Low Cost PM2.5 Sensor Calibration

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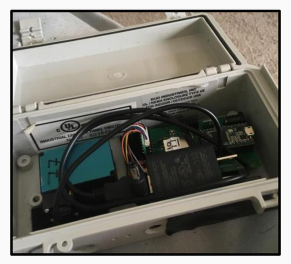
Abstract

PM2.5 (particulate matter ≤2.5 μm in diameter) has been linked to lung cancer and cardiovascular mortality (Lepeule et al., 2012). The most common sources of PM2.5 are “transportation, stationary power generation, industrial and agricultural emissions, and residential heating and cooking” (International Agency for Research on Cancer, 2013, p. 2). Typically, PM2.5 is monitored by large, stationary filter-based sensors.

Laser light scattering technology has been used to create low-cost, handheld PM2.5 sensors that use the angle at which particles scatter a laser beam to measure particle size, which is converted into mass using a density factor. Once calibrated, these sensors could be used to measure personal exposure to PM2.5, or used in networks to increase the resolution of air quality monitoring in cities.

In this project, two low-cost PM2.5 sensors were co-located with a Met One BAM 1020, a Federal Equivalent Method PM2.5 sensor used for regulations compliance monitoring. Calibration methods based on relative humidity were assessed.

Sensors



Name	Met One BAM 1020	AirVisual	Duke Device
Cost	~$21,000	$269	~$250-300
PM2.5 Sensor	---	AVPM25b	Plantower PMS3003
Method	Beta Attenuation	Light Scattering	Light Scattering
Type	Reference Federal Equivalent Method Sensor	Low cost Commercial Indoor Air Quality Monitor	Low cost Custom Duke University Arduino board device
Duty Cycle	1 hour	3 minutes	1 minute

Setup

Colocation with BAM 1020 at Maryland Department of the Environment (MDE) monitoring trailers

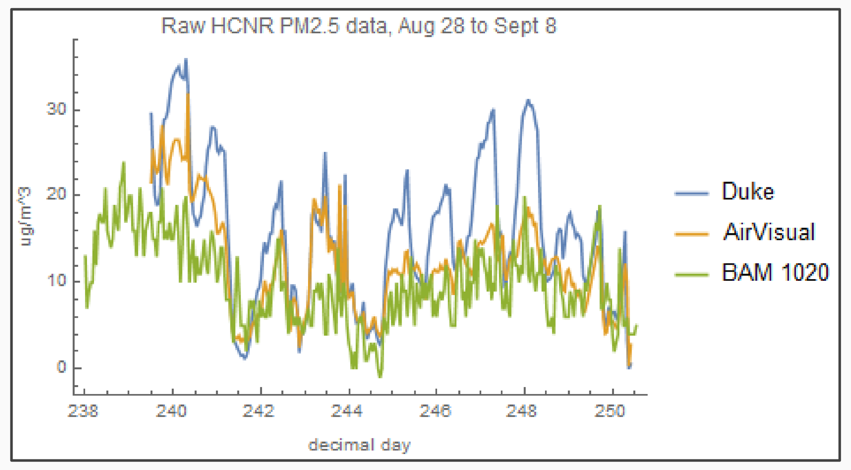
Aug 28-Sep 8, 2018: Calibration Dataset at Howard County Near Road (HCNR) trailer along I-95 South

Aug 16-Aug 19, 2018: Dataset at Howard University Beltsville Campus South Side trailer

The sensor tent has been circled in red in the images to the left.

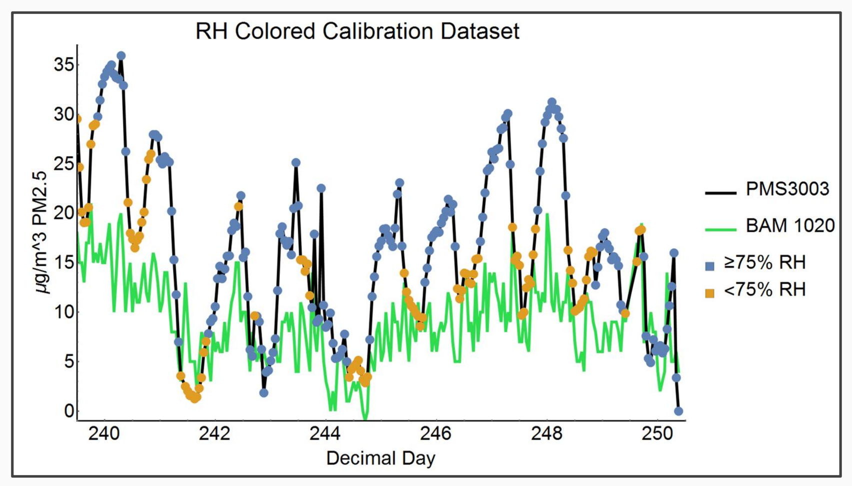
The low-cost sensors were placed on a cinder block in a tent to protect them from rain. During the day, the dark-colored tent trapped heat and created a microenvironment with increased temperature and thus lower relative humidity (RH) inside the tent. The built in Sparkfun RH sensor on the Duke device was calibrated against ambient MDE RH measurements using only night-time data. This microenvironment introduces uncertainty, as we do not know how quickly hydrated particles dry and thus decrease in size upon entering the tent.

Calibration Dataset



Location: Howard County Near Road monitoring trailer (I-95 South)
Dates: Aug 28-Sep 8, 2018
The figure at the left shows PM2.5 vs time for a period of approximately 10 days. The PMS3003 demonstrated high peaks not seen in the BAM values and seen to a lesser extent in the AirVisual values. Time is given in decimal day, with 240 representing 12:00 AM Aug 29, 2018. For subsequent calibration, the AirVisual was ignored due to lack of demonstrated response to RH and persistent difficulty retrieving data from the sensor.

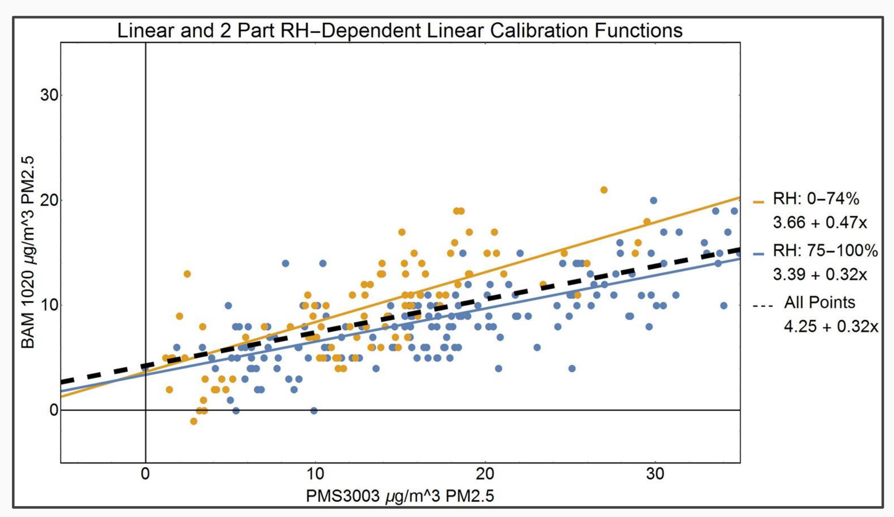
Relative Humidity



The graph to the left shows the same data as above, this time with the PMS3003 in black. Each PM2.5 data point has been colored either orange or blue to represent whether it was taken while the RH inside the tent was higher or lower than the cutoff of 75%. This graph shows that the peaks seen in the PMS3003 measurements generally correspond to periods of high humidity. The BAM 1020 has a heated inlet to control the RH of the air it samples, while the PMS3003 does not. Particulate matter is known to swell in the presence of high RH (known as hygroscopic growth) (Zheng et al., 2018). This graph suggests that more mass is found in particles that grow into or within the sampling range (<2.5 μm) than grow out of the range (>2.5 μm) during periods of high RH.

Two Part RH-Dependent Linear Regression

Using the same data points as above, separate linear regressions were created for the points within the low and high RH ranges. The graph to the right plots PMS3003 PM2.5 values on the X axis and BAM 1020 PM2.5 values on the Y axis. The black dotted line represents the linear regression line for all of the data points, while the orange and blue lines represent the linear regressions for points within the low and high RH ranges, respectively. There were more high RH points in the dataset, so the single linear regression line is more similar to the high RH regression line.

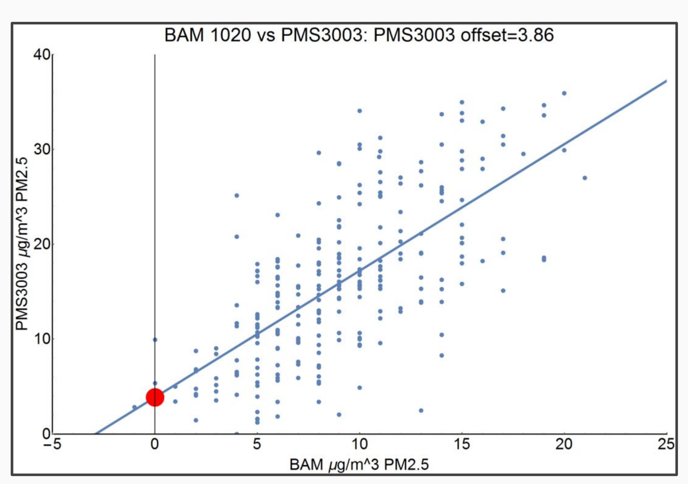


Hygroscopic Growth Equation

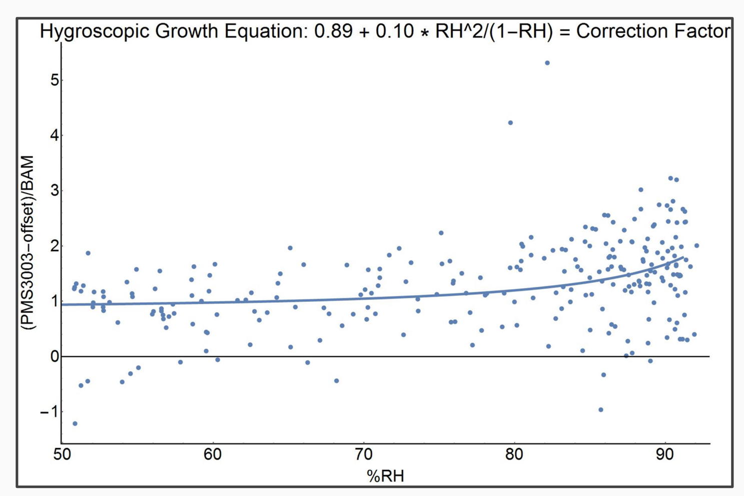
The growth of particles as RH increases can be represented by a hygroscopic growth equation in the form

$$a + b\left(\frac{RH^2}{1-RH}\right) = \frac{LCS}{ref}$$

(Zheng et al., 2018), where *a* and *b* are adjustable parameters.



Because the hygroscopic growth equation is in terms of the ratio of the LCS to the reference, and because we find that there is a bias between the two sensors, linear regression was used to find the bias in the PMS3003 sensor versus the BAM 1020 first.

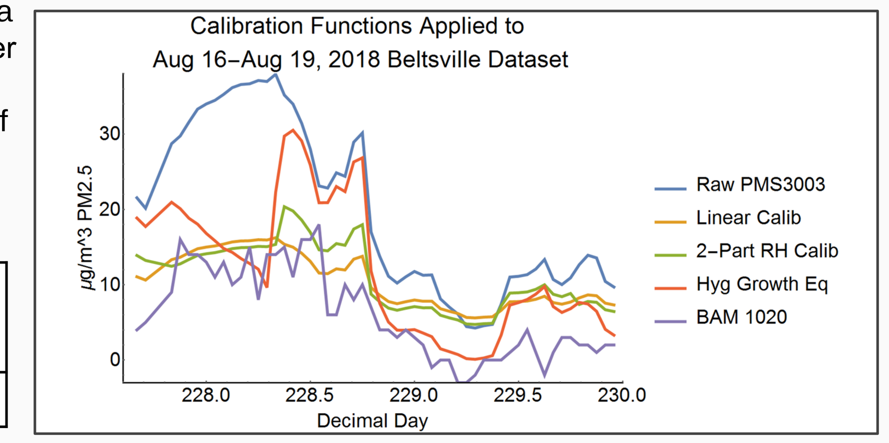


To form the ratio dataset, the bias was first subtracted from the PMS3003 PM2.5 measurements. Then, the hygroscopic growth equation was used to fit the ratio dataset as a function of RH.
To apply this calibration, the PMS3003 measurements are divided by the correction factor determined by the best fit equation.

Testing the Calibrations

Three calibration functions were applied to a dataset taken at the MDE’s monitoring trailer on the South side of the Howard University Beltsville Campus. The root mean square of the difference between the PMS3003 and BAM 1020 PM2.5 measurements was calculated for each calibration.

Function	Raw	Linear Calib	2 -Part RH Calib	Hyg Growth Eq
RMS	15.20	5.46	5.89	8.01



Summary & Discussion

Two low-cost laser light scattering sensors were co-located with a Met One BAM 1020 reference sensor at the MDE’s Howard County Near Road monitoring site. One sensor, a custom device from the Bergin group at Duke university using a Plantower PMS3003 sensor, was found to be more sensitive to changes in RH, prompting the testing of RH-dependent calibrations.

The BAM 1020 has a heated inlet to control for RH and hygroscopic growth, while the PMS3003 does not. In addition to a simple linear regression calibration, which did not account for RH, two RH-dependent calibrations were developed: a two-part linear calibration and a hygroscopic growth equation. These three calibrations were tested on another dataset taken at the MDE’s monitoring station at the Howard University Beltsville Campus. All three calibrations reduced the RMS between the PMS3003 and BAM 1020 PM2.5 measurements from the raw RMS of 15.20. The simple linear calibration had the lowest RMS (5.46), meaning this calibration worked best to bring the PMS3003 measurements into agreement with the BAM 1020. The 2-part RH-dependent linear regression calibration performed similarly, while the hygroscopic growth equation had a higher RMS of 8.01. As the test dataset was only three days, more data would be helpful in drawing a conclusion about the long term performance of these calibration functions.

Future Work

Better Shelter

The tent that housed the low-cost sensors created a microenvironment during the day with elevated temperatures and thus lowered RH. We plan to take another calibration dataset with a more adequate shelter, similar in design to the box shown to the right.

Other Goals

- Collecting more data in Winter with an improved shelter
- Testing RH-calibrations on Winter data
- Calibrating the Duke device’s Sparkfun RH sensor against NIST traceable instruments
- Calibration of more sensors and intercomparisons between replica sensors
- Using Teensy microcontroller to build our own low-cost sensor package

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Acknowledgements

We are greatly indebted to the Bergin Group at Duke University for loaning us their custom Arduino-based sensor. The Bergin Group, lead by Michael Bergin, is dedicated to developing low-cost PM sensors for citizens to be aware of the air they are breathing. For more information, visit http://bergin.pratt.duke.edu/, and to learn more about the sensor package, visit dukearc.com. We would also like to thank Ryan Auvil and Adam Reese of the Maryland Department of the Environment Air Quality Monitoring Program managed by David Krask for allowing co-location of low-cost sensors at their monitoring sites.