% were shown to influence the response.

[3] Williams, R., A. Kaufman, AND S. Garvey. Next Generation Air Monitoring (NGAM) VOC Sensor Evaluation Report. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-15/122 (NTIS PB2015-105133), 2015.

1.0 Introduction

EPA's Office of Research and Development (ORD) has been engaged in the discovery of low cost sensors potentially useful for air quality monitoring.[4] As defined in a sensors users guide focused on potential end users, the performance characteristics of many of these devices entering the market or public domain have not been reported.[5] To assist citizen scientists, state, municipal, federal air quality officials, as well as sensor developers, the US EPA has been evaluating select sensor devices in a series of laboratory and/or field monitoring research studies. To date, these include sensors associated with PM, ozone, nitrogen dioxide, and volatile organic compounds.[1,3,6]

The US EPA has focused a majority of its attention on sensors costing < $2,500.00 as it is believed such a cost would be at the upper limit to that which citizen scientists, as well as many others might be able to afford. Even so, it must be recognized that efforts such as those reported above represent a limited survey of all the sensor technologies currently being manufactured. One feature of this market is that rapid advances are being seen in product development. It is not unusual for devices to be released in multiple versions within the same calendar year. These include revisions to the sensor's physical features (such as changes in the base sensing element(s) itself or the data processing algorithm). Therefore attempting to stay current with the performance characteristics of any one sensor is almost an impossibility due to time and resource limitations.

The work being reported in this study, represents our efforts to revisit two sensors (or earlier versions of these sensors) that are being employed in communities or citizen science activities. Both of the sensors had undergone significant changes and interest from multiple EPA stakeholders encouraged their re-examination.

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[4] MacDonnell, M., M. Raymond, D. Wyker, M. Finster, Y. Chang, T. Raymond, B. Temple, M. Scofield, D. Vallano, E. Snyder, AND R. Williams. Mobile Sensors and Applications for Air Pollutants. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-14/051 (NTIS PB2014 105955), 2014.

[5] Williams, R., Vasu Kilaru, E. Snyder, A. Kaufman, T. Dye, A. Rutter, A. Russell, AND H. Hafner. Air Sensor Guidebook. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-14/159 (NTIS PB2015-100610), 2014.

[6] Williams, R., R. Long, M. Beaver, A. Kaufman, F. Zeiger, M. Heimbinder, I. Hang, R. Yap, B. Acharya, B. Ginwald, K. Kupcho, S. Robinson, O. Zaouak, B. Aubert, M. Hannigan, R. Piedrahita, N. Masson, B. Moran, M. Rook, P. Heppner, C. Cogar, N. Nikzad, AND W. Griswold. Sensor Evaluation Report. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-14/143 (NTIS PB2015-100611), 2014.

2.0 Materials and Methods

Two sensors were obtained by direct purchase for PM field evaluations. This included the Carnegie Mellon Speck, which had recently received a major update, and the PerkinElmer Elm, formerly distributed in a version known as the Airbase CanarIT. The latter had been updated to some unknown degree since the company's acquisition and market distribution through PerkinElmer. The NO_2 and O_3 measurement capabilities of the Elm were also measured in this field evaluation. The evaluation sought to compare these sensors against Federal Reference and/or Federal Equivalent Methods (FRM/FEM). The effects of temperature (° C), relative humidity (% RH), wind speed (m/s), and pressure (mb) were explored as possible interferences.

The coefficient of determination (r^2) is the square of the sample correlation coefficient and was used as a measure of linearity. Microsoft Excel was used to calculate r^2 by plotting all measured values against data acquired by FRM/FEM, which displayed the linear regression. The same plot was used to determine response factors and offsets.

2.1 PM Field Evaluations

A Grimm Technologies, Inc. (Douglasville, GA) Federal Equivalent Method (FEM) analyzer was operated by EPA's Office of Air Quality Planning and Standards (OAQPS) alongside meteorological instrumentation, an API T-265 O_3 analyzer, and a cavity attenuated phase shift (CAPS) NO_2 analyzer at the AIRS monitoring station on the EPA campus in Research Triangle Park (RTP), NC. Specifics about the description and basic operation of the model T500U CAPS NO_2 analyzer (Automated Equivalent Method: EQNA-0514-212) is described elsewhere.[7] These established reference methods are covered under a QAPP for that study (EPA, 2013).[8] Reference data were available for the time frame of the sensor evaluation as 5-min averages.

The Elm was attached to a pole mounted to the AIRS platform railing as shown in Figure 1. Zip ties were used in conjunction with the mounting bracket supplied by the manufacturer to attach the unit to the pole. The manufacturer-supplied rain shield was deemed sufficient to protect the Elm from the elements. There was not an active data contract for the Elm's subscriber identity module (SIM) card at the time of testing. Data were recovered from the micro secure digital (SD) card located inside the unit and sent to the manufacturer for processing. The manufacturer responded with the processed data in 5-min averages. The Elm ran without interruption from 2/13/2015 to 3/30/2015 with 1-min data being collected.

The Speck was placed inside one of the Bowl-on-Pole shelters described in an earlier report as shown in Figure 2.[1] The unit was placed on the shelter grating such that one of the large holes in the grating was directly beneath the bottom mounted air intake of the sensor. The micro-USB cable which supplied both a power and data connection for the unit was connected to a laptop

[7] Federal Register: Vol.79, pages 34734-34735, 06/18/2014

[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.

computer running the Speck Gateway software (April 2015 version). The laptop was located in a weather protected shelter. The Speck ran without interruption from 2/13/2015 to 3/30/2015 and provided 1-min data averages.

Figure 1. Placement of the Elm at the AIRS

Figure 2. Placement of the Speck at the AIRS

3.0 Field Evaluation Results and Discussion

3.1 PerkinElmer Elm

The Elm has three on board sensors which were evaluated in this study: NO_2, O_3, and PM_{10}. The true PM size designation of the Elm is not fully known. The output software had column headers for both $PM_{2.5}$ and PM_{10}, but only data associated with the PM_{10} designation was received following processing. We therefore report it here as PM_{10}, with the caveat above as to its particle size uncertainty. We compared the Elm output to $PM_{2.5}$ reference measurements based upon the availability of such measurements for this research effort.

The NO_2 sensor output over time is shown in Figure 3 superimposed with that of the CAPS reference NO_2 sensor. The two traces revealed minimal overlap over time, even notwithstanding the fact that their y-axes are on scales differing by a factor of 10. In some instances, the Elm reported 5-min integrated NO_2 values in excess of 3000-4000 parts per billion (ppb). Usually these response upsets were short lived (on the order of 5-10 minutes in total duration) before a more normal (~ 50 ppb) response was evident in the data pattern. The reference monitor never revealed any similar pattern of response. These occasional periods of very high response values impacted the resulting regression and the figures presented herein reflect these observations without censoring.

The reference monitor reported significantly lower values as compared to the Elm. Figure 4 compares the CAPS reference NO_2 analyzer to the Elm's NO_2 sensor directly, and revealed no significant correlation between the two monitors. Possible relationships between the Elm's NO_2 sensor and wind speed, temperature, RH, and pressure were explored. No significant correlation between the sensor's response and those meteorological parameters were established.

While the Elm's NO_2 sensor response could not be correlated to the reference measurement or meteorological parameters, we investigated the output to determine if any pattern whatsoever existed. Doing this might provide insight as to the sensor's response relative to it being the result of some undefined cofactor or simply noise. To simplify this investigation, the data were broken up into blocks based on the hour of the day. Each of the resulting 24 (1-hr) blocks were averaged and plotted in Figure 5.

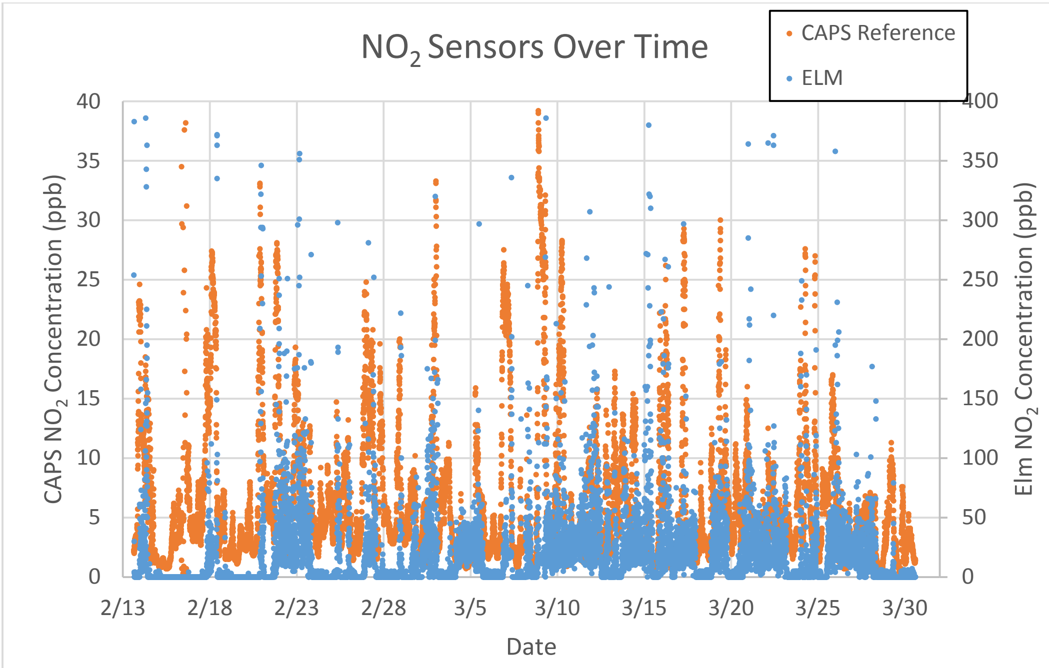

Figure 3. Trace of the Elm NO_2 and CAPS NO_2 sensors over time

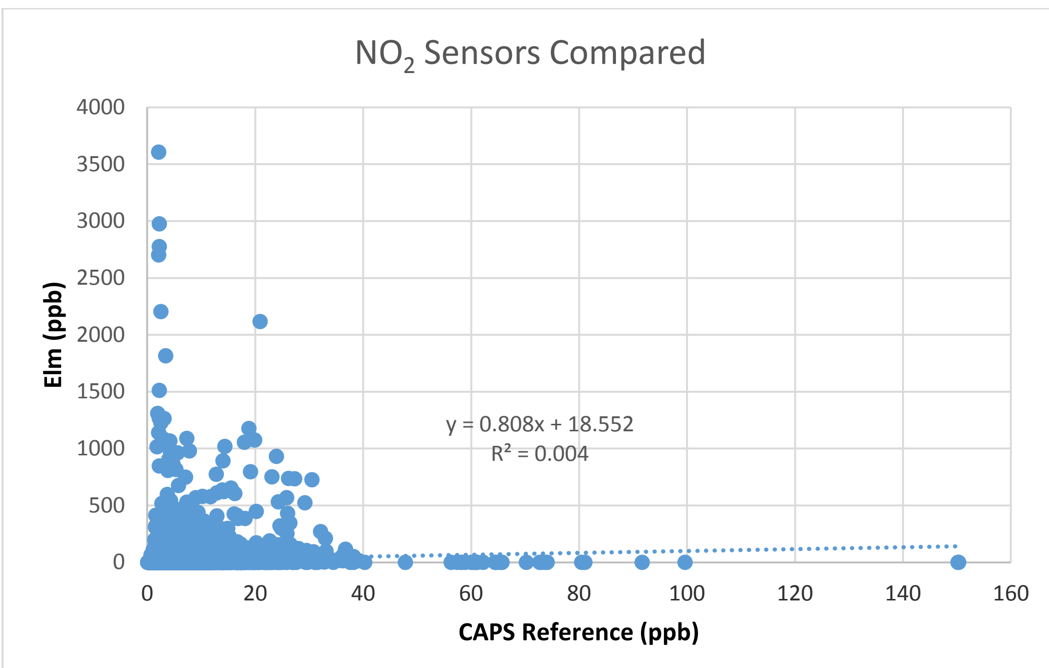

Figure 4. Five minute comparisons of Elm NO_2 sensor and CAPS NO_2 sensor

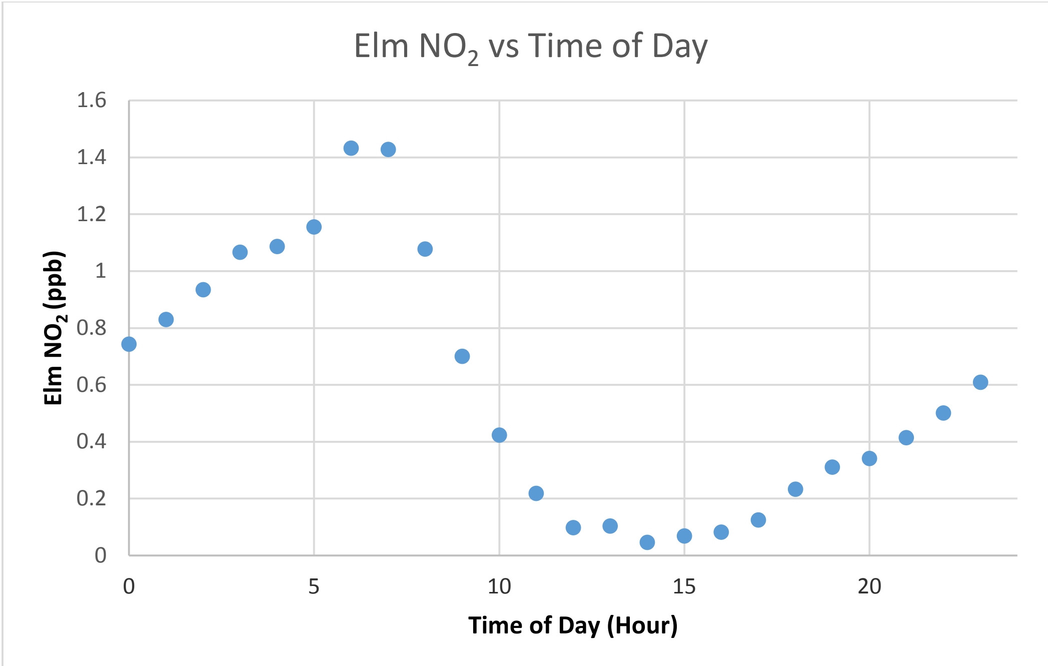

Figure 5. Elm NO_2 Sensor vs the time of day

It would appear that some base response mimicking diurnal patterns of ambient NO_2 patterns did exist with the Elm output. Such an output would normally be expected to occur. Even so, as evident in Figure 5, the overall response was low and at a level where the limit of detection was not being routinely achieved.

The Elm's onboard ozone sensor response over time is shown in Figure 6, superimposed with the API T-265 ozone analyzer (used as a reference). The two appear to show strong agreement with the T-265 generally reading slightly higher than the Elm. This is confirmed in Figure 7, which compares the two sensors directly. A coefficient of determination of 0.73 confirms that a strong, fairly linear correlation existed between the two. The response factor of 0.875 and an offset of 6.2 both support the observation that the Elm underrepresents the ozone levels compared to the T-265. Correlations between the Elm ozone sensor and meteorological data were explored. A negative correlation was found with relative humidity. However, on further examination a nearly identical correlation was found between the T-265 and relative humidity. This suggests that the correlation was a real phenomenon and not a bias or error inherent to the Elm's onboard ozone sensor.

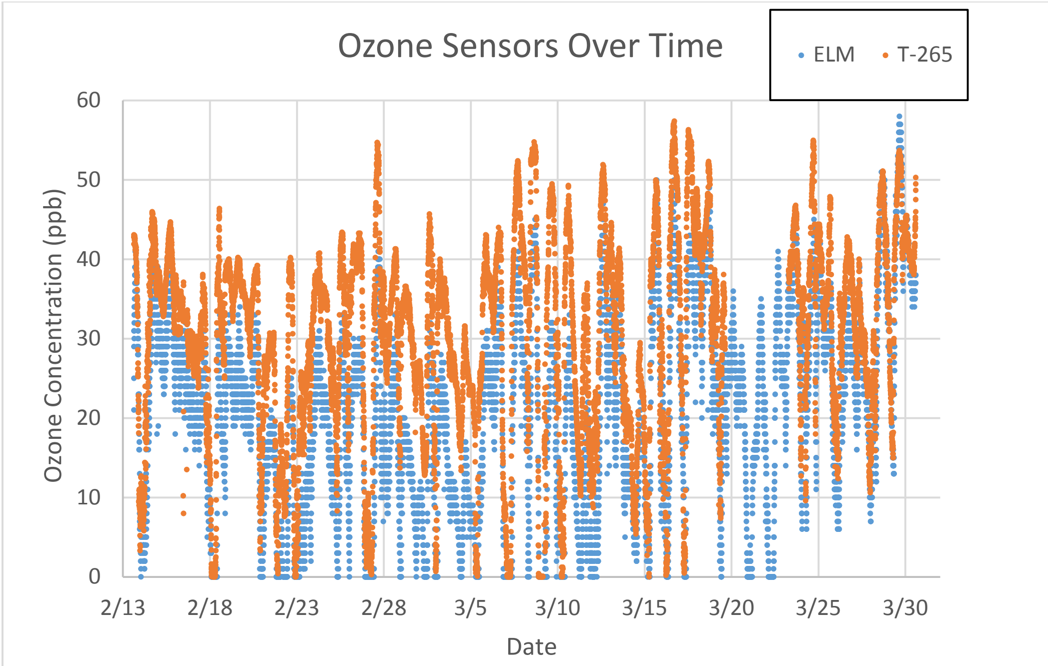

Figure 6. Trace of the Elm ozone sensor and the API T-265 ozone sensor over time

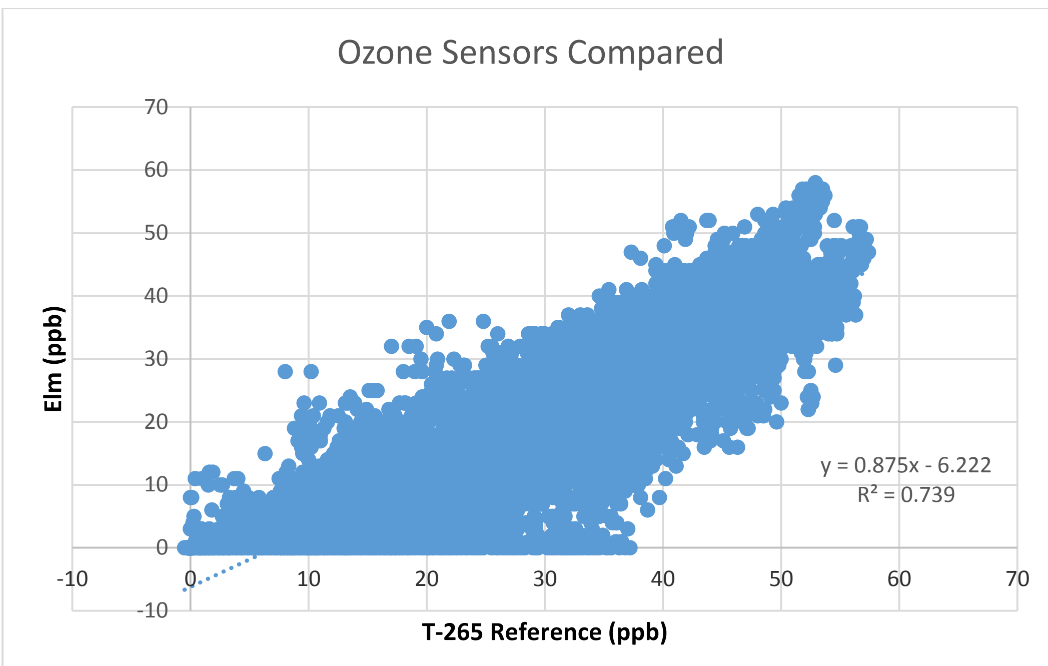

Figure 7. Elm ozone sensor compared to the T-265 ozone sensor

The Elm is equipped with an optical PM sensor. Optical PM sensors are known to frequently suffer from meteorological interferences. Most notably, high relative humidity is known to produce artificially high values in such sensors. For this reason, correlations with meteorological conditions were first explored. No significant correlations were found with wind speed, temperature or pressure. Relative humidity measurements of greater than 95% were found to be correlated with a spike in response as shown in Figure 8.

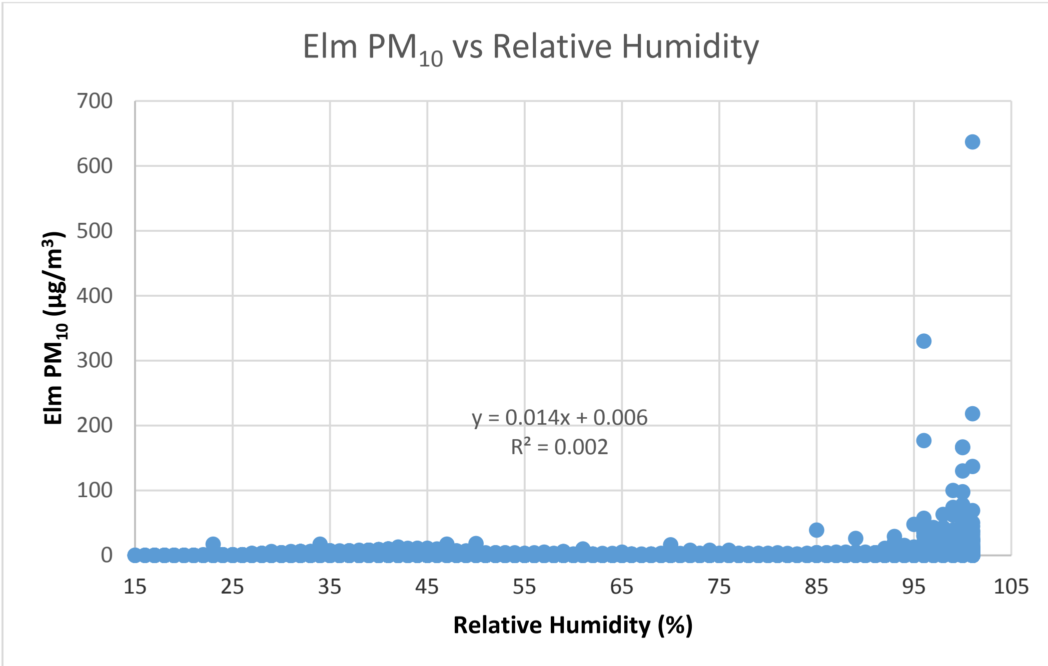

Figure 8. Elm PM_{10} compared to relative humidity

The Grimm is not the ideal reference for the Elm, because this particular model of the Elm only provides PM_{10} data while the Grimm provides $PM_{2.5}$ data. Still, it was expected the two would show some general agreement as the $PM_{2.5}$ size fraction is typically the dominant particle size associated with the test location. Figure 9 reports no general agreement between the two devices. Even if the Elm's PM_{10} sensor did not correlate with the reference measurements, observation of some recognizable response over time would support the idea that it is measuring real phenomena instead of just noise. To investigate this potential, the data were broken up into blocks based on the hour of the day. Each of these 24 (1-hr) blocks were averaged and plotted in Figure 10. The distribution appears to reflect some aspects of a diurnal pattern that one might relate to general photochemical PM development over the course of a given day.

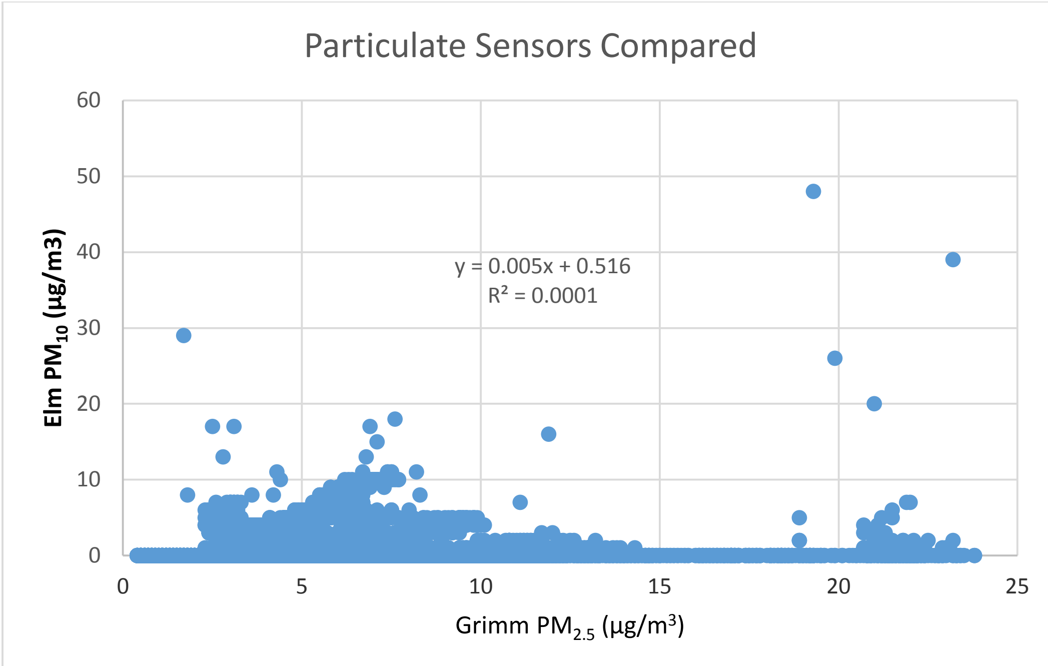

Figure 9. Elm PM_{10} vs Grimm $PM_{2.5}$

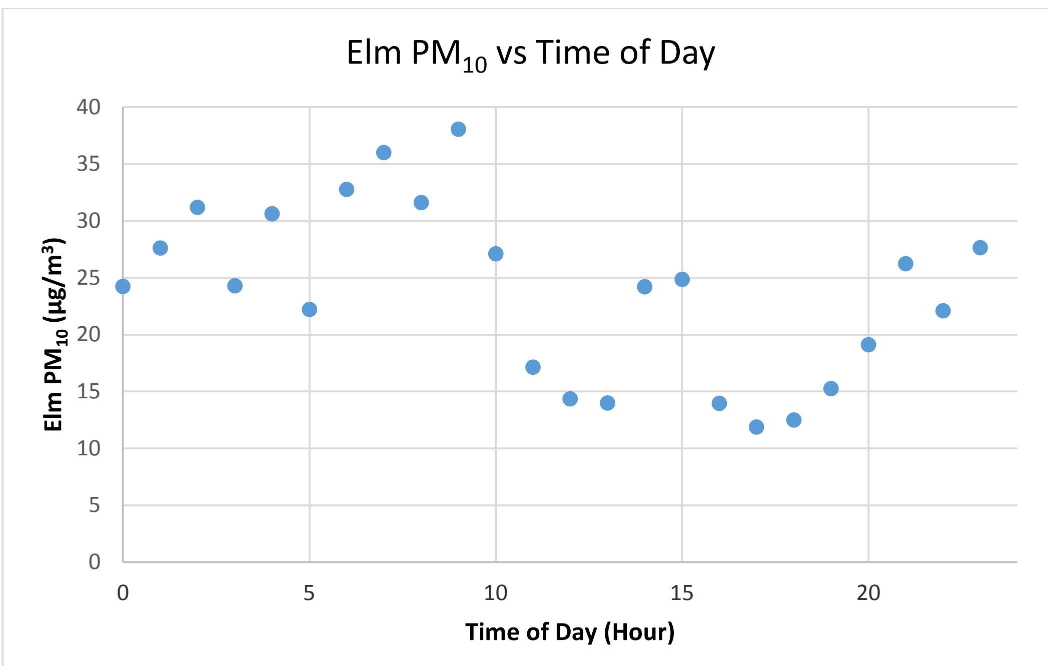

Figure 10. Elm PM_{10} vs time of day

3.2 Carnegie Mellon Speck

The Speck is an optical particle counter with an onboard algorithm to convert particle counts to $PM_{2.5}$ concentration. Relative humidity is a known interferant with optical particle counters, so its effects were first explored in Figure 11. Data collected above 92% relative humidity were found to have extremely high values far exceeding the true ambient concentration. Thus, all data taken when the relative humidity was above 92% were removed from the analysis.

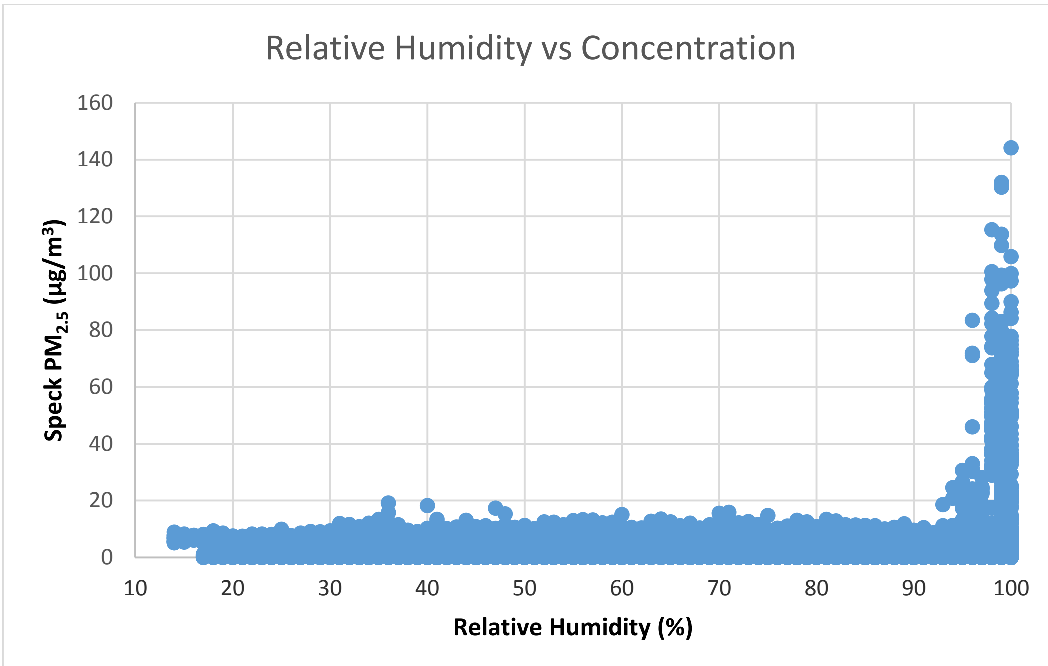

Figure 11. Speck compared to relative humidity

The concentration over time is shown in Figure 12, superimposed with that of the Grimm reference sampler. The two traces over time sometimes appear similar but diverge other times. One of the primary points of divergence is that the Speck has frequent clusters of data at very low values. These clusters are not seen in the Grimm data. These clusters do not seem to correlate with any meteorological condition. Attempts were made to remove all Speck data below a threshold value. Threshold values of both 0.1 µg/m^3 and 1 µg/m^3 were attempted, but neither attempt was found to improve the correlation between the Speck and the Grimm. Therefore, these attempts were not reported here.

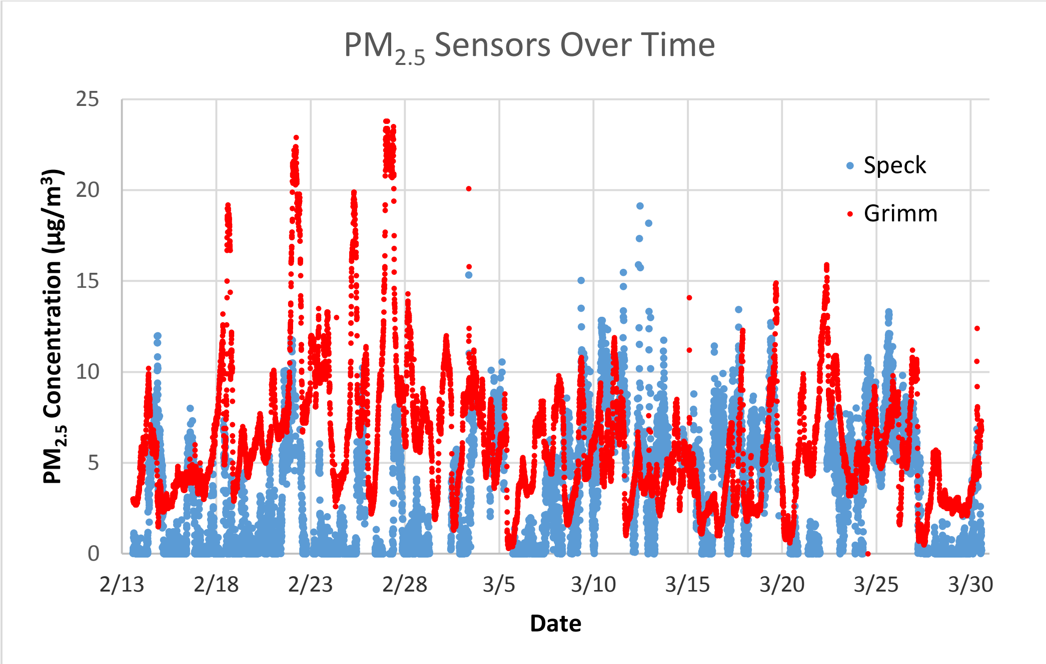

Figure 12. Trace of the Speck and the Grimm over time

Meteorological conditions were also explored for correlations with the Speck data as a whole. Temperature was found to have significant correlation with the Speck as shown in Figure 13. The Grimm was also checked for a correlation with temperature, but none was found.

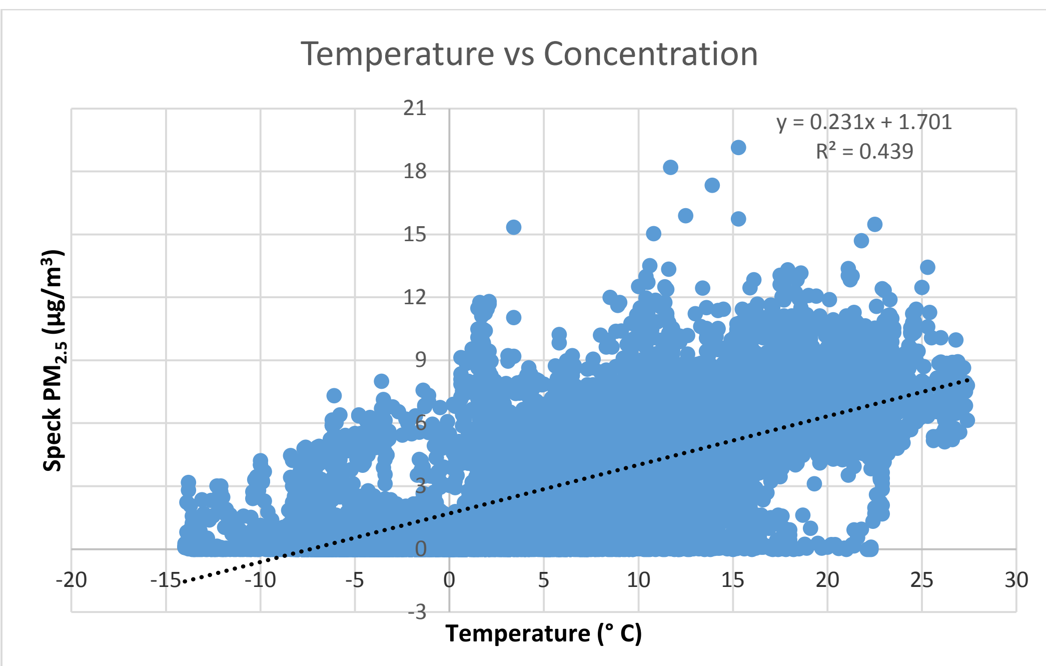

Figure 13. Speck compared to temperature

A correction to the Speck data response was made based on the temperature correlation. First, the average of all Speck data was measured to be 3.13 µg/m^3. Then a constant, 1.43 µg/m^3, was added to the Speck data such that the Y-intercept of the temperature correlation best fit line would match the average of all Speck data. That best fit line was then subtracted from the Speck data. The result was that the corrected data plotted against temperature would have no temperature dependence and would have an average equal to the average of all of the original Speck data as shown in Figure 14.

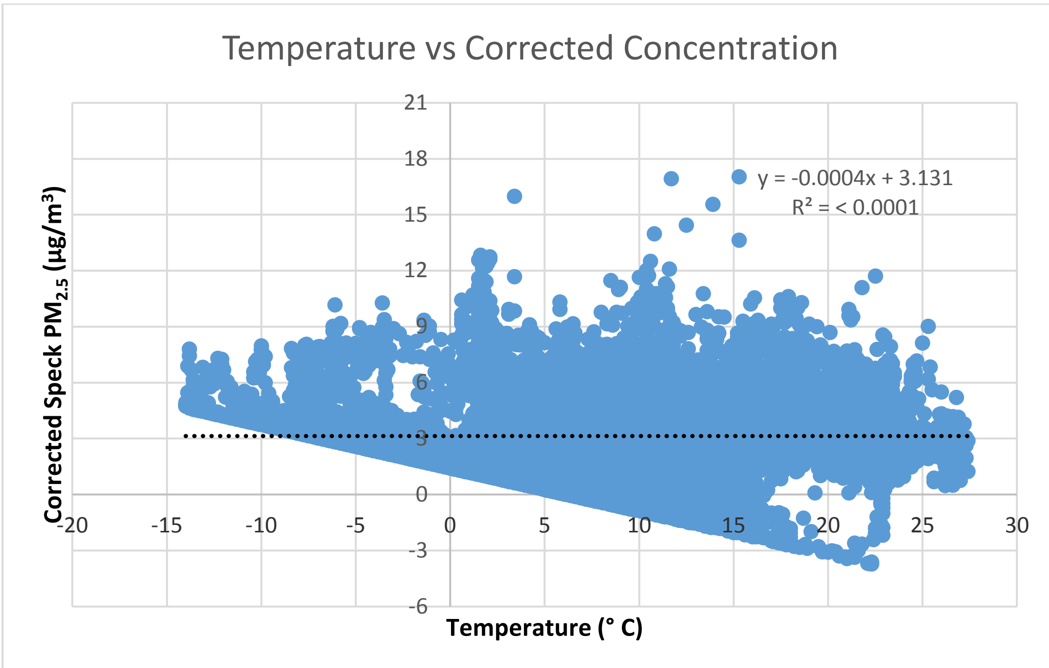

Figure 14. Speck compared to temperature after a temperature correction has been applied

This correction did improve the correlation between the Speck and the Grimm, but this correlation remained poor as shown in Figures 15 and 16.

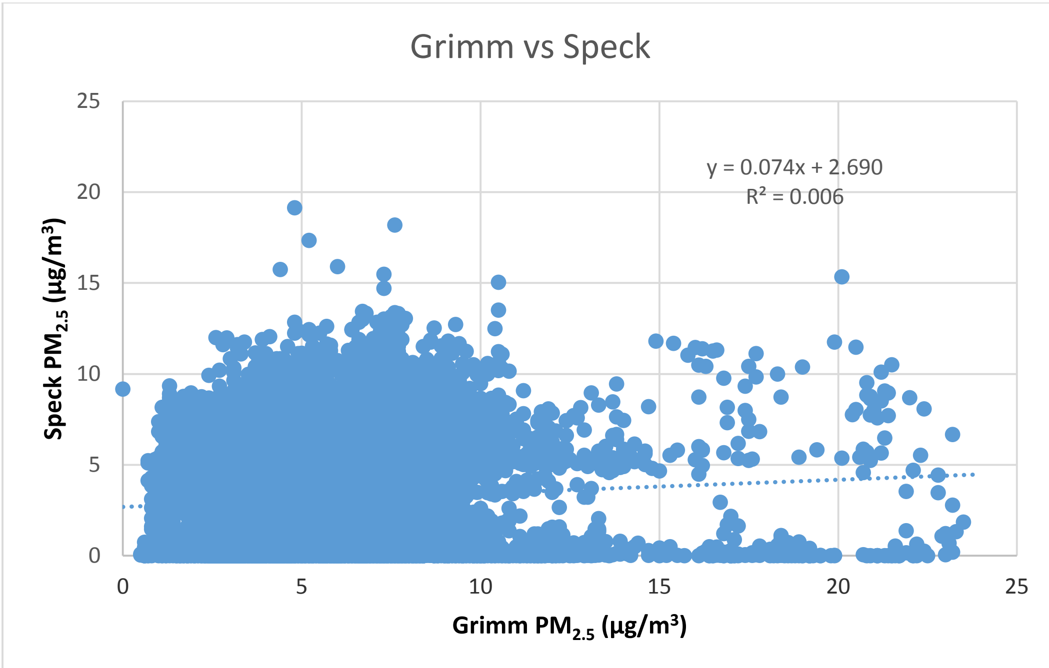

Figure 15. Speck vs Grimm without temperature corrections

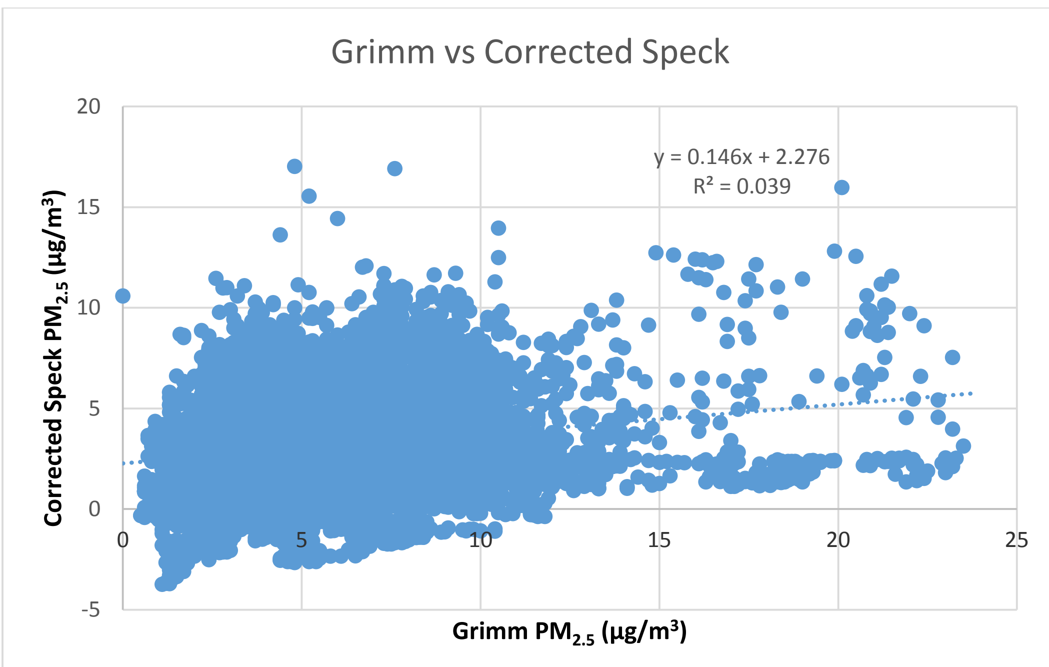

Figure 16. Speck vs Grimm with temperature corrections

Even with these corrections applied, the strongest coefficient of determination with the Grimm was only 0.04. The Speck does appear to visually track the Grimm at times, but cannot be shown to do so quantitatively. There remains a great deal of seemingly random error overlaid on top of the signal. One prominent source of error appears to be in the form of clusters of extremely low values. If this source of error can be eliminated, it is likely that correlations might improve markedly. A temperature correction factor built into the software would also likely be of value. Finally, it must again be noted that a major update to the Speck has been produced since these data were collected. This latest version of the Speck is currently deployed in an ongoing Denver sensor evaluation (CAIRSENSE). Data from the CAIRSENSE will not be available until well into 2016 and therefore no distinction between the version of the Speck evaluated here and the most current version can be provided.

3.3 General Discussion

The general performance features of the two sensors evaluated here is summarized in Table 1. The terms used in the table are defined as follows:

- 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 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 research operating procedure. Other procedures might have different requirements.

It should be recognized that uptime, ease of installation, ease of operation, and mobility descriptors provided 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 an example, 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 operation 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 alternating current/direct current (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.

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

Sensor	RH Limit	Major temp effects	Time resolution	Uptime	Ease of installation	Ease of operation	Mobility
PerkinElmer Elm	Impacts observed at RH > 95% for PM measurement	Not observed	1 min	Excellent	Good	Excellent	Fair
Carnegie Mellon Speck (particle counts)	Impacts observed at RH > 95%	Observed	1 min	Good	Fair (rain shielding)	Good	Fair

In general, the Elm was easy to operate once it was positioned at the collocation monitoring platform. No general maintenance or servicing was required once it began operation with the exception of data downloads. It did require access to a land-based power source. In its normal operation, the unit requires access to cellular data transmission. We harvested data directly from the unit without cellular service and therefore cannot share any findings relative to communication uptime and transmission activities. Data processing occurred through a file being returned to the manufacturer and the subsequent concentration values/time stamps being returned to us.[2]

We had some issues with units of the Speck operating successfully prior to initiation of this effort but once an operational unit was obtained it collected data without interruption throughout the study period. We had to protect the unit from weather events as interaction with direct precipitation would result in instrument failure. Processing of the data was performed via access to the manufacturer's software for such purposes.

4.0 Study Limitations

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

- The resources of the US EPA to conduct the extensive field tests defined herein, and
- The scope of the performance testing was not meant to fully compare the devices versus FEM standards.

4.1 Resource Limitations

4.1.1 Intra-sensor Performance Characteristics

This effort was not intended to be a definitive evaluation of the two devices. In particular, only single units of each device were evaluated and therefore the potential for poor performance to uncharacteristically reflect the sensor in general could exist. 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). We operated units in a laboratory setting for 3-5 days prior to their field placement to ensure basic operational status conditions were evident (data being transmitted or internally stored) and to provide for staff familiarization of the device. Once units were placed in the field, we inspected them on a weekly basis for operational status. We observed no obvious failures during field deployment.

4.1.2 Test Conditions

Resources prevented the US EPA from examining the sensors under a wide variety of environmental and interfering agent conditions. Field evaluation was performed only during cold weather (winter) seasonal conditions. This limited variability of temperature and relative humidity conditions certainly restricts the extent results here might be extrapolated to represent other seasons, namely summertime.

4.1.3 Sensor Make and Models

We have been made aware of an updated version of the Speck that was released after the version evaluated in the current report. Based upon conversation with the developers, it is believed this new model has an improved response algorithm. This latest version of the Speck is currently being operated in a multi-seasonal evaluation as part of an US EPA sensor evaluation study (CAIRSENSE) in Denver, CO. The CAIRSENSE will not yield preliminary data findings until mid- to late summer of 2016 and therefore cannot provide any benefit here pertaining to Speck performance. The Elm, based upon what is given at the manufacturer's website (www.Elm.perkimElmer.com/), at the time of this report (November 2015), has been deployed in multiple world-wide locations. No specific information is readily available at this website concerning the technology associated with the Elm, the types of sensors associated with the unit evaluated here, or how it might have compared with earlier versions of the system.

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