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Performance Evaluation of the United Nations Environment Programme Air Quality Monitoring Unit

Office of Research and Development
National Exposure Research Laboratory

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Disclaimer

This technical report presents the results of work performed by the US. Environmental Protection Agency's Office of Research and Development (ORD) with technical support through Jacobs Technology (Contract # EP-C-15-008) for the National Exposure Research Laboratory (NERL), U.S. Environmental Protection Agency (US EPA), Research Triangle Park, NC. The effort represents a collaboration between the US EPA and the United Nations Environment Programme (UNEP) in fulfillment of a Material Cooperative Research and Development Agreement (MCRADA) to conduct research involving emerging air quality sensor technology. It has been reviewed by the U.S. EPA and the UNEP and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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Acronyms and Abbreviations

AC	alternating current
AIRS	Ambient Air Innovation Research Site
FEM	federal equivalent method
FRM	federal reference method
GPS	Global Positioning System
MCRADA	Material Cooperative Research and Development Agreement
NAAQS	National Ambient Air Quality Standards
NERL	National Exposure Research Laboratory
NO_2	nitrogen dioxide
OAQPS	Office of Air Quality Planning and Standards
OITA	Office of International and Tribal Activities
ORD	Office of Research and Development
PM	particulate matter
$PM_{2.5}$	particulate matter of diameter 2.5 microns or less
PM_{10}	particulate matter of diameter 10 microns or less
ppb	parts per billion
ppm	parts per million
QAPP	quality assurance project plan
R^2	coefficient of determination
RH	relative humidity
ROP	research operating procedure
RTP	Research Triangle Park
SO_2	sulfur dioxide
UNEP	United Nations Environment Programme
US EPA	United States Environmental Protection Agency
VOC	volatile organic compound

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Executive Summary

A request for technical collaboration between the UNEP and the US EPA resulted in the establishment of a MCRADA. The purpose of this agreement was to evaluate a prototype air quality monitoring system (referred to as the UNEP pod) developed by the UNEP for use in environmental situations where more sophisticated monitoring instrumentation was not available. The US EPA has conducted numerous evaluations of other similar sensor pods at its Research Triangle Park, NC research campus and has trained staff as well as established research designs for such efforts. Under the terms of the MCRADA, the US EPA would operate the pod using UNEP-provided operating procedures in a manner consistent with its planned intent of deployment. The US EPA would collect air quality monitoring data from the pod for selected environmental measures over a period of approximately 1 month. Reference monitoring data collected from collocated federal regulatory monitors would be used to establish a comparison between the two systems and thus establishment of performance characteristics. In addition, the US EPA would provide informed feedback to the UNEP about the pod's observed ease of use features that would be beneficial in its future evolution and deployment.

Study Objectives

In response to the UNEP's request, the US EPA evaluated the sensor pod during a 30-day study to establish its basic performance characteristics. The effort was projected to be initiated in the fall of 2016 and fully completed during calendar year 2017. Specifically, the US EPA agreed to the following:

- Conduct a collocated comparison between the UNEP low cost sensor pod versus reference monitors under outdoor environmental conditions at the US EPA's research site in Research Triangle Park, NC for a period of approximately 1 month.
- Collaborate with the UNEP on all data summaries.
- Publish basic summary findings of the effort following peer review in a mutually agreed upon format (e.g., peer reviewed report).
- Provide a complete database detailing both the UNEP sensor pod and reference monitor response under collocated ambient challenge conditions to allow the UNEP to conduct its own independent statistical comparison of performance.

Study Approach

The UNEP sensor pod was operated under UNEP operating guidelines on an "as is" basis. That is, the US EPA technically sited and operated the prototype unit as defined by the UNEP to ensure that the performance characteristics established were representative of those to be expected from real world deployment. Although the US EPA requested that multiple copies of the device be provided to allow its precision, bias, and other performance characteristics to be established, only a single pod was made available. Whereas evaluation of the pod under fully controlled laboratory conditions would have been valuable (i.e., a chamber), no such chamber was immediately available to the US EPA for such an effort nor were there resources to conduct such an effort. Therefore, the pod was operated in a weatherproof enclosure in a collocated manner at the US EPA's Ambient Air Innovation Research Site (AIRS) for a period of approximately 1 month. One (1) minute continuous data responses ($PM_{2.5}$, PM_{10}, NO_2, SO_2, RH and temperature) were obtained. Data were continuously logged to the internal microprocessor and downloaded to a dedicated laptop computer weekly. Using applications provided by the UNEP, data were combined into a time series, converted to ambient concentrations, and recorded in electronic spreadsheets. US EPA validation of the data was performed following consultation with the UNEP on all issues that required input on data validation resolution. Reference monitoring data from the AIRS were obtained and, following validation review, integrated with UNEP pod data to allow for statistical evaluation and characterization. The statistical comparison of the UNEP pod versus the reference monitor data was compared to established performance characteristics (e.g., time series, regression, co-linearity with RH and temperature). Statistical averaging times ranging from 1 minute to 24 hours were explored to establish integration effects on performance characteristics. The impact of various quality assurance data inclusion/exclusion criteria were considered. Statistical findings, based on validated data meeting specific quality assurance criteria that were established, are presented in this report.

Sensor Performance Results

The UNEP pod was determined to have a stable electronic data collection architecture (microprocessor and integrated sensor components) in that data were collected without failure from the initiation of the study through its completion (for more than 30 days). However, processing errors using the UNEP developed firmware and software that complicated data analysis and quality assurance review were noted. Even so, a data completeness record of > 90% was observed.

Preliminary observations of raw (non-validated) NO_2 and SO_2 data following the first week of data collections indicated that the UNEP pod's response was significantly different in terms of its reported concentrations than those measured by the collocated reference monitors. Consultation with the UNEP on these observations resulted in a decision to continue data collection for these pollutants, but not to pursue establishment of their performance characteristics as part of this report. Raw data concerning these pollutants were harvested for the full duration of the evaluation and have been shared with the UNEP for their consideration.

$PM_{2.5}$, PM_{10}, RH and temperature data from the UNEP pod were compared with the collocated reference or research grade monitors. Briefly, time series, as well as regression analyses, revealed little to no agreement ($R^2 < 0.1$) of the $PM_{2.5}$ and PM_{10} mass concentrations with reference values at time averaging intervals between 5 minutes to 24 hours. Ambient RH was determined not to be correlated to pod PM response over any integration period. Direct comparison with collocated reference temperature data indicated that the UNEP pod's internal components heated the airspace within the UNEP pod, resulting in reduced RH and a ~ 7^{o}C increase in temperature as measured by the UNEP pod. The impact, if any, that this heating might have had on the resulting particulate matter or gas measurements is unknown.

Ease of Use Features Evaluation

The UNEP pod was observed to be very robust with respect to its day-to-day operation. It was of sturdy construction relative to its physical design. However, even with the technical manual provided by the UNEP, we were unable to establish some of the system's primary features (e.g., inlets, exhausts). An improved operator's manual would be beneficial to others. The US EPA did not open the pod to reveal its inner components (sensors and related electronics) to maintain the integrity of its character. Once initialized using a standalone laptop computer, the UNEP pod operated without electronic failure for more than 1 month of continuous 1-minute data collections. Direct land power (alternating current) was used to provide the needed energy resources. Data were logged to the internal microprocessor continuously. Data were downloaded to a dedicated laptop computer weekly to ensure the UNEP pod was operating and storing data. Accessing these data required some degree of technical capability. In particular, multiple third-party software applications that were needed to provide the interface between the UNEP pod's microprocessor and the laptop computer had to be downloaded from internet sources. We are concerned that other end users, especially those with limited technical skills, might have some difficulty not only in obtaining the secondary computer applications but also in their operation.

Two independent executables were used to process the raw data. These executables were provided by the UNEP, and the US EPA attempted to use them in their "as is" state. The first, a Windows command tool, was used to combine the 24 individual hourly data files into a single combined data file representing a full day of data. The second, an Excel macro, converted the raw gas data (reported as volts) to environmentally relevant concentration units (ppb). Some coding errors were discovered in the macro code used to compute gas concentrations. The code was revised, and all raw data were reprocessed using the updated code. The processing was therefore not without some concerted effort to ensure completeness. Nevertheless, the executables provided by the UNEP were robust. Since the UNEP developed the executables for the US EPA to eliminate cloud-based processing (which the US EPA does not have permission to use), it is unknown if the code script error was isolated to this specific situation or a more systematic issue with primary data processing that might be encountered by others using the data streaming capabilities of the UNEP pod.

Conclusions

The UNEP pod collected environmental data continuously with little need for operator interaction. While in the US EPA's possession, the UNEP pod appeared to operate without technical failure of any of the energized components (fans, microprocessor, sensor components). Nevertheless, significant technical effort was required to obtain and operate the secondary software applications that were needed to collect and download the data. The gas phase sensors did not provide data useful for the evaluation. It is not clear if the problems with the gas sensors were related to the algorithms used to process the data, or to the sensors themselves. Technical suggestions were provided to the UNEP on this topic, which they may wish to pursue. Details are presented in the Appendix.

While the UNEP pod successfully collected and reported data for both $PM_{2.5}$ and PM_{10} mass concentrations, comparisons over a wide range of time intervals failed to yield satisfactory agreement with collocated reference monitors ($R^2 < 0.18$). Factors that might have had a negative impact on the assessment (data completeness, RH impact) were exhaustively investigated, but little to no improvement in the observed performance characterization was observed regardless of data treatment.

1.0 Introduction

The UNEP recently developed a prototype multipollutant sensor pod called the UNEP Air Quality Monitoring Unit, herein simply defined as the UNEP pod (http://aqicn.org/faq/2015-10-28/unep-air-quality-monitoring-station/). First introduced in 2015, the UNEP pod was developed with the goal of providing an affordable air quality monitoring instrument to a worldwide audience. A basic cost of ~ $1500/pod has been reported, which would potentially allow many end users to obtain the device and operate it to achieve environmental monitoring for a variety of needs. Basic features of the UNEP pod include a weatherproof milled aluminum encasement, a series of gas phase sensors for criteria pollutant monitoring, an optical particle counter for estimations of particulate matter mass, and environmental meteorological sensors, as well as fans and other assorted electronic components. By design, the unit was intended for near-continuous operation when energized with local land power, with data transmission occurring via cellular communication to a dedicated service provider.

Although the UNEP pod was developed in 2015 and has undergone informal operational trials since its release, no formal evaluation or reporting of its performance characteristics had been conducted previously. Since emerging sensor technologies are not certified for their capabilities, and the goal of the UNEP was to establish a credible air monitoring system for less developed international settings, conducting such an evaluation was a defined need.

The US EPA has a documented history of conducting numerous technical performance evaluations of low cost (< $2500) sensors and their assembled components (EPA, 2017a). Other air quality research organizations have also begun to investigate sensor performance characteristics (EPA, 2017b; EPA, 2017c). Under such scenarios, sensor components are tested either directly under chamber (laboratory) challenge or under ambient (field) scenarios (Williams, 2014b; Williams, 2014c; Williams, 2015a; Williams, 2015b). In all such cases, sensor response has been directly compared versus Federal Reference Method (FRM) or Federal Equivalent Method (FEM) monitors to establish the performance characteristics, and this approach has been the subject of scientific discussion (Kaufman 2014; Williams 2014a; Williams 2014d). The general consensus has been that such an approach provides a peer-acceptable method of defining the basic performance characteristic of a non-regulatory air quality device. Specifically, the direct comparison of such a device under ambient (real-world) monitoring conditions not only challenges the sensor to the pollutant(s) of interest but also to potential co-factors to which the device might respond.

In the late winter of 2016, meetings were held involving representatives of the UNEP and the US EPA's Office of International and Tribal Activities, ORD, and Office of Air Quality Planning and Standards to discuss the possibility of conducting a formal performance review of the UNEP's sensor pod. Ultimately, these meetings resulted in a formal MCRADA being established between the UNEP and the US EPA's ORD to accept receipt of one or more of the sensor pods and to conduct a month-long evaluation of its performance under real-world (ambient) conditions. This research was to be conducted at the US EPA's AIRS test platform located on its campus in Research Triangle Park, NC. This location was chosen solely because of its convenience for the ORD staff who would be conducting the research. As this research was being conducted without any additional funding or resources being made available, economics dictated that leveraging of existing resources (e.g., fully operational reference monitoring platform and local US EPA staff) be used to achieve the primary goals. Both parties recognized that the AIRS test location did not represent the environmental conditions that might be expected in international locations where environmental pollution levels would be expected to be significantly higher. Even so, ambient pollution levels of particulate matter as well as of the National Ambient Air Quality Standards (NAAQS) criteria pollutant gases are routinely measured above detection limits at the AIRS test location and with sufficient day-to-day variability to enable an evaluation to be performed. The US EPA has previously reported on using the AIRS test location in this manner to evaluate a wide range of lower cost sensor components and multipollutant pod systems (Williams 2014b; Williams 2014d; Williams 2015a; Williams 2015b).

The MCRADA established that the performance characterization research would be collaborative in nature, with both parties substantially contributing to achieve its success. Hallmarks of these contributions would be the UNEP providing support documentation fully defining the operational guidelines of the UNEP pod and the US EPA operating the equipment as expressly defined by the UNEP to ensure a non-biased approach to the testing. Other key components of the MCRADA were as follows:

- Operate the UNEP pods through a ~30-day study to establish its basic performance characteristics, with a projected initiation in the fall of 2016 and completion during calendar year 2017.
- Conduct a collocated comparison between the UNEP pod versus the reference monitors under outdoor environmental conditions at the US EPA's research site in Research Triangle Park, NC. Ideally, the US EPA would test three UNEP pods side-by-side to see if the results were replicable.
- Collaborate with the UNEP on all data summaries.
- Publish basic summary findings of the effort, following peer review, in a mutually agreed upon format (e.g., peer-reviewed report).
- Provide a complete database detailing both the UNEP pod and reference monitor response under collocated ambient conditions to allow the UNEP to conduct its own independent statistical comparison of performance.

Efforts were made to obtain the UNEP pods as early as possible in the calendar year, as the US EPA had previously established, in laboratory testing, that gas phase sensor evaluations performed under low temperature conditions (at or below freezing) sometimes resulted in poor sensor performance (Williams, 2014d). It was the US EPA's goal to examine the sensor under the most favorable conditions possible, and ultimately an agreement was reached to deliver the pods in October 2016. Although a sustained effort was made to obtain multiple copies of the UNEP pod to enable precision and bias evaluation, only a single pod was made available for the research. The unit was recovered from a Kenya, Africa deployment and shipped to the US EPA's Research Triangle Park campus, where the materials were unpacked, inspected, and cataloged. A single screw was observed to be unattached in the packaging materials, and it was assumed that the screw was originally secured inside the pod encasement itself and had become free because of some movement or vibration during shipping and handling. Consultation with the UNEP on this matter yielded the same conclusion as US EPA staff that this item would not be expected to have any impact on the resulting performance evaluation.

The software modules required to communicate with the pod and download the data, all available as free shareware, were downloaded to a dedicated laptop. This software included: 1) BONE_D64.exe ver. 1.2.0.715 – a BeagleBone serial over USB driver, 2) PuTTY.exe ver. 0.67.0.0 terminal emulator software, and 3) psftp.exe ver. 0.67.0.0, a secure file transfer protocol for PuTTY. It is unknown whether these applications would have been required if the device was being used in its cellular data transmission mode, as is the case at UNEP's Kenya-based site. The dedicated laptop computer was used to communicate with the pod, to establish its operating parameters, and ultimately to recover and process the raw data on a weekly basis. Two executable files (Merge_CSV.cmd and Gas_ppb.xlsm), which were provided to the US EPA by the UNEP, were needed to process the raw data. The first of these executables, a DOS command file (Merge_CSV.cmd), merged the hourly data files into a single daily file containing all measured data with raw gas data reported in units of volts. The second executable, an Excel macro script (Gas_ppb.xlsm), transformed the raw gas data into environmentally relevant concentration units (ppb). The result was a single Excel file for each day of data collection containing the processed gas concentrations, particulate matter concentrations, temperature, and RH, with each data record within the file identified by date and time. Data from these processed data files were combined and used by the US EPA in its comparison with the collocated reference monitor data to determine the performance characteristics of the UNEP pod.

Examination of the processed data files showed that NO_2 and SO_2 concentrations were being reported as either negative or near zero concentrations when true environmental conditions were not consistent with these values. The US EPA reported these findings to the UNEP staff early in the monitoring process, but no conclusions were made about the cause of this apparent gas measurement discrepancy. Once the monitoring was completed, the US EPA revisited the issue and considered that the source of the problem might be in the executable macro provided by UNEP, rather than in the sensors themselves. The algorithms and supporting parameters used in the macro code to compute the NO_2 concentrations, as well as the macro code itself, were examined in detail. Some errors were discovered in the code, suggested revisions were made, and the data were reprocessed using the updated code. The details of this process are documented in the Appendix. The results of this detailed review were promising except for a signage problem, the cause of which remains undetermined. It was decided that gas phase data from this evaluation would not be incorporated into the results defined by this report. After the field tests were concluded, UNEP staff were provided copies of all raw UNEP pod data as well as collocated reference monitoring data to assist them in further elucidation of these issues.

Therefore, only meteorological (RH and temperature) and particulate matter data ($PM_{2.5}$ and PM_{10}) from the UNEP pod were directly compared to the collocated reference monitors' data. This report defines the specifics of the environmental test conditions used in the evaluation (systems and conditions), data observations, summarization of key performance evaluation findings, and ease of use features concerning the UNEP pod.

2.0 Materials and Methods

2.1 Instrumentation

The UNEP pod was composed of an Optical Particle Counter for $PM_{2.5}$ and PM_{10} (AlphaSense-OPC-N2) measurements, two gas phase sensors for SO_2 and NO_2 (Alphasense model B-4) measurement, a Global Positioning System (Sparkfun Venus GPS module and ANT 555 active GPS antenna), a temperature and humidity sensor (Sensirion SHT21), and a Texas BeagleBone Black. The latter is a single board computer that doubles as both the microprocessor and the system control module. The US EPA did not open the encasement of the pod, and therefore other components that might have been present (e.g., exhaust fans) but not immediately apparent are not named here. The prototype received for evaluation had previously been operated in Nairobi, Kenya to map the city's air pollution hotspots while also informally evaluating its reliability and robustness.

The gas sensors incorporated into the UNEP pod typically come with some degree of factory/manufacturer calibration. The full extent of such calibration/audit is unknown. The US EPA's experience suggests that the gas phase sensors would have undergone laboratory calibration by the manufacturer (zero and span check at temperatures ranging from -30 to 50 °C). Information found on the manufacturer's website would appear to indicate that batch-to-batch variability of the sensors is used to develop processing algorithms (Alphasense application note AAN 803-02 – September 2016). Correction algorithms are often used to compensate for known environmental artifacts (temperature, relative humidity, and interfering gasses) in field measurements. Depending upon the age of the gas phase sensors, the value of the manufacturer's original calibration is uncertain (Williams, 2017a). If the sensors were relatively young (e.g., < 1-2 months of age), then the manufacturer's calibration algorithm would be expected to be of value. The age of the gas phase sensors in the UNEP pod was unknown at the time of the evaluation, and the US EPA cannot further elaborate on this topic. The UNEP pod was used "as is" without any attempt to conduct direct calibration of the gas phase sensors.

The OPC-N2 particulate matter sensor, in like manner, was used without any secondary calibration performed by the US EPA. The OPC-N2 collects a total of 16 size-defined bin designations of particle counts from 0.38 to 17 microns to which a proprietary manufacturer's algorithm (Alphasense, 2013) is applied to develop mass concentrations ($\mu g/m^3$) for two size fractions ($PM_{2.5}$ and PM_{10}). The processing algorithm shared by the UNEP provided for US EPA to have access to the $PM_{2.5}$ and PM_{10} mass concentration data from the device (including 16 size bins). The US EPA did not attempt to investigate the size bins and how they were being used to establish the various PM size fraction mass densities. It is believed that the AlphaSense OPC-N2's algorithm for converting size bins into mass density was being used. The size bin integration algorithm is typically proprietary and investigating it was beyond the scope of this research effort.

The US EPA evaluated the temperature and relative humidity sensors included in the UNEP pod with no additional calibration. Data from these two sensors were acquired as part of the raw data output from the Beaglebone and processed as defined later into their final report state.

The US EPA operates the AIRS test platform on its Research Triangle Park campus (Williams, 2014b). A GRIMM Technologies, Inc. (Douglasville, GA) Class IIII designated $PM_{2.5}$ Federal Equivalent Method (FEM) monitor is under continuous operation at that site. The GRIMM monitor also provides PM_{10} mass concentration estimates but is not a US-designated FEM for this aerosol mass size fraction. The European Union, however, has designated this monitor as an equivalent reference monitor meeting the EN12341 standard (http://ec.europa.eu/environment/air/quality/ legislation/pdf/equivalence.pdf), and it is used herein as such to provide comparison data for informational purposes. The GRIMM monitor was used because it was already fully operational at the AIRS, required no additional EPA resources for its operation, and provided the ability to examine 1-minute data collection periods from the pod. No other reference PM monitors were available for this effort. That alternative FRM/FEM monitors, such as those involving regulatory filter-based monitoring or even the Tapered Element Oscillating MicroBalance (TEOM) approach, might have provided additional benefit was recognized. However, no such methods were available during this study.

A cavity attenuated phase shift (CAPS) NO_2 analyzer was operated at the AIRS. Specifics of the description and basic operation of the model T500U CAPS NO_2 analyzer (Automated Equivalent Method: EQNA-0514-212) are available elsewhere (EPA, 2014). Other instrumentation included a Teledyne T500U NO_2 analyzer and a Thermo 43C SO_2 analyzer. While there were no FRM or FEM temperature or relative humidity (RH) monitors, reference data for these measures were provided at a height of 3 meters at the AIRS using an R.M. Young 41382VC environmental probe, a widely accepted research grade device. These established methods are covered under a QAPP (Alion, 2013). Specifically, all gas analyzers undergo automated daily zero, span, and quality control checks. The GRIMM monitor’s optics are calibrated annually by the manufacturer, with its flow rate verified on a quarterly basis. The response of the meteorology sensor undergoes annual audit. Reference data were available for the time frame of the sensor evaluation as 5-minute averages. Study staff reviewed all raw reference data to ensure the various systems were operating in a nominal fashion within the guidelines of the QAPP noted. Only validated data were retained and used in the analysis. Photographs of the GRIMM monitor and selected reference monitors used in this evaluation are shown in Figure 1.

Figure 1. GRIMM monitor (left) and select reference monitors at the AIRS

2.2 Deployment

The UNEP pod was deployed at the AIRS facility on November 3, 2016 for approximately 1 month (33 days). Figures 2 through 4 depict the UNEP pod system as well as the reference monitoring station. Figure 2 provides a close-up of the UNEP pod installed inside the environmental shelter on the test platform at the AIRS, with the reference monitoring inlets in the near background. The two monitoring stations (UNEP pod and reference monitors) were within an inlet distance of 10 meters. The UNEP pod was housed in the aluminum shelter (1.11 × 0.91 × .94 meters). This enclosure ensured sensor protection from both windblown rain and direct sunlight while allowing unimpeded airflow. Specifics concerning the aluminum shelter have been previously reported (Jiao, 2016). The UNEP pod was placed in the center of the middle shelf at a height of 1.07 meters from the ground in an upside-down horizontal configuration to provide unrestricted access to ambient air to its inlets/outlets, presumed to be around the thin edges of the encasement. The UNEP pod was connected to 110V AC power, which was available through the power strip housed on the lower shelf. Data were logged to the internal microprocessor continuously and subsequently downloaded to a dedicated laptop computer via a direct (wired) connection weekly. As shown in Figure 2, the UNEP pod was oriented with its inlets (presumed to be through the thin edge of the encasement) fully open with respect to the ambient air plenum. Telephone conversations as well as direct inspection by a representative of the UNEP team who viewed the site early in the collocation process provided full agreement that this orientation was appropriate. The shelter was kept locked except during data recovery periods to ensure data integrity status. The US EPA is a secure facility, with restricted public access, and the only known external visitor to the site (UNEP representative) was under direct staff escort.

Figure 2. Orientation of UNEP pod and associated wiring connections

Figure 3. The aluminum test shelter with the reference monitor in the background

Figure 4. Select AIRS reference monitor inlets

At the time of deployment, the time on the BeagleBone was set to EST using PuTTY with the following command: root@beaglebone:~# date --set “DD MM YYYY HH:MMam/pm”

2.3 Data Collection Procedure

Communication between the UNEP pod and the study computer used software mandated by the UNEP. The UNEP pod operated with BeagleBone serial-over-USB drivers, PuTTY, a 64-bit PuTTY implementation of SSH and Telnet for Windows and Unix platforms, along with an Xterm terminal emulator. A tool for transferring files securely between computers using an SSH connection (psftp) was also utilized. The software application psftp was loaded onto the study computer, which used Microsoft Office Windows 7. The computer was used to set the date time stamp of the UNEP pod’s internal clock at the start of data collection and weekly thereafter, to store data downloaded from the UNEP pod’s microprocessor, and ultimately to process the raw data into a completed format. Details about setting up these programs are provided in the UNEP AQ Monitoring Unit User Manual. Specifics about the use of these key software applications are provided as part of the Appendix.

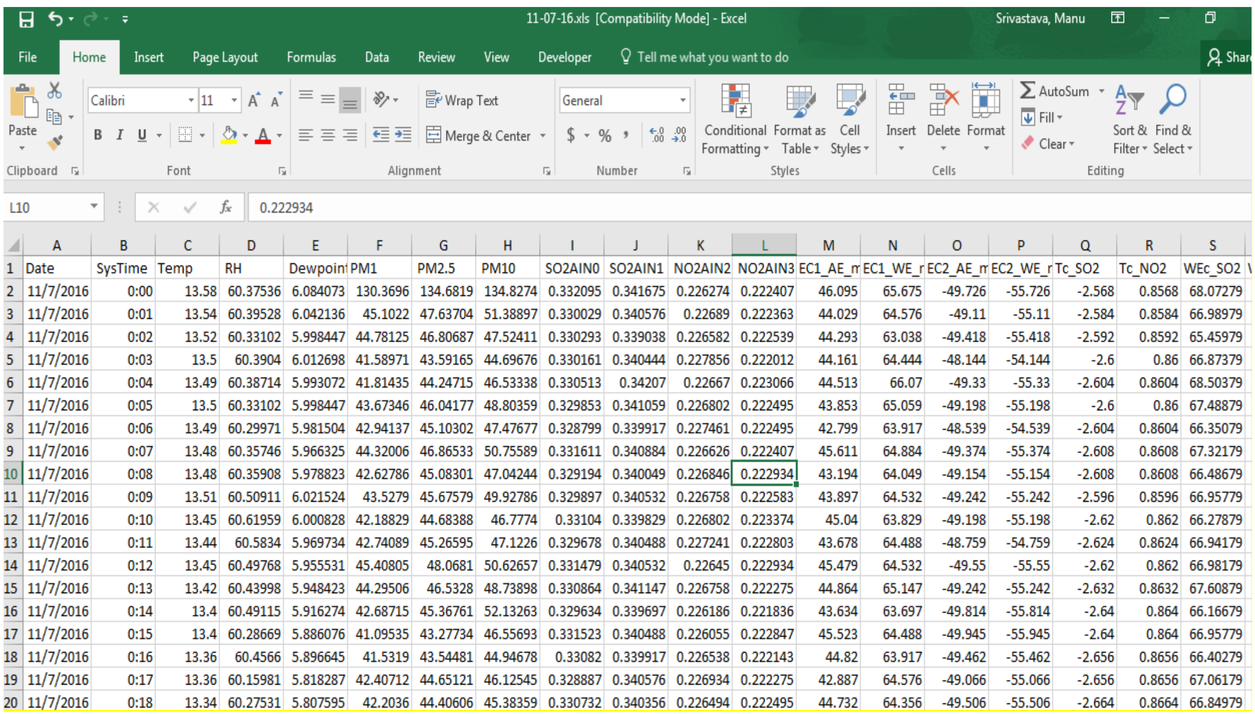
2.4 Data Processing

Data were processed following each weekly download using software programs (executables) provided by the UNEP. Initially, these software applications were used as received without change. As reported later in this document (see Appendix), corrections were made to one of the scripts to overcome a problem we observed. The two executables consisted of Merge_CSV.cmd and Gas_ppb.xlsm.

The Merge.CSV executable needed to be run once for each sampling day. The resulting file combined 24 individual hourly files into a single 24-hour daily file called "combined.csv". The hourly files as well as the combined.csv file contained raw sensor data. In the case of PM, these files contained the binned distribution of PM, which is the generic output of the OPC-N2. In brief, the data processing steps included the following:

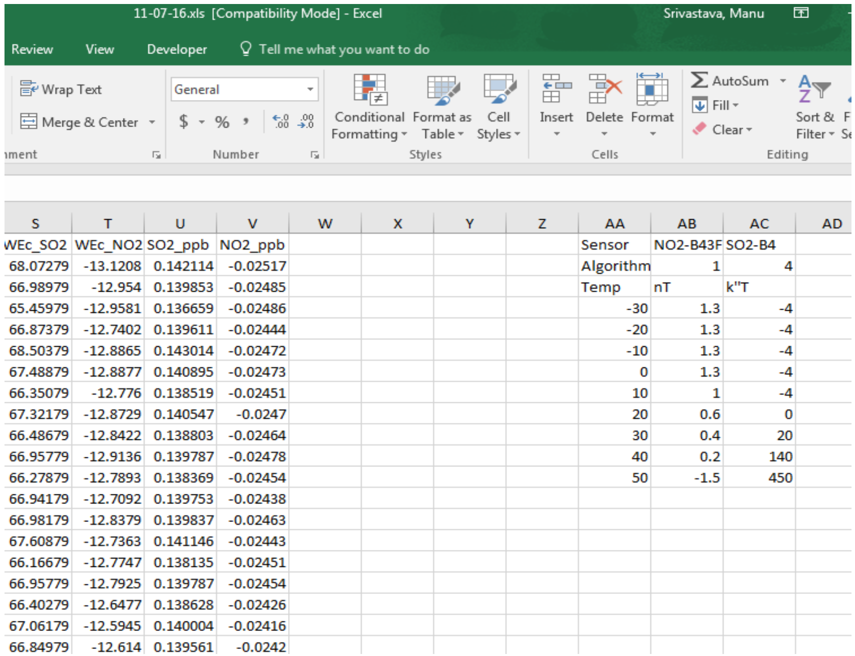
- Activating the Merge CSV.cmd application and then applying it to each hourly data set to yield a file called "Combined.csv".
- Saving the Combined.csv file as the <date>.xls (e.g. 11-07-16.xls) to give it date stamp recognition for record keeping.

The Excel macro Gas_ppb.xlsm was then executed on the <date>.xls file. This macro converted all sensor voltage data into concentration data. An example of excerpts from the raw and processed files for the date 11-07-16 are provided in Figure 5 and is continued in Figure 5a (for viewing purposes).



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	Date	SysTime	Temp	RH	Dewpoint	PM1	PM2.5	PM10	SO2AIN0	SO2AIN1	NO2AIN2	NO2AIN3	EC1_AE_m	EC1_WE_r	EC2_AE_m	EC2_WE_r	Tc_SO2	Tc_NO2	WEc_SO2
2	11/7/2016	0:00	13.58	60.37536	6.084073	130.3696	134.6819	134.8274	0.332095	0.341675	0.226274	0.222407	46.095	65.675	-49.726	-55.726	-2.568	0.8568	68.07279
3	11/7/2016	0:01	13.54	60.39528	6.042136	45.1022	47.63704	51.38897	0.330029	0.340576	0.22689	0.222363	44.029	64.576	-49.11	-55.11	-2.584	0.8584	66.98979
4	11/7/2016	0:02	13.52	60.33102	5.998447	44.78125	46.80687	47.52411	0.330293	0.339038	0.226582	0.222539	44.293	63.038	-49.418	-55.418	-2.592	0.8592	65.45979
5	11/7/2016	0:03	13.5	60.3904	6.012698	41.58971	43.59165	44.69676	0.330161	0.340444	0.227856	0.222012	44.161	64.444	-48.144	-54.144	-2.6	0.86	66.87379
6	11/7/2016	0:04	13.49	60.38714	5.993072	41.81435	44.24715	46.53338	0.330513	0.34207	0.22667	0.223066	44.513	66.07	-49.33	-55.33	-2.604	0.8604	68.50379
7	11/7/2016	0:05	13.5	60.33102	5.998447	43.67346	46.04177	48.80359	0.329853	0.341059	0.226802	0.222495	43.853	65.059	-49.198	-55.198	-2.6	0.86	67.48879
8	11/7/2016	0:06	13.49	60.29971	5.981504	42.94137	45.10302	47.47677	0.328799	0.339917	0.227461	0.222495	42.799	63.917	-48.539	-54.539	-2.604	0.8604	66.35079
9	11/7/2016	0:07	13.48	60.35746	5.966325	44.32006	46.86533	50.75589	0.331611	0.340884	0.226626	0.222407	45.611	64.884	-49.374	-55.374	-2.608	0.8608	67.32179
10	11/7/2016	0:08	13.48	60.35908	5.978823	42.62786	45.08301	47.04244	0.329194	0.340049	0.226846	0.222934	43.194	64.049	-49.154	-55.154	-2.608	0.8608	66.48679
11	11/7/2016	0:09	13.51	60.50911	6.021524	43.5279	45.67579	49.92786	0.329897	0.340532	0.226758	0.222583	43.897	64.532	-49.242	-55.242	-2.596	0.8596	66.95779
12	11/7/2016	0:10	13.45	60.61959	6.000828	42.18829	44.68388	46.7774	0.33104	0.339829	0.226802	0.223374	45.04	63.829	-49.198	-55.198	-2.62	0.862	66.27879
13	11/7/2016	0:11	13.44	60.5834	5.969734	42.74089	45.26595	47.1226	0.329678	0.340488	0.227241	0.222803	43.678	64.488	-48.759	-54.759	-2.624	0.8624	66.94179
14	11/7/2016	0:12	13.45	60.49768	5.955531	45.40805	48.0681	50.62657	0.331479	0.340532	0.22645	0.222934	45.479	64.532	-49.55	-55.55	-2.62	0.862	66.98179
15	11/7/2016	0:13	13.42	60.43998	5.948423	44.29506	46.5328	48.73898	0.330864	0.341147	0.226758	0.222275	44.864	65.147	-49.242	-55.242	-2.632	0.8632	67.60879
16	11/7/2016	0:14	13.4	60.49115	5.916274	42.68715	45.36761	52.13263	0.329634	0.339697	0.226186	0.221836	43.634	63.697	-49.814	-55.814	-2.64	0.864	66.16679
17	11/7/2016	0:15	13.4	60.28669	5.886076	41.09535	43.27734	46.55693	0.331523	0.340488	0.226055	0.222847	45.523	64.488	-49.945	-55.945	-2.64	0.864	66.95779
18	11/7/2016	0:16	13.36	60.4566	5.896645	41.5319	43.54481	44.94678	0.33082	0.339917	0.226538	0.222143	44.82	63.917	-49.462	-55.462	-2.656	0.8656	66.40279
19	11/7/2016	0:17	13.36	60.15981	5.818287	42.40712	44.65121	46.12545	0.328887	0.340576	0.226934	0.222275	42.887	64.576	-49.066	-55.066	-2.656	0.8656	67.06179
20	11/7/2016	0:18	13.34	60.27531	5.807595	42.2036	44.40606	45.38359	0.330732	0.340356	0.226494	0.222495	44.732	64.356	-49.506	-55.506	-2.664	0.8664	66.84979

Figure 5. Example of processed file



S	T	U	V	W	X	Y	Z	AA	AB	AC	AD
WEc_SO2	WEc_NO2	SO2_ppb	NO2_ppb					Sensor	NO2-B43F	SO2-B4	
68.07279	-13.1208	0.142114	-0.02517					Algorithm	1	4	
66.98979	-12.954	0.139853	-0.02485					Temp	nT	k''T	
65.45979	-12.9581	0.136659	-0.02486					-30	1.3	-4	
66.87379	-12.7402	0.139611	-0.02444					-20	1.3	-4	
68.50379	-12.8865	0.143014	-0.02472					-10	1.3	-4	
67.48879	-12.8877	0.140895	-0.02473					0	1.3	-4	
66.35079	-12.776	0.138519	-0.02451					10	1	-4	
67.32179	-12.8729	0.140547	-0.0247					20	0.6	0	
66.48679	-12.8422	0.138803	-0.02464					30	0.4	20	
66.95779	-12.9136	0.139787	-0.02478					40	0.2	140	
66.27879	-12.7893	0.138369	-0.02454					50	-1.5	450	
66.94179	-12.7092	0.139753	-0.02438								
66.98179	-12.8379	0.139837	-0.02463								
67.60879	-12.7363	0.141146	-0.02443								
66.16679	-12.7747	0.138135	-0.02451								
66.95779	-12.7925	0.139787	-0.02454								
66.40279	-12.6477	0.138628	-0.02426								
67.06179	-12.5945	0.140004	-0.02416								
66.84979	-12.614	0.139561	-0.0242								

Figure 5a. Example of processed file (continued)

2.5 Data Processing Observations

Data from the UNEP pod were recovered and processed on a weekly basis. The US EPA believed that the UNEP pod was operating nominally as the study effort continued. That is, data were being logged, given time/date stamps, and stored in specific storage registers that were specific to each hour of the collection period. The US EPA performed a cursory review of each week's data to ensure that the pod was operational and that data were being logged. Raw data was not extensively examined for completeness or quality assurance purposes on a weekly basis.

When all data collections were complete, the US EPA initiated a thorough review of all raw 1-hour data records, as well as the Combined.csv files produced from the application of the Merge_CSV.cmd file and the Excel files produced from the application of the Gas_ppb.xls macro. During this review of the full data record, the US EPA discovered that some data records corresponded to the wrong month. The problem occurred at the time when data collection moved into a new month. It initially appeared that data records were being assigned a date stamp corresponding to the previous month (November) rather than the current month (December). This raised concern that data were being overwritten, but further inspection revealed that the previous month's data record was being retrieved in addition to the current month's data when data were collected for the same date of each month (Appendix Figure A8). It appears that the data retrieval script and procedure is not specific enough to handle two different months. The directory structure assumes all data are collected in a single calendar month, so no monthly identification is specified. This problem affected all December data that had days of the month that matched those in the November data set. The US EPA suspended sampling early in December, but it is suspected that all the December data would have suffered this same re-reporting of the earlier month's data.

The same problem was observed in one of the November data downloads, wherein a few data points from September were included with the November data with the same dates, even though the US EPA did not record any data in September (Appendix Figure A9). These data looked very different from the November and December data and are likely data recorded by UNEP prior to this study that were still retained in the processor's memory.

During the collection period, the UNEP pod was not restarted and no data were deleted. However, restarting the UNEP pod (powering on/off) as well as conducting a routine (scheduled) data file deletion effort might not be the best approach to address the issue of re-reported data. The best way to address the problem might be to revise the data download code and procedures to eliminate the issue for future applications. The data directory structure in which the data are stored needs to have separate subdirectories created for each month. The collection days (1-31) would then be listed as subdirectories under each month. The directory structure currently has no such monthly designations.

2.6 US EPA Quality Assurance Review and Application

As previously stated, US EPA conducted an intensive review of the raw and processed data following the conclusion of data collection. Collocated reference monitoring data were reviewed by US EPA for compliance with the QAPP requirements of the AIRS test platform and then used without variation to yield a comparison database into which the UNEP pod data was integrated. The UNEP pod recorded raw data every minute, whereas some of the reference monitors, (e.g., the GRIMM monitor), recorded data every 5 minutes. Therefore, the first order of processing was to develop the means (steps) to allow for appropriate (matched) time intervals to be examined for comparison. Data were excluded/manipulated in some fashion if they met any of the following criteria:

- The data from the 15-minute period before and after the weekly servicing visit from the US EPA staff were excluded. Such disruptions have been shown to influence local air quality associated with particle resuspension near the monitor intake (such as would be the case here with the UNEP pod).
- Data collected during the weekly automated calibration of the reference monitors were excluded.
- Data spikes in the UNEP pod data record, indicative of some systematic condition that occurred consistently at the top of each clock hour, were excluded. The causal agent for this UNEP pod artifact is unknown. An example of this artifact has been provided in the Appendix.
- An average was computed ONLY when valid data points were present at least 90% of the time.
    - To calculate 5-minute averages for the UNEP pod, 100% (five 1-minute data records) of the raw data must be valid.
    - To calculate 1-hour averages for the UNEP pod, > 54 1-minute data records must be valid.
    - To calculate 12-hour averages for the UNEP pod, > 648 1-minute data records must be valid.

- To calculate 24-hour averages for the UNEP pod, > 1296 1-minute data records must be valid.

Additionally, while the UNEP pod never recorded an RH > 95%, an RH value known to often impact light scattering PM sensors, the ambient reference monitor recorded multiple instances of such events. To examine the impact of RH on UNEP pod PM response, UNEP pod PM data was parsed based upon the reference RH value > 95% and this subset of the data was investigated separately.

An automated executable macro was developed by the US EPA to ensure reliability in the matching of date/time stamp records from reference and UNEP pod data files. The automated process streamlined the full evaluation of the data to allow summary comparison at a wide variety of time integration values (e.g., 5-min, 1-hour). Visual highlights within the spreadsheet occurred when a data cell was empty, nonsensical (e.g., an alphanumeric instead of a value), or otherwise outside the quality assurance requirements. Ultimately, processed and validated data from both the AIRS reference and UNEP pod were integrated into a single electronic spreadsheet having a matched date/time stamp, as shown in Figure 6.

	A	B	C	D	E	F	G	H	I	J
1	UN Pod Avg. Date Time	UN Pod Temp C°	UN Pod RH %	UN Pod PM2.5 ug/m3	UN Pod PM10 ug/m3	REF Avg. Date Time	Grimm PM2.5 ug/m3	Grimm PM10 ug/m3	3m Temp C°	3m RH %
2	11/5/2016 0:00	22.52927157	49.07473626	70.35744451	78.6262086	11/5/16 0:00	9.007638889	11.58159722	15.68854167	71.42014
3	11/6/2016 0:00	17.67168198	47.90261947	63.74783816	66.47208909	11/6/16 0:00	6.455902778	8.147916667	10.03541667	74.85417
4	11/7/2016 0:00	18.49595053	47.360514	20.94406669	22.43103369	11/7/16 0:00	7.523263889	9.16875	10.75381944	74.65972
5	11/8/2016 0:00	16.98269258	46.02917471	18.42235046	20.12195629	11/8/16 0:00	5.184375	7.092708333	9.477083333	71.52431
6	11/9/2016 0:00	17.07373759	47.96910923	14.07029948	16.12286472	11/9/16 0:00	6.299652778	8.829861111	9.717013889	74.77431
7	11/10/2016 0:00	18.3130318	48.88996596	33.60964343	36.78001317	11/10/16 0:00	13.42951389	16.48229167	12.07291667	70.66667
8	11/11/2016 0:00	16.96827187	42.39615831	13.72703035	14.88755125	11/11/16 0:00	3.855208333	5.160416667	9.634027778	64.19097
9	11/12/2016 0:00	18.23010601	41.50084177	13.176741	16.07735437	11/12/16 0:00	8.873611111	13.32222222	11.159375	62.30208
10	11/13/2016 0:00	14.58621641	39.27744409	17.24384407	18.18480618	11/13/16 0:00	3.75	5.097569444	7.239583333	59.375
11	11/14/2016 0:00	14.00221908	41.16772463	25.02966162	26.02558612	11/14/16 0:00	8.156944444	9.404861111	6.310416667	64.65278
12	11/15/2016 0:00	15.81930035	62.70180348	44.81773015	48.00633315	11/15/16 0:00	12.80243056	14.72743056	9.169791667	95.05208
13	11/16/2016 0:00	16.8734417	50.86475816	27.37748779	34.61061959	11/16/16 0:00	21.81041667	25.925	8.994444444	81.72569
14	11/17/2016 0:00	17.11023355	49.71860786	21.13192672	23.92399093	11/17/16 0:00	30.10798611	34.790625	9.422569444	78.89931
15	11/18/2016 0:00	17.99556277	48.67458025	20.94949515	24.22557573	11/18/16 0:00	20.84703833	26.05609756	10.3261324	76.72125
16	11/19/2016 0:00	19.80849965	49.76366254	21.53732865	25.17405311	11/19/16 0:00	49.05625	55.9125	11.97986111	78.91319
17	11/20/2016 0:00	17.73521555	45.08251185	17.69548552	21.27294927	11/20/16 0:00	29.37708333	34.09618056	11.95763889	64.22569
18	11/21/2016 0:00	11.67861484	30.12890683	8.114227407	8.886371557	11/21/16 0:00	5.976388889	7.488194444	5.288194444	42.22569
19	11/22/2016 0:00	10.57931449	34.79296253	4.163992966	4.782626181	11/22/16 0:00	5.628819444	7.177777778	3.622916667	52.57292
20	11/23/2016 0:00	11.19658657	34.96437915	14.32285934	15.07641929	11/23/16 0:00	5.816319444	7.876041667	3.490972222	54.80208
21	11/24/2016 0:00	12.64923355	39.95206245	9.766703933	11.63295591	11/24/16 0:00	13.52256944	19.75625	5.536805556	61.10417
22	11/25/2016 0:00	19.39796886	52.74904584	13.14829628	15.01945683	11/25/16 0:00	19.16076389	21.49131944	12.22083333	81.71528
23	11/26/2016 0:00	22.65170092	53.02681887	18.4163077	21.53278171	11/26/16 0:00	19.87777778	22.190625	15.23888889	81.81597
24	11/27/2016 0:00	16.99722261	39.82199648	23.46660613	24.51347688	11/27/16 0:00	10.32256944	11.09305556	10.44861111	56.35417
25	11/28/2016 0:00	11.85524752	43.75764888	16.38422544	16.71468377	11/28/16 0:00	8.335416667	8.765972222	3.873611111	70.94792
26	11/29/2016 0:00	13.81388693	50.22238105	17.16757034	19.34154303	11/29/16 0:00	12.77676056	15.84683099	7.379929577	75.40493
27	11/30/2016 0:00	23.82958304	59.73180544	15.53505001	27.85076851	11/30/16 0:00	8.643356643	10.38811189	18.85	80.18881
28										

Figure 6. Matched time stamp data for UNEP Pod and AIRS reference data

3.0 UNEP Pod Results and Discussion

The comparisons of $PM_{2.5}$, PM_{10}, RH, and temperature data measured by the UNEP pod and collocated AIRS reference monitors are reported here. As previously stated, while gas phase pollutants were measured during the evaluation, a comparison to reference monitoring data was not pursued. This comparison was not pursued because of a lack of reasonableness in the data with respect to observed reference monitoring concentrations over the course of the study. The UNEP has been provided raw data from its pod as well as reference monitoring data to allow them to further investigate gas phase sensor response. Some observations are noted in the Appendix, but no further discussion concerning gas phase sensor performance is available in this current report.

In this study, 1-minute data from the UNEP pod were averaged over various integration periods (e.g., 5-minute, 1-hour, 12-hour, and ultimately 24-hours) and then compared with the time/date stamp matched reference data. These comparisons included time series inspection as well as linear regression statistical analyses. Data associated with the monitoring period from 11/03/16 through 12/02/16 were available for these comparisons, with a total of 40264 1-minute records collected. Ultimately, a total of 39508 1-minute records was included following full execution of all QA requirements. This equated to a 98.0% 1-minute data inclusion rate available for statistical treatment. Examination of the impact of RH on pod performance resulted in a higher exclusion rate of the data, resulting in only 91.3% of the original data records being available for analysis.

Various parameters were theorized as having a potential impact on the response of the UNEP pod with respect to reporting PM mass concentrations. More specifically, the impact of both ambient RH and temperature were investigated and reported for both PM mass fractions.

3.1 RH Comparison

A linear relationship between the UNEP pod's measured RH data and the AIRS reference RH data was observed ($R^2 = 0.91$). The slope (m=0.61) in Figure 7 indicates that while there was a linear response, the UNEP pod significantly underreported the true ambient RH (by ~ 40%). The time series plot shown in Figure 8 clearly depicts this response issue. It should also be noted that the UNEP pod had a positive bias of ~ 3% (intercept of the linear equation). In the US EPA's previous experience, it is unusual for most commercially available RH sensors to deviate this far from the true value if they are performing correctly. It is theorized, in this case, that the RH sensor resides inside the encasement of the pod, and therefore the readings it provides might be impacted by non-ambient conditions. In other words, there might be a drying effect of the interior air space inside the encasement of the pod, effectively lowering the reported RH. Heat emanating from the internal sensors might be such a drying mechanism. An alternative explanation is that the RH sensor might be positioned in a less than favorable fashion within the pod (i.e., next to something warm) or its original calibration response algorithm was less than adequate. Removal of the sensor from the UNEP pod for testing under standalone conditions would be one means of examining this question.

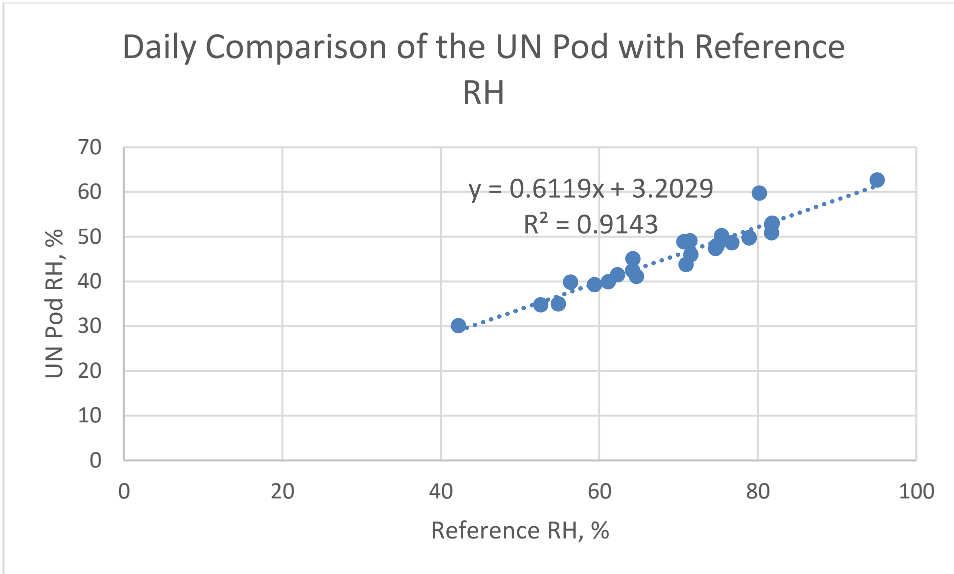


Figure 7. Linear Regression of the UNEP pod versus the AIRS reference RH

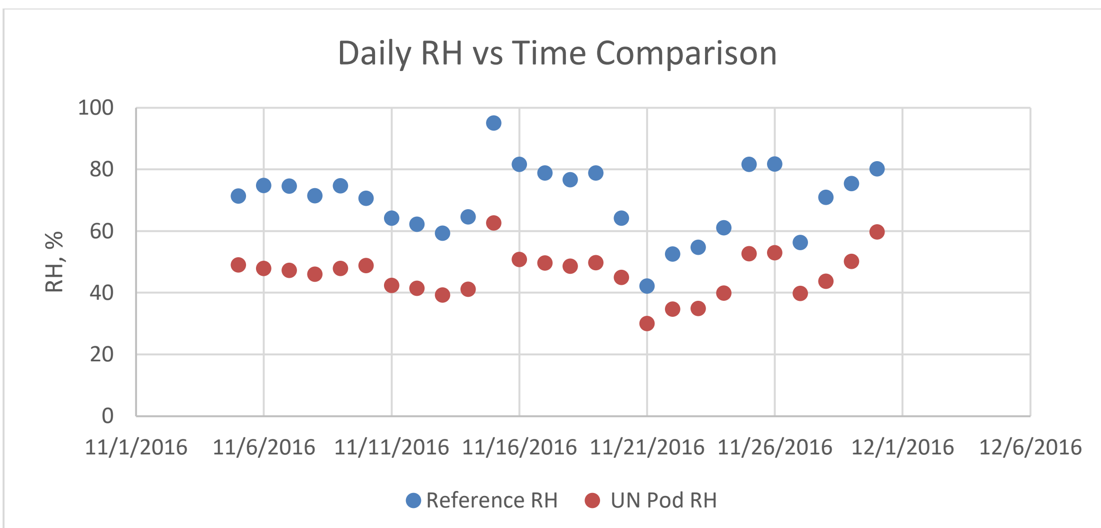


Figure 8. Time series showing the response offset of the UNEP pod versus the AIRS reference RH

It is important to have RH data that are accurate and coincide with other environmental measures. The US EPA has found optical-based PM low-cost sensors frequently to be highly sensitive to RH values exceeding 95% (Jiao, 2016). Sensors of these types often yield extremely biased (high) responses. Exclusion of sensor data above the 95% response inflection point has been shown to significantly improve performance comparisons versus reference monitors (Williams, 2014b). Therefore, the US EPA investigated the impact of RH relative to the $PM_{2.5}$ and PM_{10} responses to determine whether an additional quality assurance parameter needed to be included as part of the raw data exclusion criteria. True (ambient) RH data obtained from the collocated reference monitor were used in these investigations because of the clear underreporting of the UNEP pod's RH sensor. Time series comparison of ambient RH with respect to $PM_{2.5}$ and PM_{10} responses is shown in Figure 9. As can be seen, the RH and PM mass concentrations follow no clearly observable pattern.

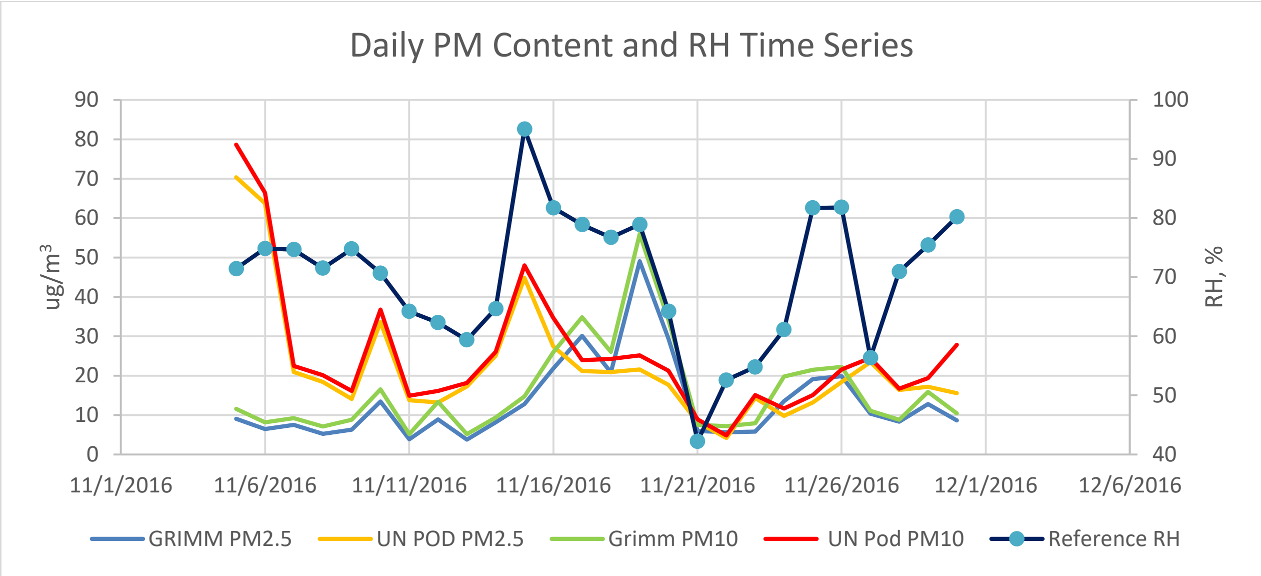


Figure 9. PM response relative to ambient RH conditions

Regression analysis of this same 24-hour average data set reveals a modest trend of an increasing UNEP Pod PM response with an increasing ambient RH, as shown in Figure 10. Even so, the regression outcome was not highly correlated sufficiently ($R^2 < 0.18$) to warrant data exclusion for this potential co-factor. Examination of shorter averaging time intervals (e.g., 5-minute, 1-hour) as reported in Table 1, and illustrated in Figures 11 and 12 using 1-hour average data, revealed even less statistical basis for RH exclusion.

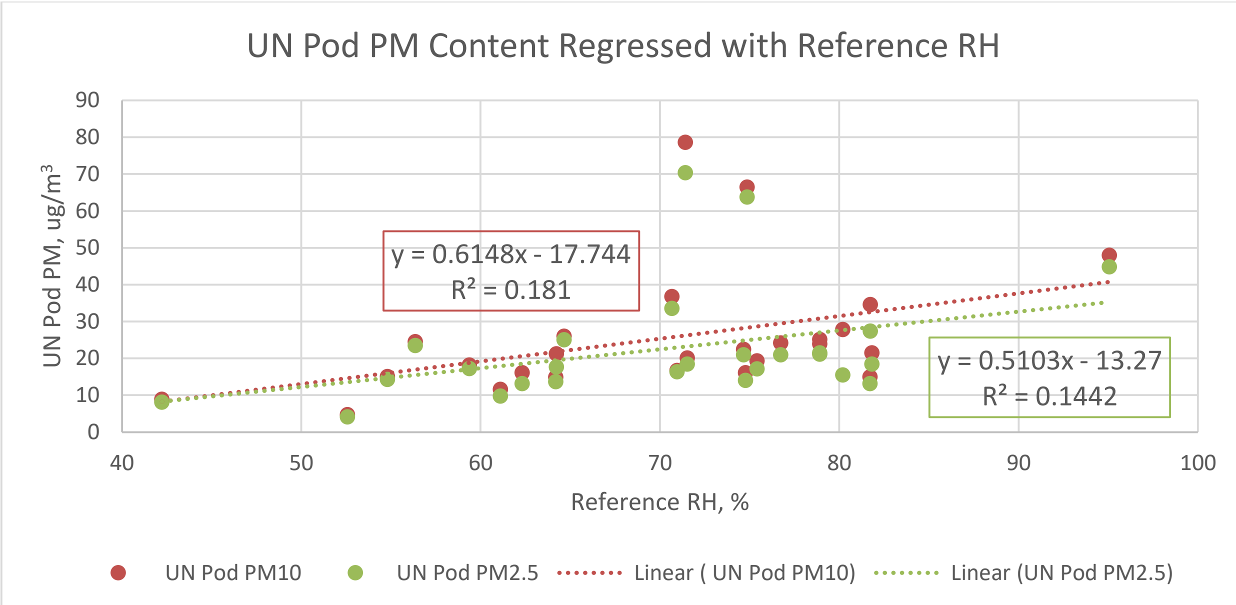


Figure 10. Regression of 24-hr average PM concentration from the UNEP pod versus reference RH

Table 1. Impact of applying > 95% RH exclusion criteria on the strength of the UNEP pod versus reference PM mass concentration comparison (reported as R^2 values) at various averaging times

Time Interval	**R^2 $PM_{2.5}$ vs Reference RH**	**R^2 PM_{10} vs Reference RH**
5 minutes	0.02	0.02
1 Hour	0.02	0.02
4 Hours	0.02	0.02
12 Hours	0.02	0.03
24 Hours	0.14	0.18

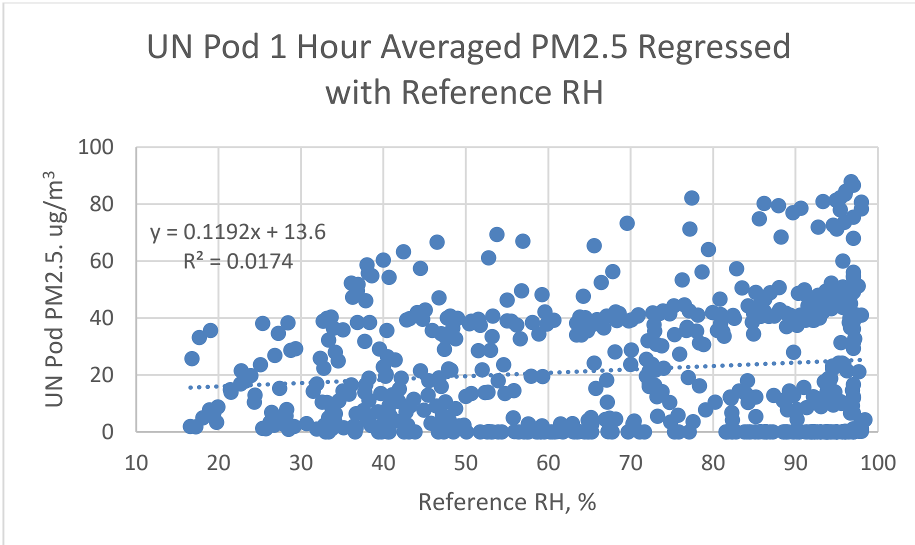


Figure 11. Regression of 1-hr average $PM_{2.5}$ concentration from the UNEP pod versus reference RH

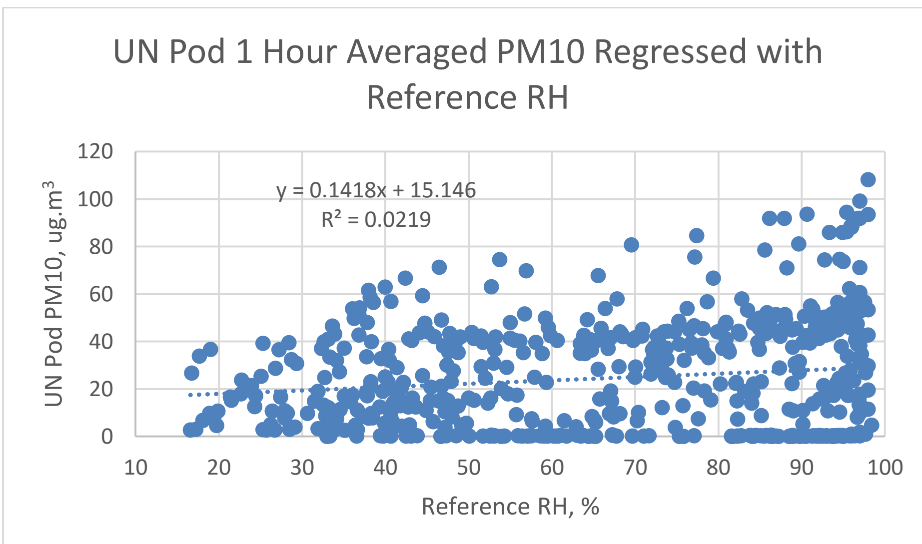


Figure 12. Regression of 1-hr average PM_{10} concentration from the UNEP pod versus reference RH

3.2 Temperature Comparison

Figure 13 shows a time series plot of temperatures measured by the UNEP pod and the ambient reference monitor. Regression of the comparison revealed excellent agreement between the UNEP pod's temperature sensor's response versus reference data, with an R^2 value > 0.96, as shown in Figure 14. Nevertheless, the sensor revealed a significant degree of positive bias (> 7 ^oC). We believe that it is likely that this bias is related to sensor being embedded within the encasement of the UNEP pod, therefore potentially being heated by its internal electronics. An alternative causality might be, as noted previously the manufacturer's calibration or the raw signal conversion algorithm developed for the sensor. As in the case of RH, the linear regression of $PM_{2.5}$ and PM_{10} versus the reference temperature, even on a 24-hour average basis, revealed no statistical association, as shown in Figure 15.

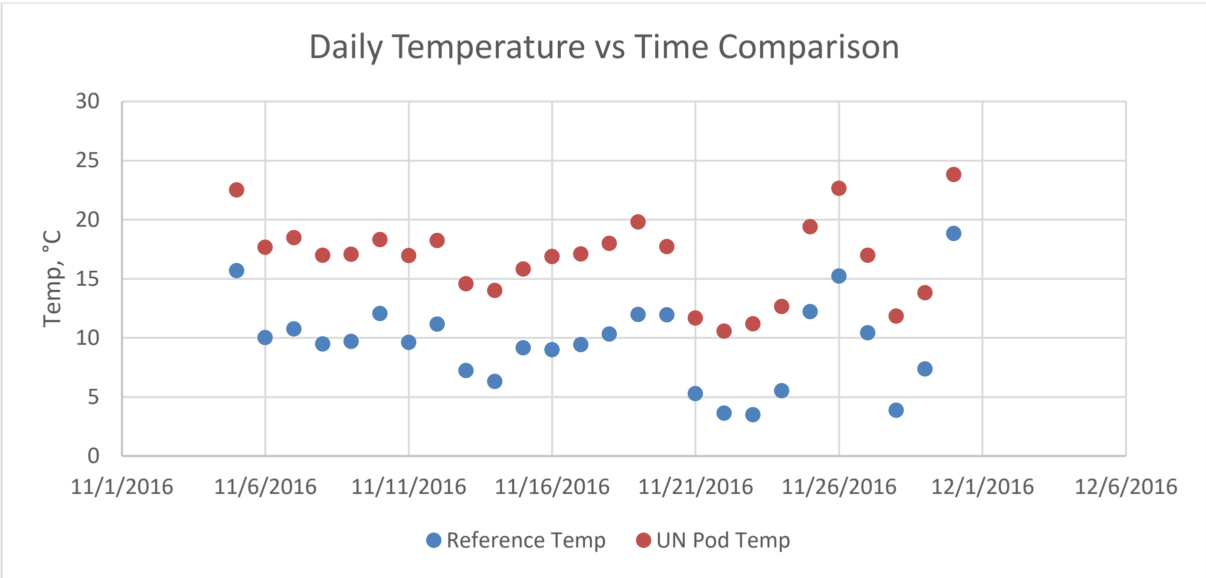


Figure 13. Time series comparison of UNEP pod versus AIRS reference temperature

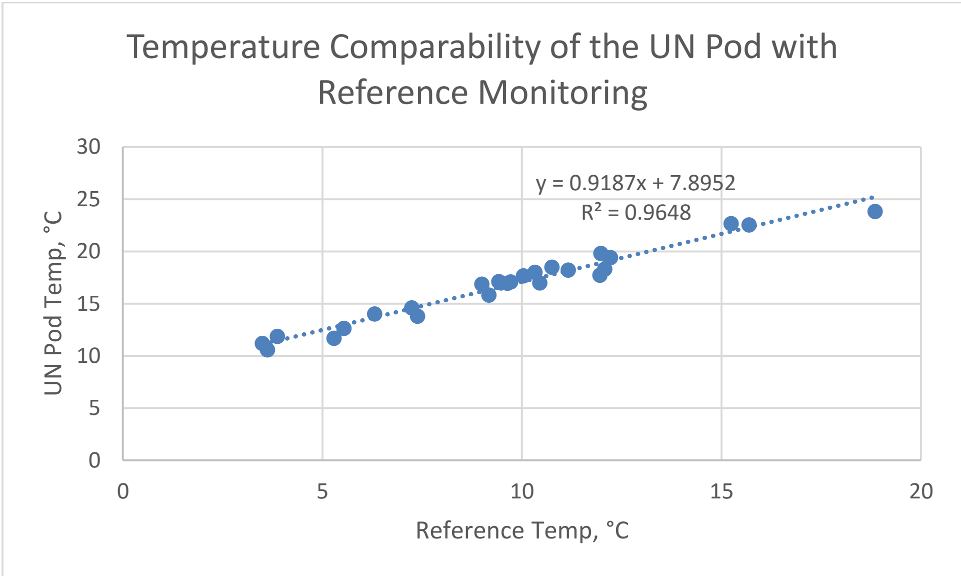


Figure 14. Regression of UNEP pod versus AIRS reference temperature

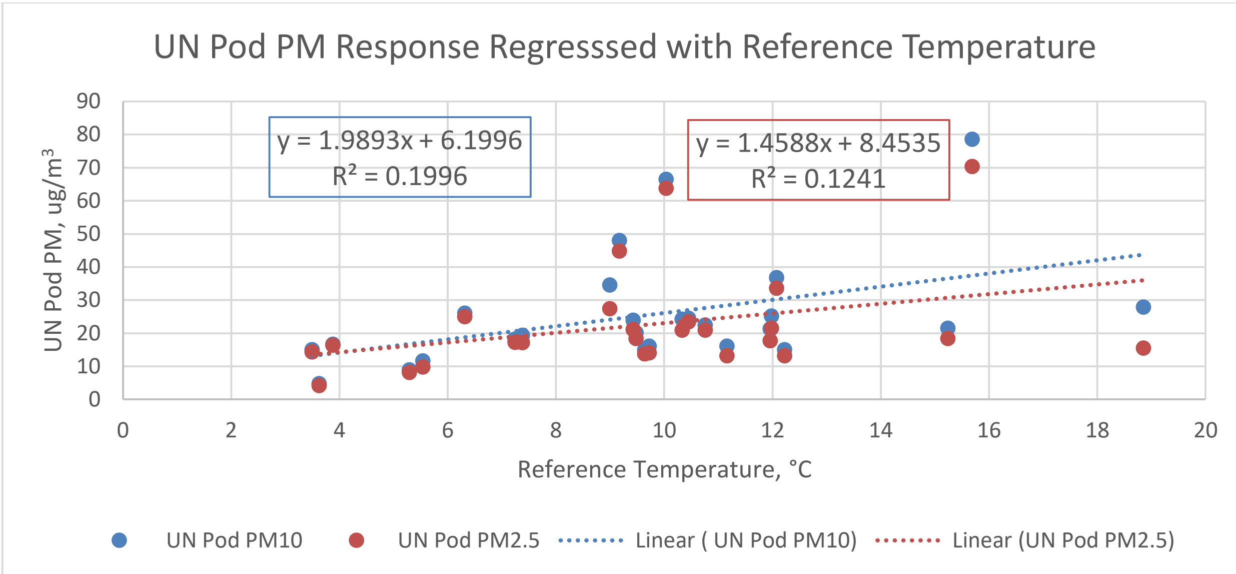


Figure 15. Regression of 24-hr average UNEP pod PM response versus reference temperature

3.3 PM Mass Concentration Comparisons

As stated in previous sections of this report, neither temperature nor relative humidity comparisons revealed any significant correlation association with the UNEP pod's PM response. Therefore, all data meeting the inclusion criteria discussed in Section 2.5 were incorporated into the comparisons reported herein, resulting in a very large data set of 1-minute measurements (39,508) available for statistical review. As reported in many US EPA examinations of sensor performance, longer averaging times (e.g., 24-hour average) typically result in improved statistical agreement between sensors and reference monitors (Jiao, 2016). This result is directly relatable to the general smoothing of data over the longer averaging times. However, the current report shares selected findings associated with shorter time intervals because many elements of the public sector attempt to use shorter periods of environmental monitoring (hours or even minutes) in conducting exposure assessments. Since PM_{10} and $PM_{2.5}$ are often highly related with respect to mass concentration trends, both mass concentrations are reported here in the general discussion of the UNEP pod's performance characteristics. In general, findings from both mass fractions resulted in the same pattern of UNEP pod response and performance characteristics. Figures 16 and 17 reveal 24-hour average time series trends associated with both mass fractions. There are periods in both mass fractions in which the UNEP pod either significantly over-reported or under-reported the true (ambient) mass concentration. In numerous instances, the mass concentration difference between the UNEP pod and reference monitor was more than 100%.

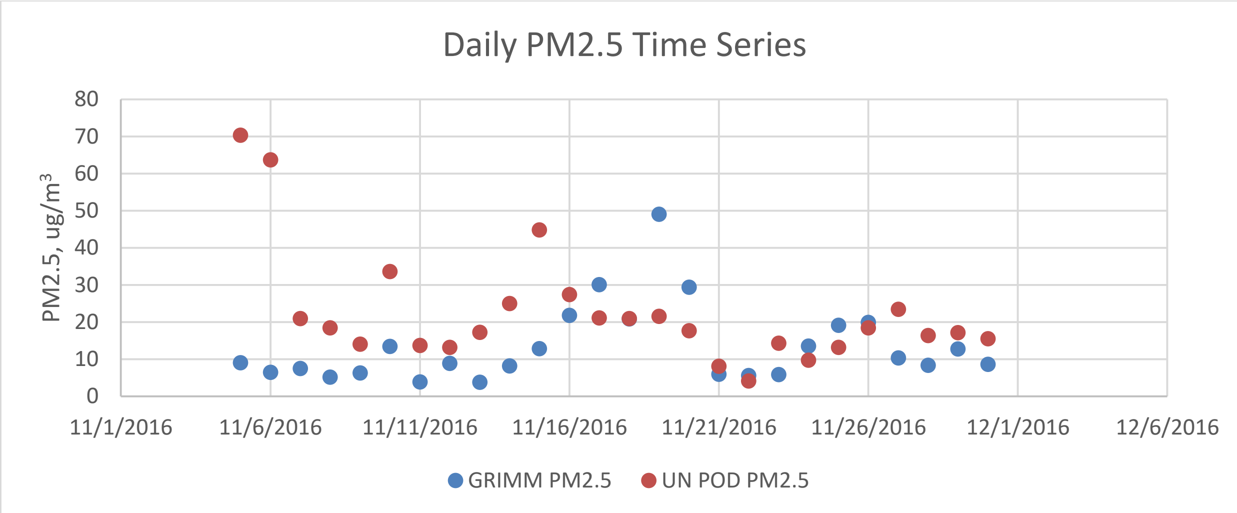


Figure 16. 24-hr average $PM_{2.5}$ concentration time series for the UNEP pod and AIRS reference monitor

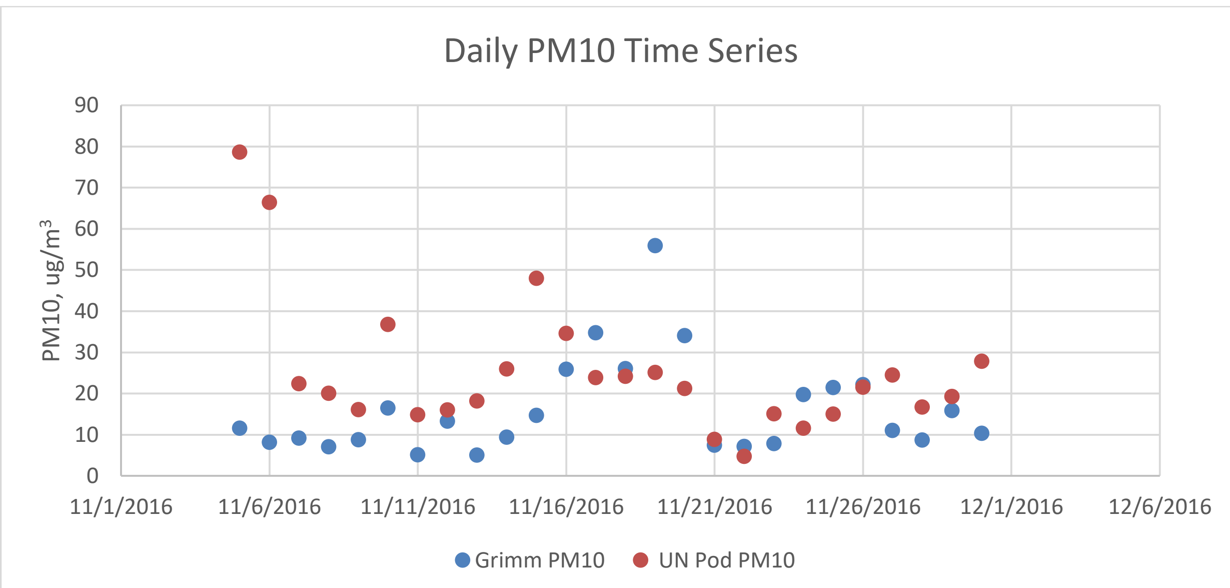


Figure 17. 24-hr average PM_{10} concentration time series for the UNEP pod and AIRS reference monitor

The 24-hour average regression comparisons for both size fractions, depicted in Figures 18 and 19, reveal no statistical association between the pod's response and collocated reference monitoring ($R^2 < 0.0002$). This lack of agreement would not be expected to be related to a sensitivity issue of the OPC-N2 based upon the manufacturer's specification data and the US EPA's own experience operating this same PM sensor (EPA, 2017a). Ambient concentrations often exceeded 15 µg/m^3, a value which should be easily detected with most optical particle sensors. Additionally, the AIRS experienced a multi-day episode characterized by transported windblown forest fire smoke during the evaluation that resulted in $PM_{2.5}$ concentrations exceeding 50 µg/m^3. It should be noted that the two $PM_{2.5}$ and PM_{10} data points > 60 µgm^3 observed on the first 2 days of the study warranted additional review, as they appeared to be potential outliers.

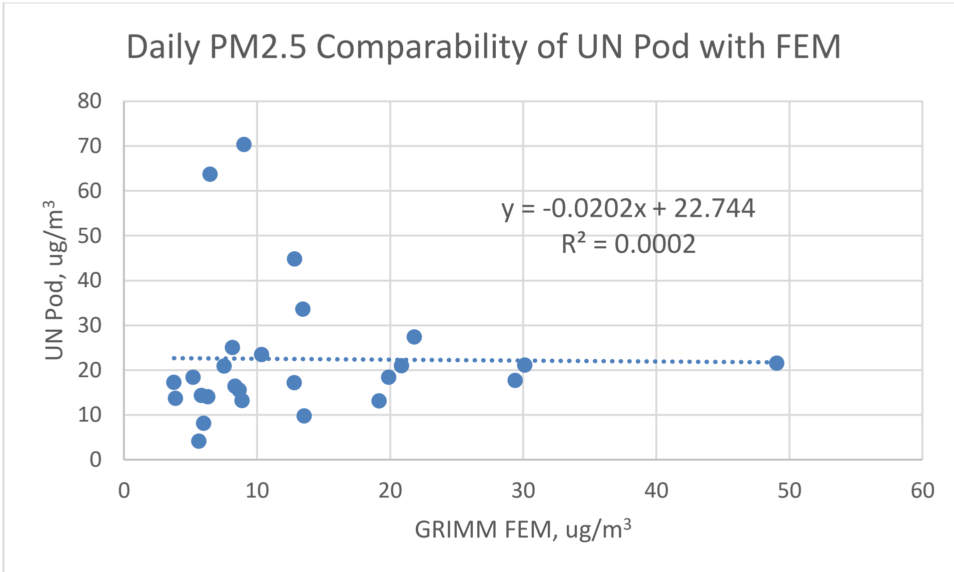


Figure 18. UNEP pod versus reference 24-hr average $PM_{2.5}$ concentration

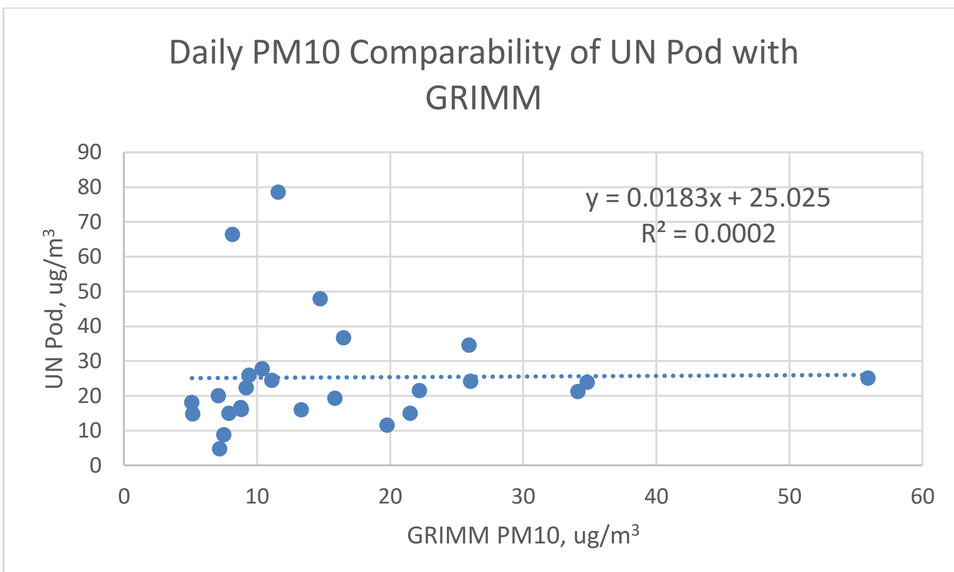


Figure 19. UNEP pod versus reference 24-hr average PM_{10} concentration

Figure 20 shows the 5-minute average data for the first half of the study only, to examine details of the pod's behavior in the first 2 days of data reporting compared to subsequent days, as well as to examine the relationship of the pod's PM to the reference RH. The pod's PM does appear to make a sudden shift early on 11/6/16, likely explaining the high 24-hour average concentrations in the first 2 days of the study. However, removal of these first 2 days of monitoring before the downward baseline shift had minimal impact on the daily pod response for both size fractions versus FEM comparisons ($R^2 < 0.07$).

Considering their relationship to RH, the PM concentrations of the pod appear generally to track ambient RH. The reason for the lack of correlation reported previously is the periodic drop in concentrations to zero or near zero, typically during or towards the end of high RH periods. Further review of these same time periods in which data were excluded when the pod's $PM_{2.5}$ response had fallen sharply to values between 0 and 5 µg/m^3 provided minimal improvement of the pod's correlation with the ambient FEM ($R^2 < 0.21$).

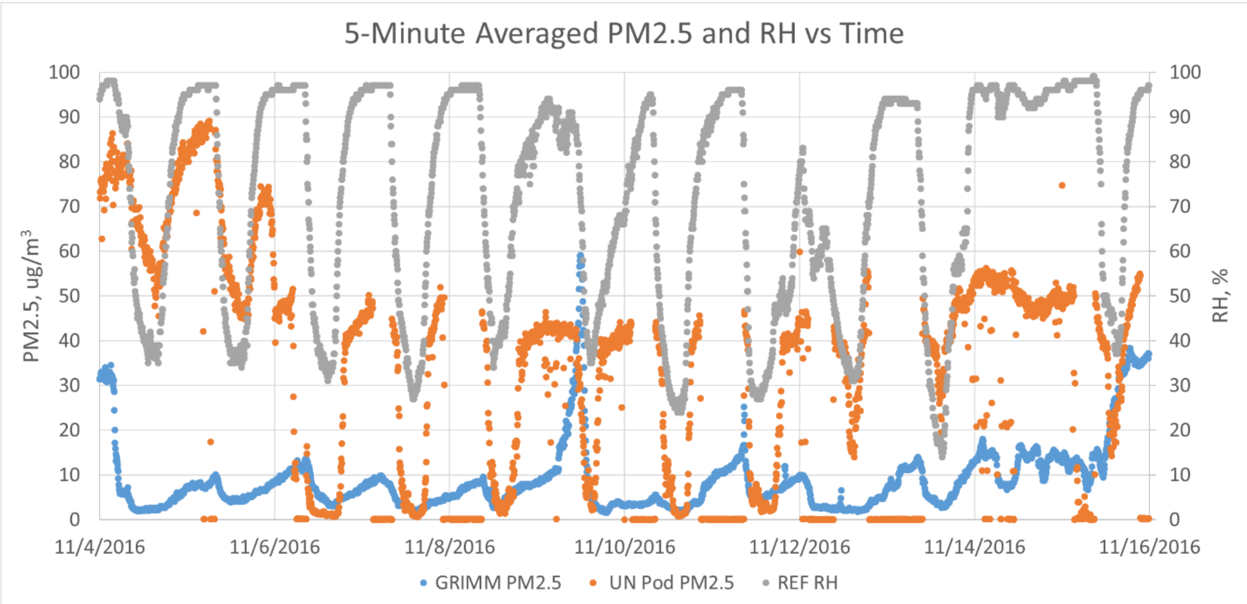


Figure 20. 5-minute UN EP pod response versus ambient RH at study onset

Regressions of 1-hour averages of UNEP pod concentrations versus reference PM concentrations are shown in Figures 21 and 22. As these two figures show, and as Table 2 reports, no observable association between the UNEP pod PM and the reference monitor PM existed for either mass fraction.

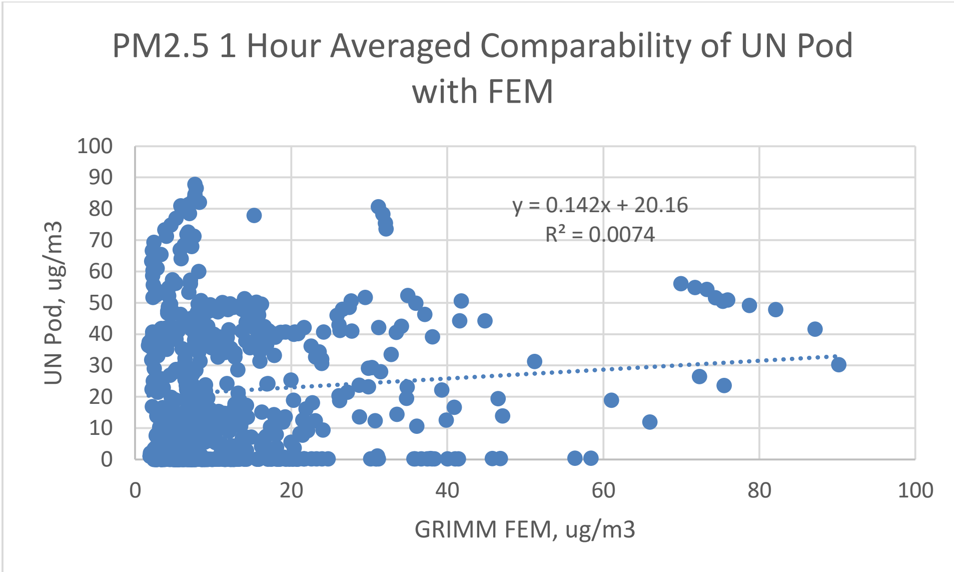


Figure 21. 1-hour average UNEP pod versus AIRS reference $PM_{2.5}$ concentration

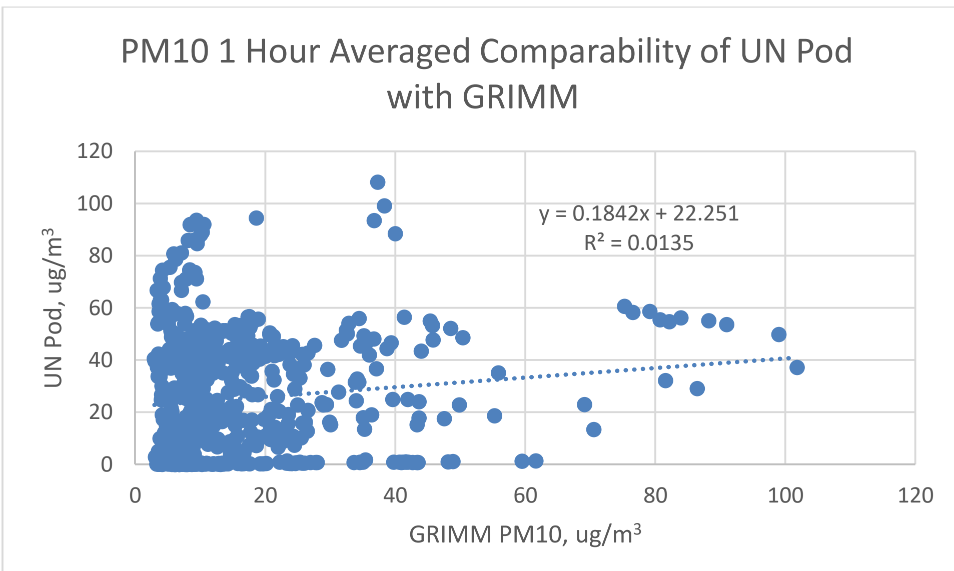


Figure 22. 1-hour average UNEP pod versus AIRS reference PM_{10} concentration

Table 2. Impact of averaging time on regression results comparing UNEP pod versus reference PM mass concentration

Time Interval	**UNEP $PM_{2.5}$ vs Reference $PM_{2.5}$**	**UNEP PM_{10} vs Reference PM_{10}**
5 minutes	$y = 0.15x + 20.05$; $R^2 = 0.008$	$y = 0.19x + 22.10$; $R^2 = 0.01$
1 Hour	$y = 0.14x + 20.16$; $R^2 = 0.007$	$y = 0.18x + 22.25$; $R^2 = 0.01$
4 Hours	$y = 0.13x + 20.49$; $R^2 = 0.007$	$y = 0.17x + 22.59$; $R^2 = 0.01$
12 Hours	$y = 0.09x + 21.09$; $R^2 = 0.004$	$y = 0.12x + 23.49$; $R^2 = 0.008$
24 Hours	$y = -0.02x + 22.74$; $R^2 = 0.0002$	$y = 0.02x + 25.03$; $R^2 = 0.0002$

4.0 Ease of Use Features and Concerns

4.1 Hardware

The US EPA found the UNEP pod to be of solid construction and robust relative to its ease of use once it was initialized (software acquisition and familiarity). The UNEP pod, in its normal state, is to be mounted on a vertical structure. The US EPA operated the UNEP pod with the primary encasement in a horizontal position, with the inlets to the sensors (presumed to be around the narrow edge) in a vertical orientation (see Figure 2). UNEP consultation concluded that this orientation would not obstruct the inlets.

It would have been beneficial for the US EPA, as an end user, to have had a greater understanding of the UNEP pod and its components available through the labeling of the UNEP pod encasement's parts. For example, defining the various inlets, fan housings, and other features either on the UNEP pod itself (preferred) or in the provided study materials (operating procedures) would have engendered greater confidence that all users could operate the device successfully. One could envision other operators orienting the device in such a manner that an inlet or other feature was hindered or impacted by its placement. Although the UNEP pod did have indicator lights reporting its base state of operation, an actual LED screen on the UNEP pod's face showing real-time data values would be beneficial for assuring basic operating status.

4.2 Data Processing

The UNEP pod was operated reliably, and data accessed successfully, with the exceptions previously noted about processing errors. Processing the data from its raw form into its final form was labor intensive. It would be valuable to other users if the developers could make the following design improvements:

- Incorporate automated processing using a script directly integrated into the microprocessor that takes the raw data and performs all the data transformations without operator involvement, allowing for the output file to be immediately useable. The US EPA has developed numerous pod systems for collecting both particulate matter and gas phase pollutants and such design features have proven to be extremely effective.
- Integrate a removable SD card. A removable SD card would allow processed data to be easily accessed from the UNEP pod in situations where cellular communication is not reliable or available.
- Consider solar power with back-up battery solutions. The current design requires access to land-based power supplies (e.g., 115 volt). It is doubtful that every remote location will have such a benefit. In the US EPA's experience, relatively small (18 inch by 18 inch) solar panels are sufficient to power a pod of this nature.

4.3 Study Limitations

Several important study design limitations need to be addressed relative to the observations reported in this effort. A primary concern is the fact that only a single UNEP pod was evaluated. The US EPA has observed in examining low-cost sensor performance that even when sensors are manufactured as part of the same bulk process, a wide range in performance can occur under various test scenarios (Jiao, 2016). Therefore, the poor association observed here with respect to the OPC-N2 response, as well as the unknown factor(s) impacting the gas phase sensors, might not be reflective of the UNEP pod's true performance if a larger number of pods had been evaluated.

Study resources limited the US EPA's ability to operate the UNEP pod for a longer period of time during the evaluation. The UNEP pod's response was examined under conditions nominal for the eastern U.S. geographical area during only a single seasonal period (fall). The site experienced a fairly narrow range of 24-hour average temperatures (typically between 3 to 20^{o}C), with some periods of extended precipitation (rainfall). Collectively, this suggests that evaluation of the UNEP pod under different climatic conditions might yield different results. Nevertheless, no statistical basis for either the RH or temperature to be a factor influencing the pod's PM performance was observed.

The Research Triangle Park area typically has ambient $PM_{2.5}$ mass concentrations well under 12 µg/m^3 (Williams, 2003). This location was selected not because it provided an expected wide range in day-to-day variability in PM mass concentrations but because of its convenience (the availability of US EPA staff and operating reference monitors). Tests conducted in a more challenging environment might have yielded improved performance. The US EPA has witnessed such improvements when PM sensors of the same type have been examined by other scientists conducting evaluations where historically higher ambient levels of PM mass concentrations have been reported (SCAQMD, 2017). Some low-cost PM sensors, such as the one examined here, might have improved performance at the higher end of their operating range as opposed to values at or near their lower detection limit. However, ambient concentrations observed during the study did reflect a major emissions plume that significantly impacted local air quality for some period of time (24-hour averages of $PM_{2.5}$ > 50 ug/m^3). Evaluation under even more extreme conditions, such as those that might exist in many developing countries, may have resulted in different performance characteristics.

The US EPA operated the pod using data recovery software developed by the UNEP specifically for this study due to telecommunication restrictions (data security requirements). As such, data were harvested weekly from the UNEP pod and then processed using executables provided. It is unknown if the UNEP pod, when used in its normal state (data transmission via a telecommunication service to a dedicated server with presumed automated data processing), might have had an impact upon data quality.

The internal components of the UNEP pod were not examined, as the US EPA purposefully tested the pod without any opportunity to negatively influence (damage) such components. It is unknown if all internal components worked as the UNEP desired. A failure of various components responsible for movement of air mass over or through the various sensor bodies could have occurred without our knowledge.

4.4 Conclusions

The US EPA's previous experience with low-cost sensor performance evaluations provided a context in which to draw conclusions concerning the UNEP pod and its overall capabilities to accurately estimate local environmental concentrations. The device was determined to be extremely stable relative to its operational status. It worked without failure with respect to collecting data for more than a 1-month period once it was initialized. The device appeared to be solidly constructed (external encasement) and, to US EPA knowledge, no failure of primary operating components (e.g., fans, electronic boards) occurred during the evaluation. The US EPA speculates that the RH and temperature sensors within the UNEP pod are being influenced by other electronic components, as observations indicate measurement values indicative of some systematic influencing factor. This might present a significant issue if RH exclusion criteria were ever applied to the data as a normal practice during UNEP pod operation.

5.0 References

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.

Alphasense Air. Particulates. c2013. http://www.alphasense.com/index.php/products/optical-particle-counter/, last accessed June 18, 2017.

Jiao, W., Hagler, G., Williams, R., Sharpe, B., Brown, R., Garver, D., Judge, R., Caudill, M., Richard, J., Davis, M., Weinstock, L., Zimmer-Dauphinee, S., Buckley, K. Community air sensor network (CAIRSENSE) project: Evaluation of low-cost sensor performance in a suburban environment in the southeastern United States. Atmospheric Measurement Technology, DOI:10.5194/amt-9-5281-2016.

Kaufman A., Brown A., Barzyk T., and Williams. R. 2014. The Citizen Science Toolbox: A One-Stop Resource for Air Sensor Technology. EM. 48-49.

South Coast Air Quality Management District (SCAQMD). 2017. Air Quality Sensor Performance Evaluation Center. http://www.aqmd.gov/aq-spec. Accessed June 18, 2017.

U.S. Environmental Protection Agency (EPA). 2014. Ambient Air Monitoring Reference and Equivalent Methods: Designation of Four New Equivalent Methods. *Federal Register*. 79: 34734-34735.

U.S. Environmental Protection Agency (EPA). 2017a. Air Sensor Toolbox for Citizen Scientists, Researchers and Developers. https://www.epa.gov/air-sensor-toolbox, last updated April 6, 2017; last accessed June 18, 2017.

U.S. Environmental Protection Agency (EPA). 2017b. Air Sensor Toolbox: Resources and Funding. Resources from the Air Quality Sensor Performance Evaluation Center. https://www.epa.gov/air-sensor-toolbox/air-sensor-toolbox-resources-and-funding#AQSPECenter, last updated April 6, 2017; last accessed June 18, 2017.

U.S. Environmental Protection Agency (EPA). 2017c. Air Sensor Toolbox: Resources and Funding. Resources from the European Commission Joint Research Centre. https://www.epa.gov/air-sensor-toolbox/air-sensor-toolbox-resources-and-funding#EUCommission, last updated April 6, 2017; last accessed June 18, 2017.

Williams, R., A. Kaufman, and S. Garvey. 2015a. Next Generation Air Monitoring (NGAM) VOC Sensor Evaluation Report. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-15/122 (NTIS PB2015-105133). https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=308114, last accessed June 18, 2017.

Williams, R., A. Kaufman, T. Hanley, J. Rice, and S. Garvey. 2015b. Evaluation of Elm and Speck Sensors. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-15/314. https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=310285, last accessed June 18, 2017.

Williams, R. 2014a. Findings from the 2013 EPA Air Sensors Workshop. EM. January: 5. https://www.epa.gov/sites/production/files/2015-06/documents/emmagazine.2013_air_sensors_wkshop.pdf. Accessed June 18, 2017.

Williams, R., A. Kaufman, T. Hanley, J. Rice, and S. Garvey. 2014b. Evaluation of Field-deployed Low Cost PM Sensors. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-14/464 (NTIS PB 2015-102104). https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=297517, last accessed June 18, 2017.

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. 2014c. Sensor Evaluation Report. U.S. Environmental Protection Agency, Washington,DC, EPA/600/R-14/143 (NTIS PB2015-100611), https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=277270, last accessed June 18, 2017.

Williams R., Watkins T., Long, R. 2014d. Low-Cost Sensor Calibration Options. EM. January: 10–15.

Williams, R., Suggs, J., Rea., A., Leovic, K., Vette, A., Croghan, C., Sheldon, L., Rodes, Thornburg, J., Ejire, A., Herbst, M., Williams Sanders Jr. 2003. The Research Triangle Park particulate matter panel study: PM mass concentration relationships. *Atmospheric Environment,* 37: 5349-5363.

6.0 Appendix

Data Harvesting and Processing Procedures

Before each data extraction, the current time on the BeagleBone was set by the study computer using PuTTY using the following command:

root@beaglebone:~# date

The results are provided in Figures A1-A5.

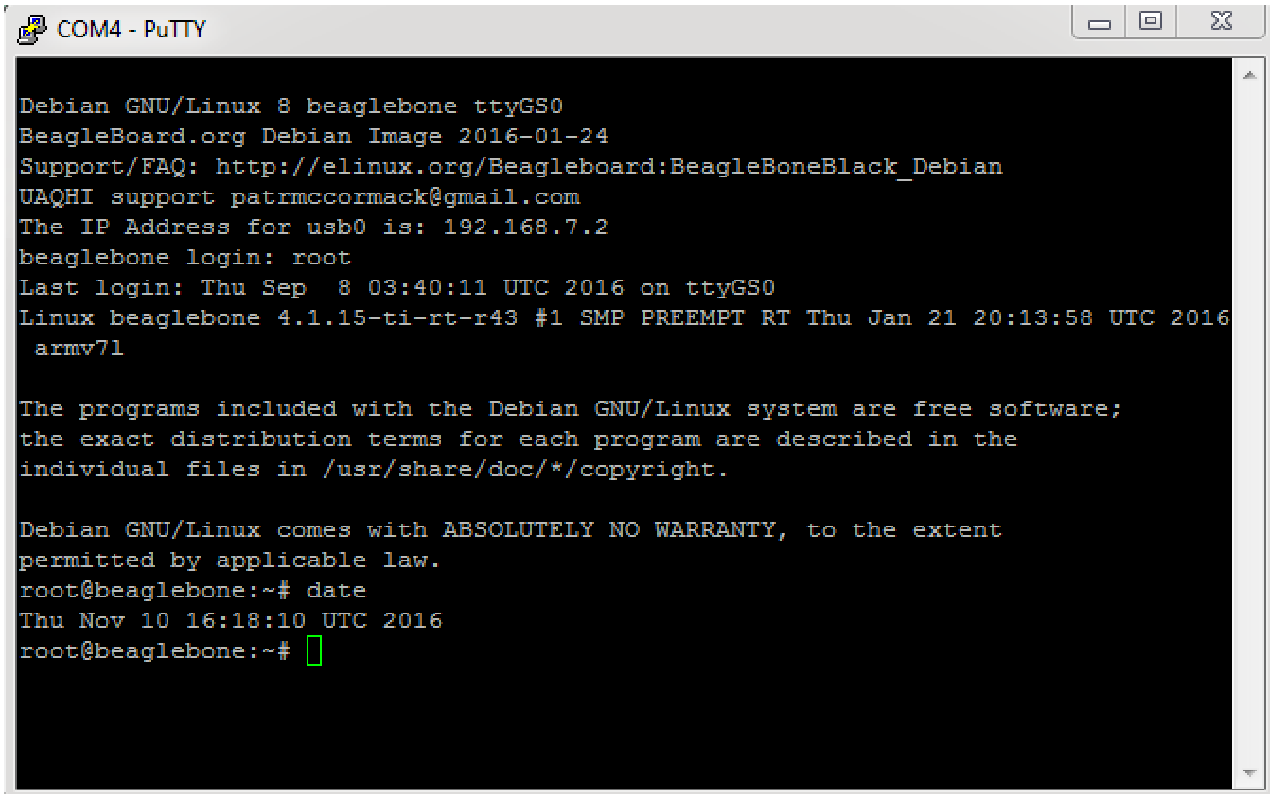


Figure A1. PuTTY command code.

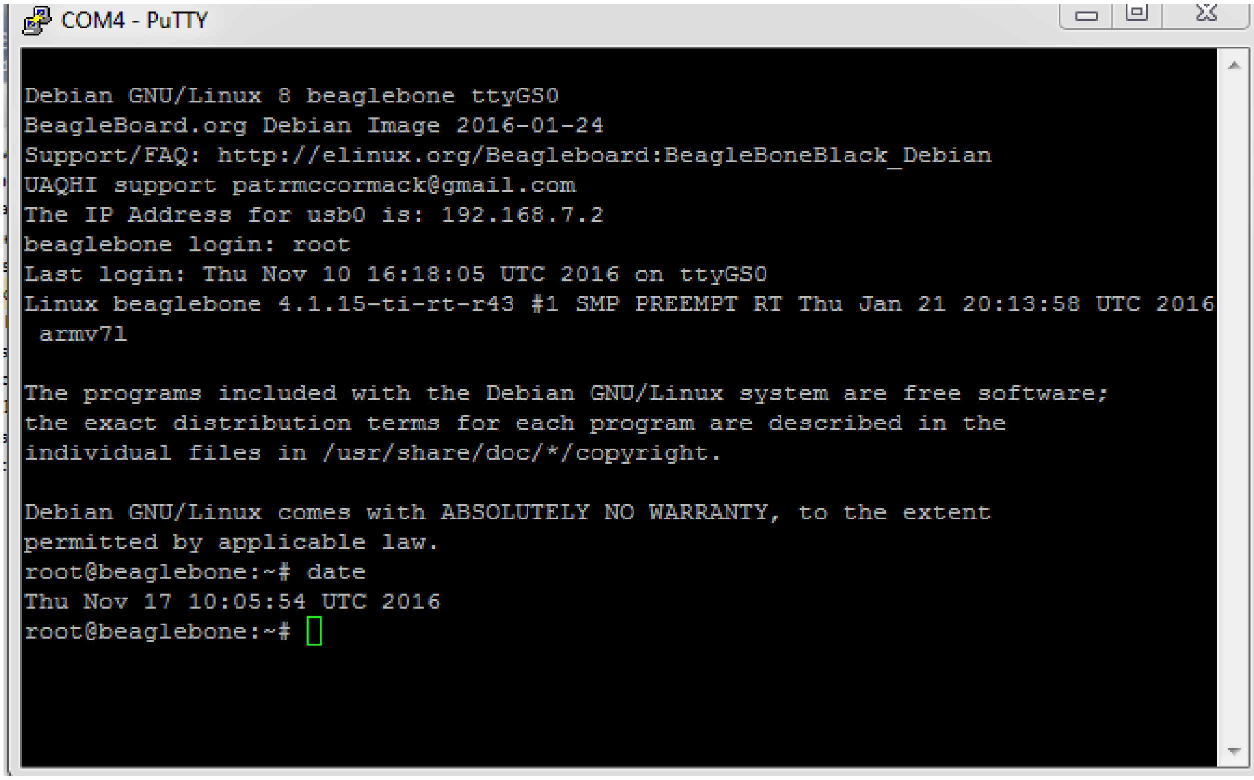


Figure A2. PuTTY command code (continued)

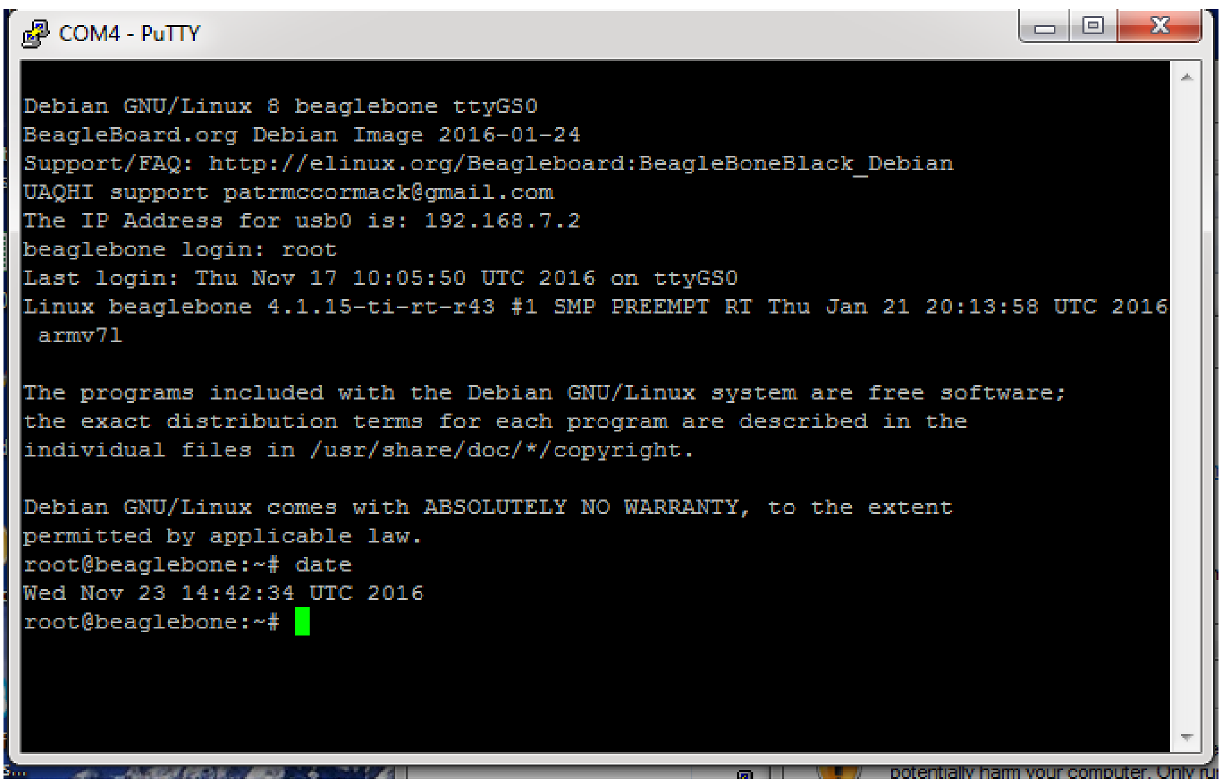


Figure A3. PuTTY command code (continued)

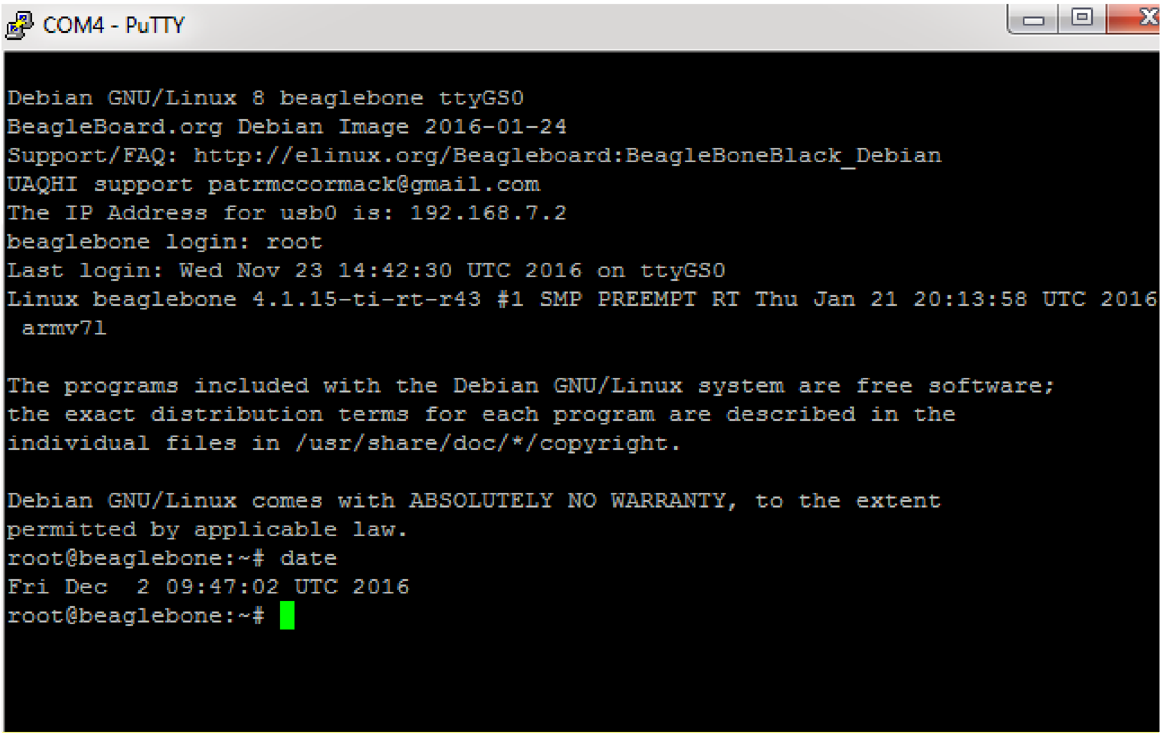


Figure A4. PuTTY command code (continued)

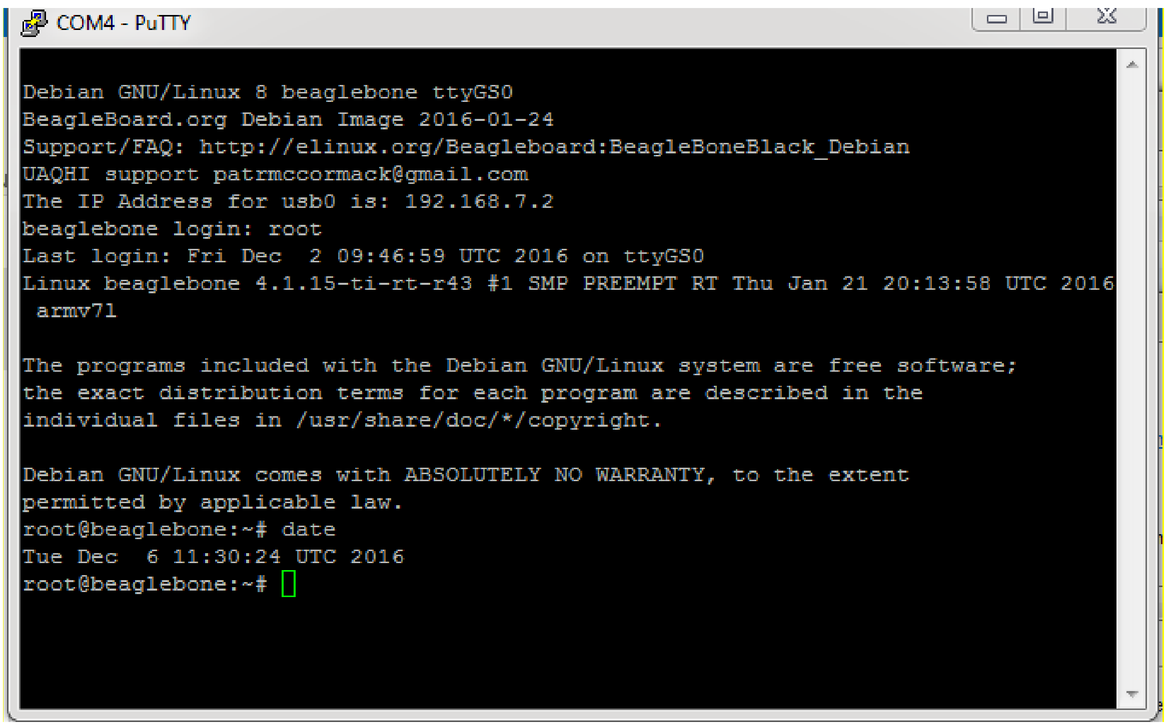


Figure A5. PuTTY command code (continued)

Data were extracted and archived ***weekly without restarting*** the UNEP pod using the following commands in the psftp console:

psftp> open

psftp> mget -r data

The data were copied into the windows folder that stores the psftp.exe file. Data were archived in a different folder to prevent other historical files from being amended during the data extraction process.

The directory structure after the final extraction on 12/06/16 is shown in Figure A6.

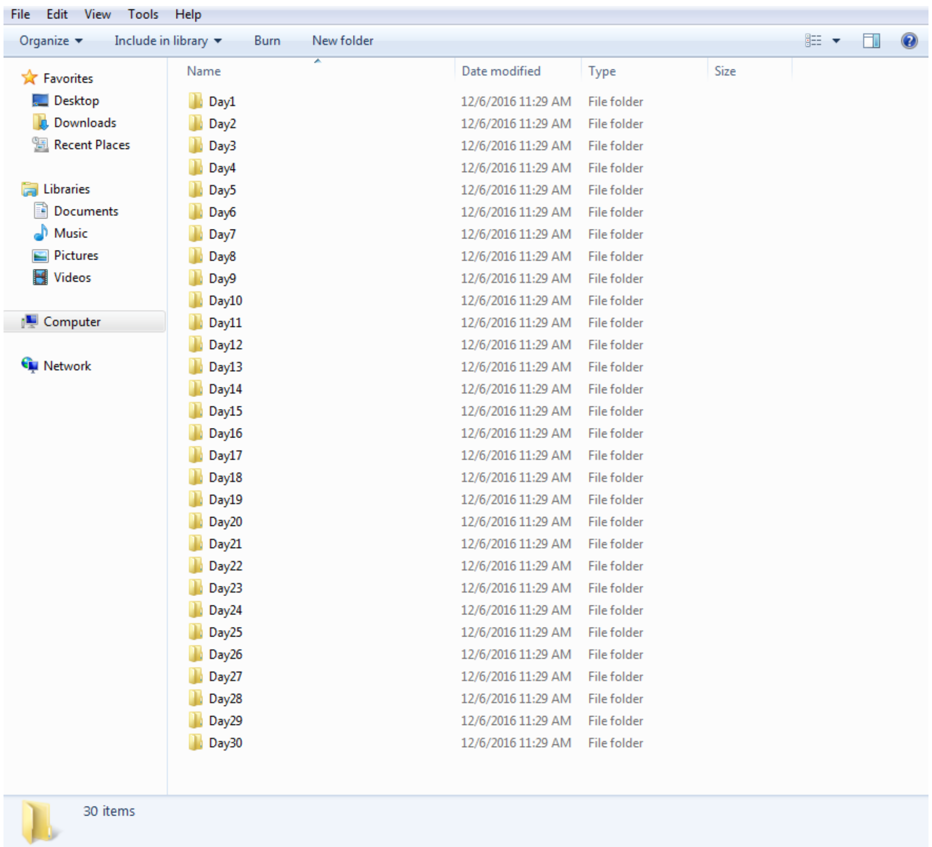


Figure A6. Example file directory

The directory structure did not provide for separate folders for each month, resulting in new data and data from the previous month (but same day of the month) being integrated together in the same file.

Inside these folders, raw hourly data were stored in separate files, as shown below in Figure A7.

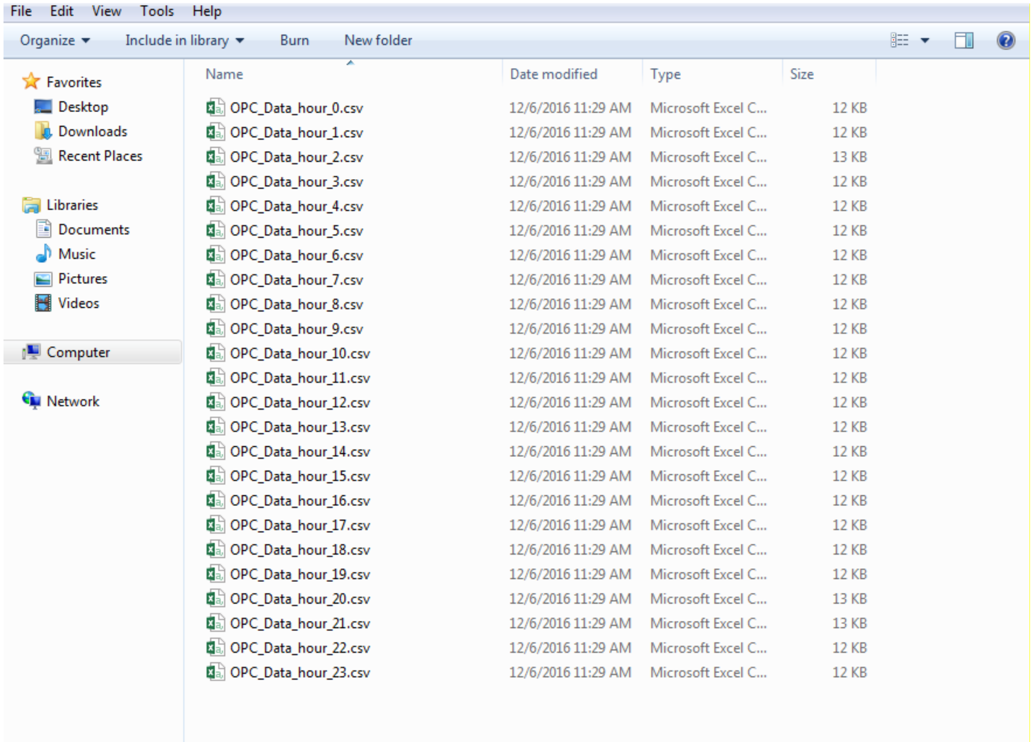


Figure A7. Example hourly data file directory

Data for Different Months in the Same File

Below are two examples in which data from a previous month's data collection are mixed in with data from the current month. Figure A8 shows that every other record is data from a previous month. Figure A9 shows only two records that are data from a previous month. The September data records are thought to be data previously collected by UNEP in testing the device that remained in the processor's memory.

	A	B	C	D	E	F	G	H	I	J	K	L
1	Date	SysTime	Temp	RH	Dewpoint	PM1	PM2.5	PM10	SO2AIN0	SO2AIN1	NO2AIN2	NO2AIN3
2	11/4/2016	0:00	25.01	61.09828	17.01777	327.5334	339.0214	339.2819	0.334687	0.341279	0.22478	0.223726
3	12/4/2016	0:00	13.16	43.13038	0.903038	42.19044	44.27616	45.51957	0.324053	0.338203	0.226802	0.222319
4	11/4/2016	0:01	24.95	61.30525	17.02604	65.873	72.86686	85.01807	0.334292	0.341894	0.226186	0.224165
5	12/4/2016	0:01	13.14	43.00455	0.863152	41.04337	43.12896	43.67744	0.324756	0.338027	0.227593	0.222363
6	11/4/2016	0:02	24.86	61.59757	17.00468	65.07874	72.48885	89.9003	0.33438	0.343125	0.226582	0.223154
7	12/4/2016	0:02	13.16	42.87984	0.812264	40.46441	42.524	44.49227	0.3248	0.338247	0.22645	0.2221
8	11/4/2016	0:03	24.87	61.59757	17.00468	64.61438	71.09325	83.72368	0.334204	0.341367	0.225659	0.223066
9	12/4/2016	0:03	13.12	42.9078	0.813018	41.92199	44.00334	45.63352	0.323701	0.335918	0.227153	0.221704
10	11/4/2016	0:04	24.86	61.59757	16.98502	64.66737	70.55445	78.01881	0.335303	0.342554	0.225703	0.223682
11	12/4/2016	0:04	13.12	42.93927	0.823202	40.95029	42.83891	43.51115	0.325415	0.340093	0.227593	0.221704
12	11/4/2016	0:05	24.84	61.68631	17.01056	65.65934	72.23067	86.68894	0.334512	0.340752	0.226582	0.223726
13	12/4/2016	0:05	13.12	43.06512	0.85371	39.75611	41.66798	42.81568	0.32647	0.339477	0.226802	0.223022
14	11/4/2016	0:06	24.83	61.77824	17.0341	66.14	72.62684	80.80582	0.334028	0.343301	0.226494	0.223682
15	12/4/2016	0:06	13.1	43.18738	0.856498	39.20398	40.97005	41.10087	0.324097	0.339082	0.227197	0.222231
16	11/4/2016	0:07	24.83	61.71695	17.00659	66.36286	72.77432	85.51762	0.334951	0.342114	0.225967	0.223813
17	12/4/2016	0:07	13.12	43.15948	0.874704	40.13837	42.27982	43.82177	0.326162	0.33895	0.22645	0.221836
18	11/4/2016	0:08	24.86	61.65888	17.03023	67.41539	74.00703	84.00356	0.33583	0.34185	0.227021	0.223594
19	12/4/2016	0:08	13.1	43.22	0.886179	41.20727	43.13165	44.69537	0.325283	0.33873	0.226494	0.222012
20	11/4/2016	0:09	24.87	61.65888	17.03023	67.05836	73.83238	82.07001	0.334468	0.341191	0.225923	0.223506
21	12/4/2016	0:09	13.11	43.18974	0.885511	41.79809	43.83794	44.35567	0.324228	0.337676	0.227109	0.2221
22	11/4/2016	0:10	24.84	61.77662	17.02227	66.27876	73.20253	85.45659	0.334556	0.341499	0.22645	0.224077
23	12/4/2016	0:10	13.1	43.15712	0.875389	39.59308	41.41007	41.91201	0.325547	0.338467	0.227153	0.221924
24	11/4/2016	0:11	24.8	61.98614	17.05733	66.57748	73.4444	84.45973	0.334204	0.34185	0.226186	0.223989
25	12/4/2016	0:11	13.1	43.21882	0.895626	40.3156	42.23076	44.47506	0.326206	0.339829	0.226186	0.222012

Figure A8. Example of suspected monthly data file reporting error

215	11/8/2016	3:33	8.82	60.30468	1.593058	0.001565	0.117049	0.412528	0.330249	0.33939	0.226011	0.222275	44.249	63.39	-49.989	-55.989	-4	1.0354	67.21979
216	11/8/2016	3:34	8.93	59.95524	1.620155	0.002529	0.112996	0.232267	0.330864	0.339785	0.225176	0.221792	44.864	63.785	-50.824	-56.824	-4	1.0321	67.61479
217	11/8/2016	3:35	8.83	60.49935	1.691278	0.002829	0.173538	0.528631	0.330908	0.339521	0.225308	0.221704	44.908	63.521	-50.692	-56.692	-4	1.0351	67.35079
218	11/8/2016	3:36	8.87	60.35985	1.62692	0.0003	0.060547	0.296379	0.331787	0.339477	0.224736	0.222451	45.787	63.477	-51.264	-57.264	-4	1.0339	67.30679
219	11/8/2016	3:37	8.82	60.38248	1.593058	0	0	0	0.329546	0.339346	0.225	0.222539	43.546	63.346	-51	-57	-4	1.0354	67.17579
220	11/8/2016	3:38	8.79	60.22974	1.540963	0.002829	0.173557	0.52869	0.330117	0.339961	0.225132	0.221924	44.117	63.961	-50.868	-56.868	-4	1.0363	67.79079
221	11/8/2016	3:39	8.8	60.64536	1.588297	0.0003	0.060546	0.296377	0.331611	0.340181	0.225615	0.221484	45.611	64.181	-50.385	-56.385	-4	1.036	68.01079
222	9/8/2016	3:40	29.94	42.21175	15.70961	430.1873	453.0135	465.6525	0.354375	0.355649	0.221748	0.219463	68.375	79.649	-54.252	-60.252	19.88	0.4012	59.59879
223	11/8/2016	3:40	8.86	60.00231	1.607291	0.001264	0.056495	0.116127	0.331919	0.339521	0.225615	0.222671	45.919	63.521	-50.385	-56.385	-4	1.0342	67.35079
224	9/8/2016	3:41	30.22	41.8752	15.81527	101.8284	112.3463	132.1761	0.347519	0.351474	0.22188	0.220825	61.519	75.474	-54.12	-60.12	22.64	0.3956	52.66379
225	11/8/2016	3:41	8.8	60.35985	1.567362	0.000368	0.105904	0.897723	0.331348	0.338423	0.224912	0.222539	45.348	62.423	-51.088	-57.088	-4	1.036	66.25279
226	11/8/2016	3:42	8.77	60.49604	1.613386	0.001933	0.222971	1.31038	0.329238	0.339873	0.225088	0.221792	43.238	63.873	-50.912	-56.912	-4	1.0369	67.70279
227	11/8/2016	3:43	8.79	60.25898	1.582724	0	0	0	0.329502	0.339038	0.224517	0.221528	43.502	63.038	-51.483	-57.483	-4	1.0363	66.86779
228	11/8/2016	3:44	8.74	60.03158	1.602361	0	0	0	0.329722	0.338467	0.225044	0.222803	43.722	62.467	-50.956	-56.956	-4	1.0378	66.29679
229	11/8/2016	3:45	8.78	60.18113	1.447417	0.001563	0.116947	0.412171	0.329634	0.338994	0.224648	0.222495	43.634	62.994	-51.352	-57.352	-4	1.0366	66.82379

Figure A9. Example of suspected monthly data file reporting error (continued)

Sensor Pod PM Sensor Spikes

As shown in Figures A10 and A11, anomalous spikes in $PM_{2.5}$ and PM_{10} concentrations occurred at the top of every hour (XX:00). These data were removed from the colocation correlation analysis.

57	11/4/2016	0:55	24.46	64.03549	74.7328	96.73585
58	11/4/2016	0:56	24.44	64.27158	74.11503	92.42737
59	11/4/2016	0:57	24.41	64.42154	74.59512	99.87106
60	11/4/2016	0:58	24.38	64.47373	76.1834	89.75808
61	11/4/2016	0:59	24.4	64.32382	74.45122	84.61952
62	11/4/2016	1:00	24.48	63.88361	324.6425	330.8294
63	11/4/2016	1:01	24.42	64.11649	73.111	83.18977
64	11/4/2016	1:02	24.38	64.32382	74.49226	97.53886
65	11/4/2016	1:03	24.38	64.32382	70.95723	73.54578
66	11/4/2016	1:04	24.38	64.38278	76.88055	89.86658
67	11/4/2016	1:05	24.38	64.35415	71.20496	89.90846

Figure A10. Anomalous concentration spikes

115	11/4/2016	1:53	24.02	65.68365	82.99122	119.5055
116	11/4/2016	1:54	24.06	65.56647	82.55427	109.7412
117	11/4/2016	1:55	24	65.8309	80.70968	103.0655
118	11/4/2016	1:56	24.01	65.68021	78.60008	91.88626
119	11/4/2016	1:57	24	65.74049	77.47578	96.93566
120	11/4/2016	1:58	23.99	65.79904	78.03426	98.67557
121	11/4/2016	1:59	24.05	65.56647	75.6331	85.33802
122	11/4/2016	2:00	24.04	65.68365	340.7785	343.8685
123	11/4/2016	2:01	24.1	65.36554	76.55142	105.2826
124	11/4/2016	2:02	24.04	65.56819	77.77175	88.68311
125	11/4/2016	2:03	24.09	65.45266	76.60575	83.38798
126	11/4/2016	2:04	24.1	65.27667	78.25141	92.45849
127	11/4/2016	2:05	24.1	65.30515	76.72618	90.39031
128	11/4/2016	2:06	24.13	65.10053	77.76107	88.47563
129	11/4/2016	2:07	24.15	65.04008	73.24411	84.04717
130	11/4/2016	2:08	24.06	65.4794	76.91001	85.59264

Figure A11. Anomalous concentration spikes (continued)

Repetition of Time Stamp

Same time stamps:

28762	11/23/2016	23:58	14.02	40.67147	0.142399	0.433776
28763	11/23/2016	23:59	13.96	41.36422	0.23844	0.772264
28764	11/24/2016	0:00	13.88	41.92297	0	0
28765	11/24/2016	0:02	13.87	42.1737	0.096044	0.338497
28766	11/24/2016	0:02	13.86	42.36333	0.192078	0.67696
28767	11/24/2016	0:03	13.87	42.33404	0.099361	0.486379
28768	11/24/2016	0:05	13.86	42.33288	0.096035	0.338467
28769	11/24/2016	0:06	13.87	42.13978	0.145707	0.581618
28770	11/24/2016	0:07	13.86	41.82689	0.096059	0.338552

Figure A12. Repetitious time stamps

In Figure A12, note that the PM data for identical time stamps (highlighted) are different. For these analyses, the second instance of the same time stamp was deleted and not included in the correlation analysis. Though it is likely that the first instance shown in this illustration describes time stamp 0:01 and the second describes for timestamp 0:02, determining which data record to delete is inconsequential since a full set of data records (five 1-minute measurements) was required to compute 5-minute averages based on the 90% data completeness rule.

Investigation of the NO_2 Concentration Computation

A macro file provided by UNEP (Gas-ppb.xlsm) was used to compute the gas concentrations from the electronic output of the sensor. All the reported NO_2 concentrations in the resulting processed data files were small negative numbers. A cursory look at these results would lead one to suspect that the sensor was not functioning properly. However, these concentrations are based on a temperature correction algorithm and other correction factors and applied to the raw sensor output through the macro code. Such a situation creates numerous opportunities for errors to be introduced, so the algorithm, correction factors, and their application in the macro were examined in detail. The findings are best illustrated through an example calculation performed manually.

Alphasense Ltd., the manufacturer of the gas sensors used in the UNEP pod, has developed correction algorithms for correcting zero background currents due to temperature changes. These are provided by the Alphasense Application Note AAN 803-02, "Correcting zero background currents of four electrode toxic gas sensors due to temperature changes". Both the recommended algorithm and the alternate algorithm for NO_2 provided in this application note are for the "A" series sensors. However, the UNEP pod uses the "B" series sensor for NO_2. The implications of applying the algorithms to the B series sensor are not discussed in the application note.

An example calculation was performed manually and compared with the results provided by the macro to confirm the macro code or identify errors. Two errors affecting NO_2 computations were found and corrected (discussed under the heading "Macro Code Errors" later in this Appendix). All computations going forward were based on the corrected macro. The following explanation demonstrates an example calculation for data record 11/18/2016, 13:00 EST, which was selected based on the high NO_2 concentrations reported on that day by the reference monitors to ensure a robust measurement.

For NO_2, the recommended algorithm is $WE_C = WE_T – n_T*AE_T$, where WE_C is the corrected working electrode, WE_T is the uncorrected working electrode, n_T is the temperature dependent correction factor, and AE_T is the uncorrected auxiliary electrode.

Alphasense supplies electronic offsets that are unique to each sensor. For the NO_2 sensor in the UNEP pod, these offsets (as provided to the US EPA by UNEP) were 282 mV for the working electrode and 276 mV auxiliary electrode. These electronic offsets must be subtracted from the raw readings before applying the temperature corrections. The raw WE and AE are reported in units of volts (V), so these values must first be converted to mV.

The following is an example of the calculation for data record 11/18/2016, 13:00 EST, which was selected based on the high NO_2 concentrations reported on that day by the reference monitors, ensuring a robust measurement.

Raw WE = 0.224165 V = 224.165 mV

Raw AE = 0.220737 V = 220.737 mV

Raw WE minus offset = 224.165 – 282 = -57.835 mV = WE_T (uncorrected working electrode, EC2_WE_mV, column P)

Raw AE minus offset = 220.737 – 276 = -55.263 mV = AE_T (uncorrected auxiliary electrode, EC2_AE_mV, column O)

A temperature of 31.26 degrees C was reported by the UNEP pod for this data record. The temperature dependent correction factor n_T was 0.3728, as interpolated from discrete values supplied in table in the Alphasense Application Note. (This computation was also confirmed manually.)

These results were applied in the recommended algorithm as follows:

$WE_C = WE_T – n_T*AE_T$ = -57.835 mV – 0.3748*(-55.263) = -37.122 mV

The algorithm requires each term of the equation to be in units of nA rather than mV, so this result must be converted to nA using the correction factor -0.73 nA/mV (supplied by Alphasense and provided to the US EPA by UNEP):

WE_C (nA) = (-0.73 nA/mV)*(-37.122 mV) = 27.099 nA

To obtain the concentration units, this result is divided by the sensitivity factor (SF) -380.5 nA/ppm (supplied by Alphasense and provided to the US EPA by UNEP):

NO_2 concentration = WEc (nA)/SF = 27.099 nA/(-380.5 nA/ppm) = -0.0712196 ppm

The concentration is converted to ppb by multiplying by 1000, yielding a concentration of -71.2 ppb. The concentration reported by the reference monitor for this time period was 55.5 ppb. But for the signage issue, this would be a reasonable comparison. A cursory review of the output for some other data records comparing the macro-computed NO_2 concentrations with the reference monitor NO_2 concentrations shows that this observation is backed by reasonable evidence, and that it is not unreasonable to pursue this line of inquiry to solve the NO_2 measurement problem. It is recommended that such a line of inquiry involve detailed sharing and review of these findings with the manufacturer.

The Effect of Reported Temperature on Gas Concentration Computations

As reported in section 3.2, the temperature sensor in the UNEP pod showed a positive bias > 7ºC compared with the temperatures reported by reference devices. It was hypothesized that this bias might be the result of heating within the encasement of the UNEP pod, or of a calibration bias. Either hypothesis raises the question of which temperature should be used in the gas concentration algorithms. If the true temperature in the UNEP pod that is influencing the gas sensor measurements is lower than what is being reported, then what is the effect on the computed concentration?

To resolve this issue, the ambient reference temperature of 22.6 °C was substituted for the UNEP pod temperature of 31.26 °C for the above example. The corresponding temperature dependent correction factor is then 0.548. Applying this to the example yields an NO_2 concentration of -52.857 ppb, compared with the reference concentration of 55.5 ppb. This would be quite a good comparison were it not for the signage issue.

Macro Code Errors

Errors in the macro code were discovered during the investigation of the computation of the NO_2 concentrations. The errors, and their recommended solutions, are summarized here:

1) In computing the uncorrected working electrode value (column P – EC2_WE_mV), the code referred to the column for the raw auxiliary electrode (column K – NO2A1N2) rather than to the column for the raw working electrode (column L – NO2A1N3). The following is the code affected:
   - Change Range (“P”) select
   - ActiveCell.Formula R1C1 = “(RC[-5]x1000]-282

   The US EPA recommended that the relative cell indicator be change from RC[-5] to RC[-4] to refer to the correct column, and UNEP supplied the corrected code.

2) Sensitivity factors are in units of nA/ppm, but the macro-produced spreadsheet identified computed concentrations as ppb. The US EPA recommended that a factor of 1000 be applied in the code to report the results as ppb, and UNEP supplied the corrected code.

Through further examination of the data files, a data sorting error was discovered. The date/time stamps in the processed output showed that some time periods had apparently been omitted. Upon closer examination, it was found that a block of records that should have appeared earlier in the time column were added instead to the end of the column after 23:59. The issue was found to lie in the sorting subroutine, wherein all sorting code referred to rows 2 through 1440 (or less). The US EPA recommended that the sorting code be amended to refer to rows 2 through 1441 (assuming no extra records are included from previous months). The US EPA determined that the best approach to managing these data files, some of which contained extra data records, was to sort the data again manually following application of the macro to complete the data sorting and put records in the proper order.

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