Development of the UCB-L Particle Monitor

For Future California Applications in Environmental Justice

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Abstract

As the public becomes more knowledgeable about air pollution and its effect on health, local community-based air pollution monitoring projects have become more important. Community members and groups want to protect themselves from localized exposures to high concentrations of particulates, and require high quality, low cost, simple to use instruments. Ambient aerosol monitoring commonly requires either expensive or difficult to use instrumentation with lab backup. This study modified a low cost, simple and accurate optical commercial particle counter, the Dylos™, and evaluated its use as an ambient fine particulate monitor. The preliminary name of the prototype device is the Berkeley Aerosol Information Recording System (BAIRS). Based on lab an ambient monitoring, the limit of detection of the BAIRS is less than 1 µg/m^3 and the resolution better than 1 µg/m^3. The BAIRS accurately sized 0.49 µm particles, and is able to count particles of varying composition including organic, inorganic, and ambient particles. It is also robust, and able to measure concentrations up to 1.0 mg/m^3. The project funding ended before development of multiple field-capable devices could be built and deployed, which should be the next step in evaluation for use by non-technical community groups.

Executive Summary

BACKGROUND

Combustion in its many forms is the largest source of health-damaging air pollution in the United States and globally. It has come to be accepted that the best single measure of the major health impact from combustion-derived air pollution is small particles, which, according to recent WHO publications, are estimated to be responsible for nearly 3 million premature deaths annually around the world, not counting active tobacco smoking. Combustion particles and their health effects have been the focus of many studies. The vast bulk of measurements for health studies have relied on 24-h or annual mean mass concentrations, although there are efforts to understand effects using other metrics, for example short-term peak levels or particle number.

Recent studies have shown that 24 hour stationary average concentrations may not be the best measure of particulate matter exposure due to the varying concentrations both temporally and spatially. However measuring these changes in concentrations over a shorter time frame is a challenge due to the cost, portability, and laboratory needs in current particle monitoring equipment. As in scientific work, community groups interested in environmental justice (EJ) and other community applications also increasingly require particle monitors that can be used to determine spatial and temporal resolution easily. Such groups cannot afford the cost or time delay involved in working with a laboratory to process gravimetric filter samples.

There are commercial instruments available, generally designed for the occupational market, that partly fill this need, e.g. the DustTrak™. These devices are fairly small and robust, although they are not designed for continuous long-term unattended deployment, but retail cost is > $4k each at present and even if purchased in large numbers, the likely per unit cost still makes them prohibitively expensive for most community-based applications. Thus there is a real need among both technical and community groups for reliable, quiet, portable, long-lasting, easy-to-deploy, quick reading, datalogging, high temporal resolution, and inexpensive devices for monitoring particles, what might be called "small, smart, fast, and cheap."

METHODS

The original goal of this project was to use a high-quality laser smoke detector (Pinnacle™) to create a small, smart, and cheap particle monitor able to work at particle concentrations experienced in California. Although the specification from the manufacturer indicated that this would be possible, in practice the device was not able to meet the required limits of detection. Thus the focus of the project changed to evaluating a commercially available indoor particle counter, the Dylos™, for use as an ambient and ultimately personal particle monitor. Improvements were made to the monitor by request to the manufacturer as well as after market changes. These improvements included adding additional bins of particle sizes measured, reducing the power consumption of the blower fan, and the addition of the OWL datalogger. The upgraded commercially available monitor, now called the Berkeley Aerosol Information Recording System (BAIRS), was tested to determine its ability to meet the following criteria, as described in the project objectives.

1. Small, quiet, and low enough power that it can be battery operated – for non-intrusiveness, ease of placement, and long deployment
2. Cheap – potentially available at <$500 per unit at the retail level.

3. Discriminating (high resolving power) – resolution of 2 μg/m^3 or smaller for $PM_{2.5}$ mass.
4. Sensitive –$PM_{2.5}$ lower limit of detection of at least 5 μg/m^3
5. Robust – Accurately measures $PM_{2.5}$ at concentrations up to 1.0 mg/m^3
6. Accuracy - Able to accurately discern $PM_{2.5}$ concentration in ambient aerosols for varying size distributions and compositions.
7. Linear Response – Able to precisely measure at high and low concentrations.
8. Stable – Low drift of all calibration factors and low variation from one device to the next or between batches.

The original proposal also described the need for a monitor which was rugged enough to operate in various environments without special housings and to be transported without damage. This is still a desirable quality. The BAIRS was tested using multiple aerosols in an indoor aerosol chamber to determine its sensitivity to differing aerosol compositions and concentrations. Ambient testing was conducted to evaluate its ability to measure ambient aerosols and compared to commonly used commercial particle monitors.

RESULTS

The BAIRS ability to properly size particles was tested using standard polystyrene latex spheres. The instrument was able to distinguish the 0.49 um spheres from larger particles. This is crucial as air pollution standards as set based on particle size. The limit of detection of the BAIRS for fine particulates (<2.5 μm), those that are most linked to health effects, is 1 μg/m^3 and the resolution is less than 1 μg/m^3. It performed better in our tests than the much more expensive commonly used commercial particle monitor, the DustTrak™. The sensitivity of the BAIRS varies with differing aerosols, but can be calibrated with filter-based measurements, which is the standard practice for all light-scattering particle monitors, including the DustTrak™. Ambient multi-day testing was used to evaluate the BAIRS ability to perform as an ambient particle monitor. The BAIRS accurately measured changes in fine particulate concentrations on a minute by minute basis for 4 days.

CONCLUSIONS

The BAIRS is small (10 cm by 8 cm by 4 cm), quiet (only noise is from a small computer fan), and light (454 g) but at present does not contain an internal battery. Through an external connection, however, any size battery or other power source can be attached. The length of sampling time is limited by the size of the battery, of course. The cost of each prototype is ~$500 and could be lower if produced at a larger scale. The higher resolution of the BAIRS provides an added benefit for both environmental justice uses as well as for larger scale epidemiological or other scientific studies. The higher resolution allows the impact of local sources to be more easily discerned. For example the increase in particles at a playground during rush hour from near by traffic may be able to be distinguished at greater distances and higher time resolution.

One of the main drawbacks is that this instrument is an optical particle counter and the conversion from particle number to particle mass requires assumptions about the characteristics of an unknown ambient particle load, which can affect the accuracy of the measured mass concentrations. This is a drawback not unique to the BAIRS but all optical particle monitors. In addition, two operating software programs are needed, one internally in the datalogger as firmware and one on the associated lap or desktop PC used for initiating and downloading the monitor. Overall the BAIRS meets or exceeds all of the stated criteria from our original research plan, with the exception of battery life which can be resolved in future models.

INTRODUCTION

Combustion in its many forms is the largest source of health-damaging air pollution in the United States and globally. It has come to be accepted that the best single measure of the major health impacts from combustion-derived air pollution is small particles. According to the World Health Organization (WHO) Comparative Risk Assessment solid fuel use produces small particles from combustion biomass and coal, is estimated to be responsible for more than 2.4 million premature deaths annually around the world [1] , not counting the 4.83 million premature deaths caused by tobacco smoking [2]. Ambient air pollution from fine particles is responsible for 0.8 million premature deaths each year, or 6.4 million lost life years annually world wide [3]. The vast bulk of measurements and health effect studies have relied on 24-hr or annual mean mass concentrations [4, 5], although there are efforts to understand effects using other metrics for example short-term peak levels or particle number. In addition to particulate matter with aerodynamic diameter less than 10 μm (PM_{10}), health-based standards in the US and increasingly elsewhere have come to specify separate limits according to the specific particle size cut of particles less than 2.5 μm ($PM_{2.5}$). Some studies seem to indicate potential benefits of limits at even smaller sizes, perhaps particles less than 1.0 μm ($PM_{1.0}$) [6, 7]. Combustion particles are nearly all in the size range of 2.5 μm or smaller [8].

Epidemiological studies using PM measurements at ambient monitoring stations routinely show consistent effects for important health endpoints [5, 9, 10]. There is also recognition that actual human exposures may differ substantially in temporal and spatial distribution from what these stations show. Indeed, recent evidence from Los Angles based on better exposure assessment methods indicates that chronic exposure to particles in urban environments may result in health effects that are two to three times greater than earlier believed [11, 12]. Increasing concern exists for populations with systematically elevated exposures as a result of local point sources in urban environments. To better understand the relationship of particle exposures and ill-health and to better target control measures to address exposure, there is a need for technologies to monitor particle levels in a wide range of locations, preferably with high temporal resolution.

Although scientific research is an important driver of air pollution policy, community groups and other members of the public have also been important in bringing this issue to the forefront and ensuring that policy protects communities with limited voices, but who are commonly the most impacted [13]. The current costs and/or complexity of commercial instruments, however, limits the ability such groups have for monitoring pollution in their communities. For example the shipping ports of West Oakland California are blamed by the nearby residents for the increased levels of asthma and many adverse health issues. Reports have been published and community groups have been formed to combat the problem, however these groups do not have easy access to the instrumentation to measure the distribution of diesel exhaust which is most likely the culprit. Dispersion modeling has been conducted [14, 15], but actual exposure monitoring is yet to occur.

There is a real need among both technical and community groups for reliable, quiet, portable, long-lasting, easy-to-deploy, high temporal resolution, and inexpensive devices for monitoring particles, what might be called "small, smart, fast, and cheap. Our research group has developed and tested a small, smart, fast, and cheap particle monitor, called the Particle and Temperature

Sensor (PATS formerly known as the "UCB" particle monitor). Although widely deployed in developing country settings with high particle levels, due to its lack of sensitivity, (limit of detection = 40 µg/m^3) it is not very useful in California conditions. To address the need for California we evaluated a low-cost commercial device designed for monitoring indoors for estimating mass concentrations in ambient US settings. This work follows from previous success in adapting commercial smoke detector technology for monitoring in high particle environments in developing countries [16].

To be most useful for both epidemiological research and by community groups such a device should have the following characteristics:

1. Small, quiet, and low enough power that it can be battery operated – for non-intrusiveness, ease of placement, and long deployment
2. Cheap – potentially available at <$500 per unit
3. Discriminating (high resolving power) – resolution of 2 µg/m^3 or smaller for $PM_{2.5}$ mass.
4. Sensitive –$PM_{2.5}$ lower limit of detection of at least 5 µg/m^3
5. Robust – Accurately measures PM2.5 at concentrations up to 1.0 mg/m^3
6. Accuracy - Able to accurately discern $PM_{2.5}$ concentration in ambient aerosols for varying size distributions and compositions.
7. Linear Response – Able to precisely measure at high and low concentrations.
8. Stable – Low drift of all calibration factors and low variation from one Dylos to the next or between batches.

MATERIALS AND METHODS

This project began as an improvement to our currently PATS. The PATS uses smoke detector technology to measure $PM_{2.5}$ concentrations from indoor household cooking. Its drawback is its inability to measure concentrations lower than ~40 µg/m^3. Initially we planned to adopt an off the shelf laser smoke detector, the System Sensor Pinnacle™ which was advertised to have a higher sensitivity as compared to standard smoke detectors. We intended to re-purpose that detector in a manner similar to what we had already done with the First Alert detector, the basis of the PATS, and produce a similar instrument, but with greater sensitivity and stability. The System Sensor Pinnacle™, however, did not meet expectations in performance. There were additional hurdles having to do with lack of interest by the manufacturer in cooperating, uncertainty about the long-term availability sensors, as well as cost and the needed re-packaging.

Initial evaluation of the Pinnacle smoke detector as the UCB-L was conducted. To evaluate the sensitivity of the UCBL prototype we introduced combustion-generated aerosols into the test chamber at a range of concentrations in series of discrete events, using a DustTrak referenced to gravimetric concentrations as the reference measure. Sensitivity of the raw electronic signal of these prototypes was ~15 µg/m3/mv. Applying this conversion to the standard deviation of a baseline signal in the absence of particles resulted in the noise equating to 17 µg/m3. Assuming a limit of detection at three times the noise, this equates to an LOD of ~50 µg/m3. Since the DustTrak uses a 15 point smoothing filter on raw data we evaluated the response of the UCBL using a 15 point smoothing summarized in the table below.

	UCBL signal (mv)	UCBL 15pt smooth (mv)	TSI Dusttrak* (ug/m3)
background noise	1.15	0.31	0.19
Peak response	6.9	4.4	87.5
Peak response to noise ratio	6.0	14.5	461.2
SD noise in micrograms	16.86	6.98	0.190

* 15 point smooth in Dusttrak

Baseline Stability

Baseline stability was assessed by analyzing photoelectric response over time in a low particle environment. During stable temperature periods of ±1°C, no fluctuations were observed in photoelectric signal over 24 hours. A test was also conducted in which temperature was increased by ~3°C within the chamber and resulted in an apparent inverse relationship with the photoelectric signal, although clearly the range of the temperature change was not adequate to fully characterize this dependency, it was sufficient to indicate whether this was an issue of concern. In subsequent consultation with Tracy Allen, he determined the photoelectric signal integration is conducted on a relatively rudimentary chip which is known be impacted by temperature. Use of more advanced integrating chip may help to resolve this issue in future prototypes.

Amplification Stability

The Pinnacle sensor has a two stage amplification process used to amplify the scattering response. EME systems evaluated the performance of the amplification circuitry, through circuit analysis and by sending known electronic signals equivalent to 100μg/m^3 through the Pinnacle electronic circuitry (i.e. not generated by aerosols, but direct application of current from a signal generator). Given the theoretically expected power at the photodiode for a particle concentration of 100μg/m^3, we expected a first stage output of near 4 millivolts, and a second stage output (at the 350 μs integration time) of near 160 millivolts. However the second stage was problematic. The discrepancy between the theoretical expected values and the actual performance as supported by the UCI chamber tests, in comparison to the reported sensitivity by System Sensor, might be the result of the instability of the second amplification step due to the sensitive nature of the amplification step which is also prone to oscillation.

A sequence of additional laboratory tests were performed to evaluate sensor performance in an attempt to stabilize the second stage amplification. Two UCBLs were placed in the combustion chamber with a DustTrak used as the reference instrument and particles were generated by burning small pine chips. A high-range test in which peak events were ~100-4000 µg/m^3, demonstrated strong agreement with the new prototype UCBL response (r^2>.096), though the millivolt response per µg m^{-3} was similar to previous UCBL version (0.068 for the previous version and 0.057 and 0.053 for the newer prototype). A low range test in which peak events ranged from ~15-30 µg m^{-3} indicated the UCBL did respond to these levels, but similarity in response with earlier prototypes demonstrated that the amplification was still unstable, as evidenced by a high level of noise in the data set.

Evaluation of the Pinnacle™'s components revealed that both components and construction of the laser smoke detector were inadequate to measure a particulate concentration of 5 $\mu g/m^3$. The prototype developed using the Pinnacle has a low signal to noise ratio. Testing revealed two main causes of the noise: 1. Variability of the laser firing energy and; 2. Instability in the photodiode amplifier circuit. Appendices A and B contains a series of reports describing the development problems with the Pinnacle™. Correcting these issues would have required major alteration to the device itself, discarding all but the prefabricated chamber and rebuilding the support circuits from scratch.

As a result of these problems, after 15 months from the start of the project, we decided that we needed to abandon the Pinnacle™. Around this time, we identified that the Dylos™ Particle Monitor might serve a similar purpose and took up a plan to test it for meeting our objectives.

Figure 1. Dylos Particle Monitor

The Dylos™ particle counter is designed, manufactured and distributed by the Dylos Corporation located in Riverside California. Roger Unger, the owner and chief engineer at the company has a background designing particle counters for a major respected manufacturer of optical particle counters (Climet Inc.). The Dylos™ Air Quality Monitor is advertised on the company's web site (http://www.dylosproducts.com) for use in homes and offices to monitor particulate concentrations. Stated examples include testing the efficiency of in-home air cleaners, or monitoring particulate concentrations in woodworking shops.

The Dylos™ is a laser particle counter. It uses a small computer fan to draw air and particles in at the top, funnel them through baffles molded into the case, past the red laser beam, and out at the bottom. The wide air path allows the low pressure head fan to draw a relatively large volume flow of air. A photodiode is located close to the scattering volume, positioned so that it captures scattered light from many angles. There are no lenses, mirrors or other focusing optics or critical adjustments.

The "off the shelf" instrument is sold with two size bins. $PM_{0.5}$ which measures particles sized 0.5µm and greater, and $PM_{2.5}$ which measures particles sized 2.5µm and greater. The instrument does not use a physical size selector such as an impactor or cyclone, but conducts the size selection using an algorithm on the signal from scattered light. Maintenance of a precise flow rate is not required, as fluxuations are compensated using the measured width of the peaks from the light scattered from the larger particles.

Roger Unger of Dylos Corporation has patent application in progress for the construction of the monitor [17]. Much of the content of the patent has to do with the unitary construction of the monitor, which integrates the injection molded plastic case with the air flow baffles, up against the circuit board that holds the laser and photodiode on one side, and on the other side the signal processing, microprocessor, power supplies, and user interface. This construction in patent language claims a novel high performance to cost ratio.

Roger Unger has another patent, assigned to his former employer (Climet, division of Thermodyne), which was studied to gain a rough idea of the type of signal processing that may be used in the Dylos™, and that patent is attached also [18]. However, it is likely that those ideas apply only in a broad sense. Due to the large scattering volume in the Dylos™, characterization falls between an individual particle counter and a bulk photometer. Its signal processing makes use of patented algorithms that are in embodied in the Dylos™ microcontroller. Those algorithms and the exact method of calibration used to achieve the 0.5 and 2.5 µm settings are trade secrets of Dylos Corporation.

Initial Testing

Instrument Configuration

The Dylos™, as supplied by the manufacturer, does not meet all the requirements needed for an ambient real-time particle monitor as described in the introduction. This is to be expected as the stated application is different. Several modifications were made to make the Dylos™ usable for ambient particulate monitoring. Some were made at our request by the manufacturer and others by the project through our collaboration with EME Systems. The resulting modified Dylos™ is referred to as the Berkeley Aerosol Information Recording System (BAIRS).

Particle Bin Size

In order to provide a more accurate particle concentration we requested that two additional size bins be added by the manufacturer. The two main bins are calibrated at 0.5 µm and 2.5 µm by the manufacturer, and the two extra are uncalibrated values in between 0.5 and 2.5 µm. The two intermediate bins are based on a measure of the peak height in the raw voltage from the photodetector, not particle size directly, but they should correlate with size and give us a couple more ratios to use during calibrations. They were not calibrated by the manufacturer.

Datalogging

The Dylos™ can be ordered with a serial port to retrieve data and accept commands. The standard Dylos™ includes a datalogger, capable of storing very few data points. We required larger storage and a finer time resolution. The Dylos Company provided us with modifications of their standard protocol, which allowed requests for data from all four channels at frequent intervals.

The Owl™ datalogger (http://www.emesystems.com/OWL2pepr.htm) has been incorporated into the BAIRS through external connection to the 9 pin COM Port. It records the processed signal from the photodiode as particles per standard cubic foot (scf), as sent by the Dylos™. The datalogger can be programmed to record data at any time interval. All testing was conducted at time resolution of 1 minute, but the instrument can record up to a 1 second basis. It can also log temperature data and well as data from other sensors and allows for a variety of communications options. The BAIRS responds to requests for data at an interval set by the datalogger, which allows better time resolution in comparison to the standard Dylos™.

Battery Life

The standard Dylos™ is powered by line current and demands too much power for convenient use of batteries. At our request, the manufacturer provided a more efficient, quieter fan and commands that permit external control of the display screen back light and the power for the entire instrument. This allows for lower overall power consumption as well as non-continuous sampling schemes. The BAIRS also incorporates modifications designed to accommodate a rechargeable battery.

Experimental Methods

Chamber Samples

An indoor aerosol chamber was utilized to sample various aerosols in a controlled repeatable setting. The ~ $1m^3$ chamber is lined in aluminum and has an adjustable side to allow for filter sampling while maintaining atmospheric pressure. The chamber is equipped with a TSI DustTrak™ (model 8520, Shoreview, MN) for continuous particle monitoring as well as a model PCXR8 SKC (Eighty Four, PA) personal sampling pumps and BGI Triplex™ Cyclone (Waltham, MA) to achieve a cut point of either 2.5 or 1.0 μm. Flow rates were calibrated for either 1.5 or 3.5 liters per minute (lpm) respectively, immediately before and after sampling using a Gilian Gilabrator™ (Sensidyne Mülheim, Germany). A low particle environment was created in the chamber using an air compressor connected to a HEPA filter was used to remove all particles from ambient air before experiments.

Particles were added to the chamber using two methods. Ammonium sulfate (0.1M $(NH_4)_2SO_4$) and polystyrene latex spheres (PSL) were introduced into the chamber using a medical grade nebulizer, mean particle diameter (0.5-0.7 μm), in series with a diffusion dryer. Combustion particles were also tested by burning a predetermined mass of wood in the chamber burn pot. Particle concentration was controlled by adding clean air while concurrently removing the same volume of air using a sampling pump while smoke was added. A small mixing fan ran during each experiment to ensure the chamber was completely mixed. The experiments conducted are listed in table 1, the results are discussed in the following section.

The BAIRS was placed inside the chamber. The DustTrak™, and pump-filter combination were placed outside of the chamber and samples were taken through Tygon™ tubing.

Ambient Samples

Ambient particulates were sampled to evaluate the ability of the BAIRS to perform in an outdoor setting with real atmospheric aerosols. All ambient samples were conducted concurrently with a DustTrak™ and an E-BAM™ beta attenuation monitor (Met-One) on the roof of the State of California Health and Human Services Air Pollution Lab in Richmond, CA. The DustTrak™ had a $PM_{2.5}$ impactor as a particle size selector, while the E-bam™ was affixed with a cyclone to measure $PM_{2.5}$.

Table 1. Summary of experimental runs conducted.

Aerosol Type	*Location*	*Mass Concentration Range*	*# of Runs*
Woodsmoke	Chamber	0 - 1200 μg/m^3	4
0.5 μm Polystyrene Latex Spheres	Chamber	0 - 190 μg/m^3	2
Ammonium Sulphate (crystalline)	Chamber	0 - 170 μg/m^3	4
Ambient Aerosol	Rooftop	0.8 - 39 μg/m^3	4

RESULTS

Laboratory tests

Here we discuss the results of the experiments listed in table 1, with exception of the ambient samples which are discussed in the ambient sampling section.

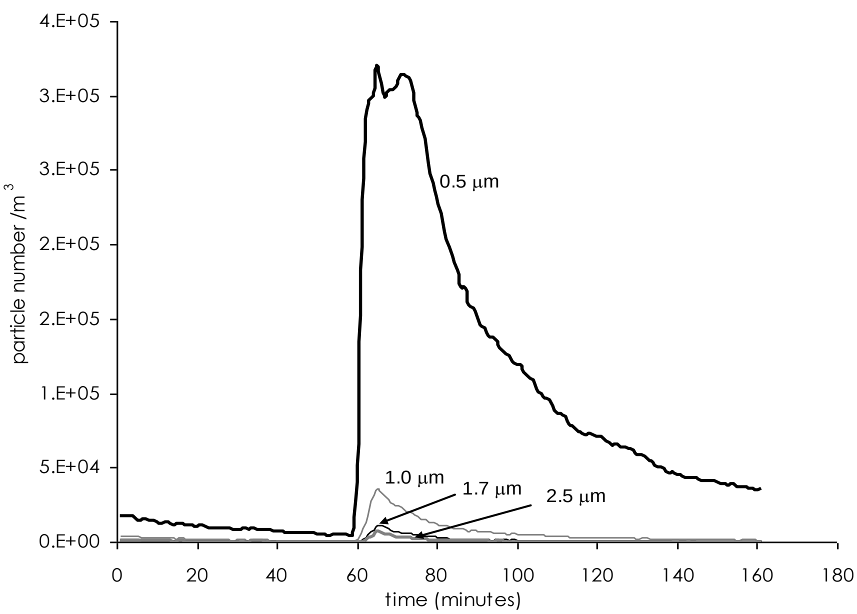


Figure 2. Particle number concentration of PLS spheres in chamber. The 0.5 μm and 2.5 μm channels are factory calibrated, while 1.0 μm and 1.7 μm are estimated.

Polystyrene Latex Spheres (PSL) The BAIRS' ability to distinguish fine particles was tested using PSL in the indoor smoke chamber. The PSL were 0.490 μm calibration standard spheres. A mono-size particle distribution is used to display the ability of the device to correctly size particles at concentrations which are relevant for the proposed application. In Figure 2, the 0.5 μm size bin has the largest response to the PSL as is expected. At a concentration of 1E5 particles/m^3 the BAIRS isolates the PSL in the 0.5 μm bin, and the other size bins do not respond to the PSL spheres as expected because there are an insignificant number of larger particles present in the chamber. At higher concentrations the larger size particle bins also showed a response to the PSL although there are no additional larger particles added to the chamber. The largest response is 2 orders of magnitude less in comparison response of the 0.5 μm size bin making it negligible.

Sensitivity to Different Aerosols

The BAIRS, like all light-scattering instruments, can respond differently to particles of varying compositions. In comparison to the DustTrak™ the relative response between the two instruments changes as the particle source changes (Figure 3). The differing slopes suggest either the DustTrak™ or the BAIRS has a varying sensitivity to composition (which is directly related it color), or to particle size. The value of the slope should not be used to estimate the mass concentrations measured only to show that a linear relationship exists, confirming that the linear response to particle concentrations are proportional to the Dust Trak. Like any light scattering instrument the Dylos will require a separate mass calibration factor for specific aerosols as the Dust Trak does. However figure 3, shows that The PSL are the smallest aerosols at 0.49 μm tested, the approximate mean particle diameter of the woodsmoke and the ammonium sulfate are ~0.7 μm and 0.8 μm respectively [20]. The refractive index for PSL is 1.58, wood smoke 1.57, and ammonium sulphate is 1.53 [19]. The ability of particles to scatter light is dependent on both particle size and composition and the differing sensitivity are a caused by both factors.

Mass Concentration

Equation 1. $$m(d_p) = \pi \frac{d_p^3}{6} \rho n(d_p)$$

To convert the number concentration $n(d_p)$ into a mass concentration $m(d_p)$ as a function of particle diameter, Equation 1.0 is used, where ρ_p is the particle density, and d_p is mean particle diameter. In the indoor chamber, a single source of particles was used, and the physical and chemical compositions of these aerosols were known. The nebulizer used to generate the inorganic aerosols produced particles with a mean aerosol diameter of ~0.7 µm, and the PSL spheres were a single diameter. The particle density of the inorganic aerosols were estimated using the AIM online model [21], the model requires solution molar concentration and ambient temperature and humidity. Woodsmoke has been well characterized for both composition as well as particle size, however in the case of ambient aerosols, much less was known. In the absence of a known particle size distribution, the aerosol mass was calculated for each particle size bin. The BAIRS measures particle number concentration at four different particle sizes (0.5, 1.0, 1.7, 2.5 μm). Only two of the sizes bins (0.5 and 2.5 μm) are calibrated by the manufacturer. In order to estimate the mass concentration the mean particle size of each bin (0.75, 1.4, 2.1 μm) was used to estimate the mass concentration (density = 1.0 g/cm^3).

The DustTrak™ measured aerosol concentration was adjusted with the mass concentration from gravimetric filter sampling for the chamber experiments and a federal approved reference standard Met-One E-bam™ for the ambient samples. The ratio of the concentration determined by gravimetric concentration or the E-Bam to the mean concentration measured by the DustTrak™ for the same time period was used to adjust the DustTrak™ minute scale data.

Limit of Detection

The limit of detection (LOD) is defined as 3 times the standard deviation of the instrument signal during sampling in a near-zero particle environment. The chamber was filled with filter room air to create near-particle-free air. The limit of detection of the BAIRS is 16 particles/scf or 0.45 particles/m^3 or a mass concentration of $2.83*10^{-7}$ μg/m^3 ($6.28*10^{-7}$ μg/particle) assuming a mean particle size of 1.0 μm and density of 1.2 g/cm^3. Figure 4 shows the number concentration for the BAIRS, and the un-adjusted mass concentration for the DustTrak™. The resolution of the BAIRS is much finer than the DustTrak™, and it has a lower limit of detection. The Dylos™ does not measure less than 1 particle; however the unit conversion from scf to m^3 creates numbers less than 1.

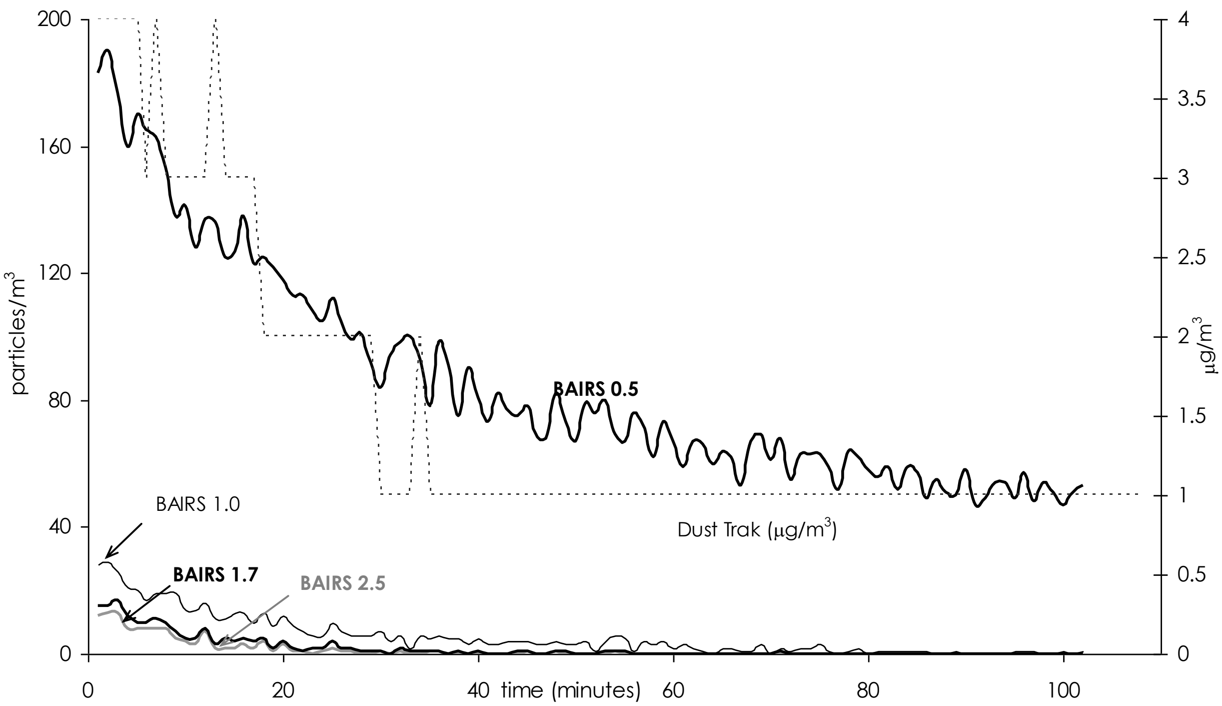


Figure 4. BAIRS and DustTrak™ in low particle environment. BAIRS number counts reported for calibrated sizes of 0.5 and 2.5 μm and larger and uncalibrated sizes of ~1.0 and 1.7μm and larger. DustTrak™ mass concentration was not adjusted by gravimetric filter measurement.

Concentration Dependence

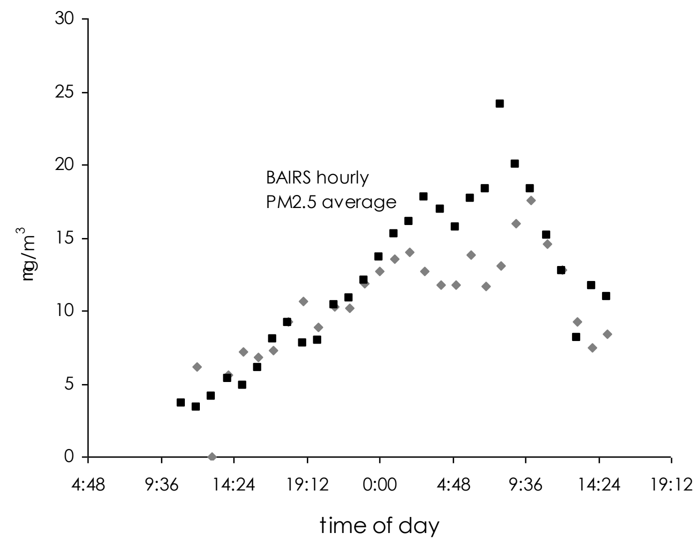
Figure 3 shows the particle number concentration from the BAIRS compared to the adjusted mass concentration from the DustTrak™ using varied concentrations of wood smoke in the indoor chamber. Figure 3 shows the linear relationship at both a high and lower concentration of wood smoke. At both levels of smoke concentrations the slopes are almost the same.

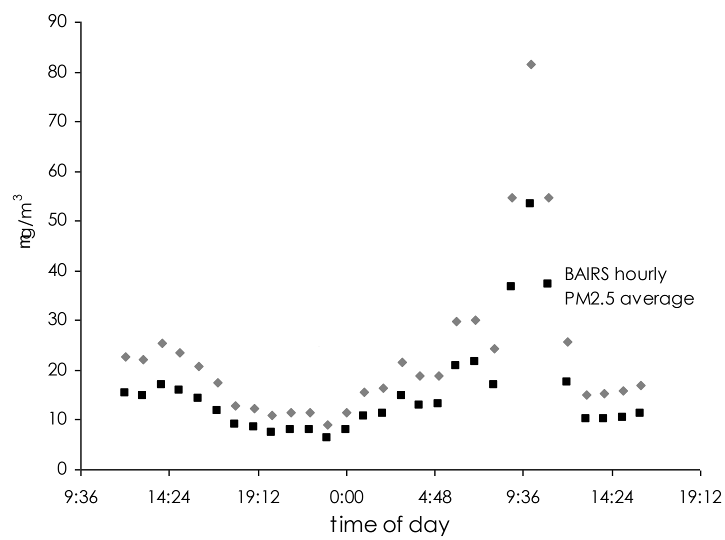
Ambient Testing

The E-Bam™ was used to adjust the readings from both the DustTrak™ and the BAIRS to provide a direct comparison between the ability of the two instruments to measure PM2.5 in an outdoor environment. The correction factors for both the DustTrak™ and the BAIRS using the

E-Bam™ were determined using data for the entire sampling period. The composition of ambient aerosols can change temporally due to varying sources, which can affect the particle optical properties and the response of the instruments. The mean correction factor over the entire sampling period allows the temporal changes in the particle optical properties to be averaged out over the entire sampling period. This is the correction method commonly used to correct optical aerosol monitoring instruments for various types of aerosols. The correction factors were 0.28 (E-bam μg/m^3)/(Dylos count/scf) and 1.06 (E-Bam μg/m^3)/(Dust Trak μg/m^3).
Testing was conducted for a total of 110 hours over three weeks.

Figure 5 shows the hourly averaged data from the DustTrak™ and the BAIRS collocated for two different ambient monitoring periods. The two instruments track extremely close reporting almost the same values over both sampling periods. Period 1 had very clean air, as it had rained immediately prior to the sampling period and the humidity remained very high during the entire sampling period. Period 2 had higher concentrations and reported values were close. The average concentration for period 1 was 11.9±0.3 μg/m^3 and 11.1±0.2 μg/m^3 using α=0.05 to calculate the confidence intervals. Period 2 had a mean average concentration of 25 ±8 μg/m^3 and 32 ± 6 μg/m^3 for the BAIRS and DustTrak™ respectively.





Figures 5. E-bam calibrated minute by minute results for two sampling periods. **A.** Period 1. DustTrak™ adjusted, BAIRS adjusted **B**. Period 2. DustTrak™ adjusted, BAIRS-adjusted, mean particle diameter.

Figure 6 shows the hourly mean mass concentrations from the two instruments plotted against each other. The R^2 values are lower in comparison to Figure 3 where particle number was plotted versus DustTrak™ mass for wood smoke in the chamber on a minute-by-minute basis. Ambient aerosols are of varying composition and also vary temporally. Optical instruments respond different depending on the aerosol composition. In the chamber test a single aerosol was used reducing the variability in the response to the aerosols producing higher R^2 values. On February 10-11, the slope between the BAIRS and the Dust Trak are near one indicating the both instruments measured the same concentrations. However on the other two sample days the slopes were closer to 0.5 indicating a difference in the responses. The differing responses may be due to changes in the measured air masses on the sampling days. Further evaluation should be conducted to better understand this data.

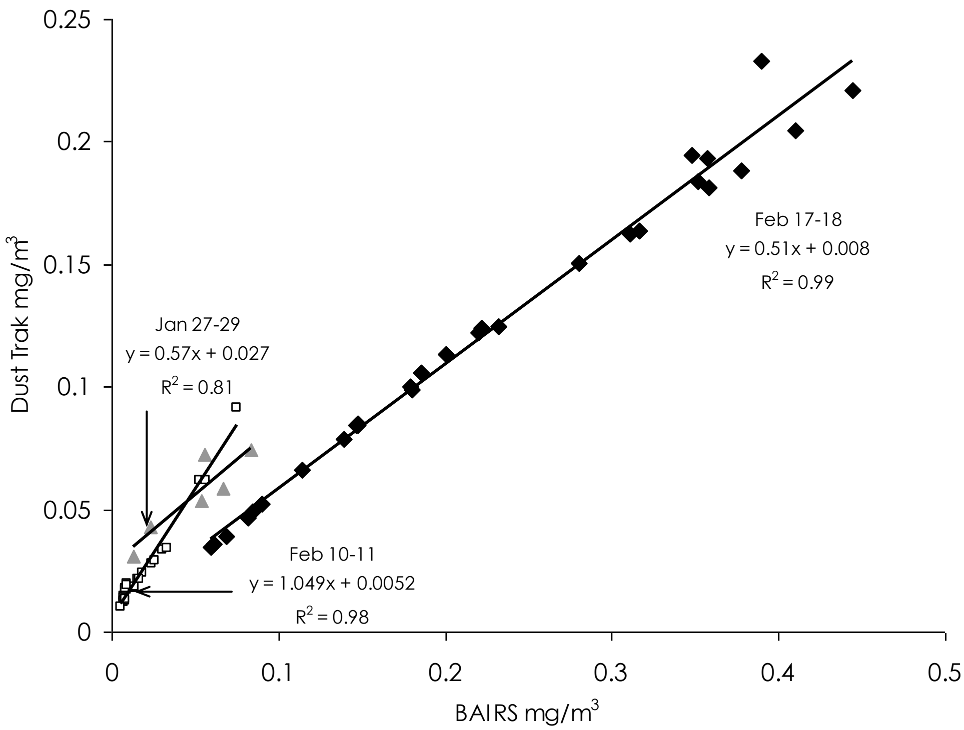


Figure 6. Linear regression between DustTrak™ and BAIRS for ambient particle sampling for three periods, each period at least 24 hours. Both BAIRS and DustTrak™ measurements adjusted by E-Bam**™** 24-hour measurement.

DISCUSSION

The BAIRS has the possibility to be ground-breaking inexpensive technology for fine PM exposure measurement. The results of this study have shown it is as good as the instruments commonly used for real time ambient sampling.

- The size, weight, and low cost of the BAIRS make it easier to increase the number of monitors in a single study, potentially decreasing exposure misclassification in epidemiological studies.
- One the largest hurdles for community groups interested in conducting air pollution monitoring face is the cost of monitors. The low cost of the BAIRS has significantly reduced the size of that hurdle and, if combined with user-friendly software, it could have a widespread application.

The final cost of the BAIRS is ~$500 for a setup that includes 2 additional size bins and an OWL datalogger, roughly one-tenth that of commercial monitors that are not as capable. With the extra channels available in the datalogger, future applications can include a GPS device, as well as additional sensors, e.g. NO_2, CO, CO_2, etc.

The BAIRS is able to size particles as demonstrated by the tests using PSL. Even at higher concentrations the monitor performed well. The maximum number concentration of the PSL in the chambers was 3.2E7 particles/m^3, much higher than expected in an ambient setting. For example researchers at Clarkson University [19] monitored particle number concentrations in New York and reported a mean concentration of ~1E6 particles/cm^3 in the 0.1-0.47 μm particle size range. Although some agglomeration/accumulation of PSL would be expected, response from the three larger size bins is most likely caused by optical particle counters counting the scattering by more than one particle in the laser path as one larger particle as opposed to several smaller particles [20].

The BAIRS does have differing sensitivity to different types of particles, however the sensitivity does not appear to be concentration dependent. All light-scattering particle counters are sensitive to changes in particle composition however this can be compensated for with correction to gravimetric measurements.

SUMMARY AND CONCLUSIONS

The need for a low cost, simple to use, and accurate particle monitor is shared by scientific and environmental justice groups. This project ultimately focused on evaluating a particle monitor to meet their needs. Eight criteria were listed in our proposal as being essential to meet the needs of both scientific and environmental justice groups equally. The test results of the BAIRS shows the monitor meets the majority of the stated criteria and is useful as an ambient particle monitor.

1. *Small, quiet, and low enough power that it can be battery operated – for non-intrusiveness, ease of placement, and long deployment*

The BAIRS, with the Owl datalogger attached weighs 1 pound and is 10 cm by 8 cm by 4 cm in size. Currently the power draw is 500 mA, meaning that available rechargeable batteries would give about a one-day deployment limit. There is a trade-off with battery weight and volume, of course.

2. *Cheap – potentially available at <$500 per unit*

The current cost estimation is ~$500 per unit for the tested configuration. Additional changes to make the BAIRS usable as a personal particle monitor will involve development costs, but perhaps no increase in manufacturing cost.

3. *Discriminating (high resolving power) – resolution of 2 μg/m^3 or smaller for $PM_{2.5}$ mass.*

The measured resolution of the BAIRS is less than 1.0 μg/m^3. The resolution was measured in a low particle environment at larger concentrations the resolution may not be larger.

4. *Sensitive –$PM_{2.5}$ lower limit of detection of at least 5 μg/m^3*

The measured limit of detection is much lower than 1.0 μg/m^3

5. *Robust – Accurately measures PM2.5 at concentrations up to 1.0 mg/m^3*

The BAIRS seems to have a usable range up to 1 mg/ m^3. At higher concentrations the current version becomes less accurate.

6. *Accuracy - Able to accurately discern $PM_{2.5}$ concentration in ambient aerosols for varying size distributions and compositions.*

The BAIRS was tested for its ability to measure ambient aerosols which vary in both mean particle diameter as well as compositions in ambient aerosols. The monitor performed well in comparison to a DustTrak. Both instruments measured the changes in concentration, and tracked each other as the particle diameter changed over time.

7. *Linear Response – Able to precisely measure at high and low concentrations.*

With aerosols of consistent size and composition, the BAIRS gives a linear response from 1 $\mu g/m^3$ to 1 mg/m^3.

8. *Stable – Low drift of all calibration factors and low variation from one device to the next or between batches.*

In all the testing of this instrument we have not had any problem with a base line drift. Over the course of years the instrument may need to be opened and cleaned to help prevent a higher baseline reading. We have instruments from 2 different batches, they give reading within 98% of each other, however this is only comparing two batches and 5 instruments.

In addition to being well suited as an ambient particle monitor the BAIRS shows promise as a personal particle monitor, an application we did not test in this project. The current construction of the BAIRS is not designed for repeated ambient measurements. A more rugged case is needed.

RECOMMENDATION

The BAIRS is suited to be used as a portable particle monitor for use in a wide range of environments. The tested version is not a ready to use field version as additional software developments and batteries need to be included. Improvements to the software should include the ability to graph data when downloaded; the ability to automatically calculate standard descriptive statistics; easy control of the monitor data logging time resolution, start time, and duration of sampling; easy insertion of calibration factors to transform particle count per scf to mass concentration for aerosols from differing sources; batch processing of data from multiple BAIRS at once. A further addition could be firmware/hardware that allows the built-in screen to show estimated particle mass at a particular size range. Depending on funding, it would also be possible to add software controls for incorporating data from other sensors and GPS chips which can be attached to the BAIRS. Ultimately, it might be possible to create a software/hardware package to show graphically and numerically the locations of a device within a network of BAIRS and the concentrations of PM0.5, PM1.0 and PM2.5 as well as temperature, humidity, and possibly CO, NO/NO_2, and O_3.

In addition the BAIRS has not been tested as a personal monitor. This ideally would require modifications to the battery and case (made smaller). The BAIRS should perform well as a personal or portable monitor as it is not sensitive to low wind levels or physical movement. The effect of these parameters should be tested in real field conditions, however. Needed also are modifications in the case to incorporate an appropriate rechargeable battery and perhaps connectors to other sensors. The current prototype of the BAIRS is very accurate and sensitive at the low and medium concentration ranges those commonly seen in ambient aerosol monitoring. However at higher concentration ranges (above 1 mg/m3) the BAIRS loses accuracy. Personal monitoring will require a larger particle range as a person is more likely to encounter short burst of high concentrations of particles when in close proximity to a source, such as a fire place, a cigarette, or the tail pipe of a vehicle. A recent meeting of the research team with the manufacturer resulted in suggested straightforward changes that could be made to increase the high end of the usable measurement range, but would require additional funding to achieve.

The current prototype is ready to be developed into a field-usable portable fine particle monitor. It is our recommendation that this be done next for field testing by environmental justice groups and others.

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Publications

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Low-cost particle counter as a direct-reading fine-particle monitor.

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Glossary of Terms

BAIRS	Berkeley Aerosol Information System
EJ	Environmental Justice
PM	Particulate matter
$PM_{2.5}$	Particlulate matter with an aerodynamic diameter less than 2.5 μm
$PM_{0.5}$	Particlulate matter with an aerodynamic diameter less than 0.5 μm
WHO	World Health Organization
PATS	Particle And Temperature System
μg	microgram
m^3	cubic meters
scf	standard cubic feet
lpm	liters per minute
$(NH_4)_2SO_4$	ammonium sulfate
PSL	polystyrene latex spheres
LOD	limit of detection
NO_2	nitrogen dioxide
CO	carbon monoxide
CO_2	carbon dioxide