Comparison of Fine Mass, UC Davis DRUM versus FRM, at the ARB 13th and T Street Site

May 28, 2009

Thomas A. Cahill and David E. Barnes, UC Davis DELTA Group, and the Breathe California of Sacramento-Emigrant Trails Health Effects Task Force
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Executive Summary

A recent analysis (Lippmann, 2009) has concluded that continuous size, time, and compositionally resolved data are needed to allow health researchers to connect the statistical impacts of aerosols on health to the causal components. The UC Davis rotating drum impactor (8 DRUM), widely used in research studies, offers many of the aerosol sampling capabilities desired for aerosol monitoring for health impact studies, including size and time resolution, continuous mass and elemental analysis, especially when enhanced by addition of a filter to collect ultrafine mass. In order to compare with current 24 hr PM$_{2.5}$ data, we must sum 48 individual DRUM mass measurements/day by size and time to the mass of a standard 24 hr Federal Reference Method (FRM) filter, although there is no intent to have the inherently less precise DRUM replace regulatory instrumentation. With ARB concurrence (see Appendix A), a DRUM with ultrafine stage was operated for one year side by side with standard FRM aerosol sampling at the ARB 13th and T Street site in order to compare masses collected by the DRUM to standard mass measurements. An example during a period of high fine (23.1 µg/m$^3$) and ultrafine (12.3 µg/m$^3$) mass is shown below.

The agreement over the entire 43 day comparison was good, with a ratio DRUM to FRM of 1.01 ± 0.21, despite the inherent propagation of uncertainty problem of combining 48 mass DRUM measurements/day into a single PM$_{2.5}$ FRM mass value.
# Table of contents

Introduction 4  
Background 5  
   Existing ARB data at the 13th and T Street site 5  
Experimental procedures 6  
   Sampling methodology and quality assurance 6  
   Analytical methodology and quality assurance 7  
Results 10  
   January 12 – February 20 10  
   February 20 – March 24 16  
   August 23 – October 2 18  
   October 2 – November 8 22  
   November 8 – December 13 23  
Conclusions 25  
Future Work 26  

Appendices  
Appendix A  Letter from Robert Sawyer 27  
Appendix B  Costs 28  
Appendix C  Ancillary studies 28  
   1. Mass closure for the ultra fine filters 28  
   2. Comparison of aerosols at Sacramento Country Day School 29  
      (well removed from all freeways) and the 13th and T Street site. 29  
   4. Organic matter from DRUM impactors 31  
Appendix D  DRUM publications 32
List of figures

Figure 1  24 hr PM$_{2.5}$, 13th and T Street, annual, 2007  5
Figures 2 and 3 DRUM sampler in enclosure at the ARB 13$^{th}$ and T Street site, (top) with parallel ARB samplers (bottom) 7
Figure 4 Precision of mass measurements for 5.0 to 2.5 µm diameter particles as part of the US EPA continuous ultra fine DRUM development. 8
Figure 5 Analysis of the very fine particle size mode at Roseville rail yard. 9
Figure 6 Weather in Sacramento, Winter, 2007  10
Figure 7 NOAA HYSPLIT trajectories  11
Figure 8 DRUM samples, winter, 2007  11
Figures 9 and 10 Mass values for the DRUM sampler (top) and ARB filters (bottom). 13
Figures 11 and 12 Plots of DRUM mass data, reduced to 24 hr values, versus ARB 24 hr filter data. 14
Figure 13 Sacramento weather for the February – April period  16
Figure 14 Qualitative comparison between DRUM mass and ARB 24 hr filter data 17
Figure 15 ARB PM$_{2.5}$ mass for fall and winter, 2007.  18
Figure 16 Weather for the Period III summer sampling from August 23 to Oct 2 18
Figure 17 DRUM samples from the summer sampling period. 19
Figure 18 PM$_{2.5}$ mass from the ARB 13$^{th}$ and T Street site 19
Figure 19 DRUM PM$_{2.5}$ mass from the ARB 13$^{th}$ and T Street site 20
Figure 20 MODIS satellite image of the Moonlight fire on September 5, 2007  21
Figure 21 Sacramento weather for the Period III fall sampling 22
Figure 22 PM$_{2.5}$ mass data from the ARB 13$^{th}$ and T Street site 22
Figure 23 DRUM PM$_{2.5}$ data from the ARB 13$^{th}$ and T Street site 23
Figure 24 Sacramento weather for the winter, 2007 sampling period. 23
Figure 25 PM$_{10}$ and PM$_{2.5}$ DRUM mass for the Period III winter sampling 24
Figure 26 PM$_{2.5}$ DRUM mass and ARB filter mass for the Period III winter Sampling 24
Figure 27 PM$_{2.5}$ DRUM mass and ARB filter mass for the Period III winter sampling. The slope was about 10% above unity and $r^2 = 0.74$ 25

List of tables

Table 1  S-XRF comparison, all blind tests since 1999  9
Introduction

“One of the most urgent needs for future progress in reducing the substantial impacts of ambient air particulate matter (PM) on human health is to determine which of the components are having the greatest effect.” … “Furthermore, because of cost considerations, there is virtually no prospect of collecting the data needed by health researchers for more definite analyses as long as there is continued reliance on current FRM sampling and analysis methodologies.”\(^1\) This statement in Lippmann’s paper was based on two national meetings and a summary of work done using the US EPA Speciation Trends Network (STN), which has full composition for fine particles every 3rd day at circa 150 sites. The consensus was that the health community urgently needs continuous data, time resolved to at least 6 hours, size resolved into at least 5 size modes, including ultra fines, with mass and composition, as a foundation for epidemiology studies like the Dockery et al 1994, Six Cities Study. Recall that this pivotal study was only possible because a dichotomous network had been deployed years before.

A credible method for generating such data at reasonable cost is via rotating stage drum samplers developed by Dale Lundgren in 1967. Their use was key to the lead and catalytic converter studies 1972 - 1974, and pioneered in California for monitoring 14,100 sampling days 1973 – 1977 in 3 size modes, 15 to 3.5, 3.5 to 0.5, and 0.5 to 0.0 micrometers (Flocchini at al, 1976 ff to Motellabi et al, 1992). This program expanded to the US EPA national parks program in 1977, but died as the US EPA insisted on dichotomous filter samplers for air monitoring. Drum samplers continued to be developed (Cahill et al, 1985, Raabe et al, 1988, Bench et al 2002) and became an essential research tool for US EPA, IMPROVE, NPS, National Science Foundation Atmospheric Sciences and Polar Programs, and NOAA programs, 1988 – present. (Appendix D. publication list)

These newer versions, the Davis Rotating-drum Unit for Monitoring (DRUM) began to be examined as a potential air monitoring asset in the ARB Fresno Asthmatic Children’s Study, FACES (2001) and by TRPA and CalTrans with the ARB Lake Tahoe Atmospheric Deposition Study of 2003, as analytical improvements allowed for the first time measurements of mass versus size and time to supplement the excellent synchrotron induced x-ray fluorescent (S-XRF) capability developed by the NSF for our research programs. The purpose of this current study was to extend the proven capabilities of the UC Davis DELTA Group 8 stage (10, 5.0, 2.5, 0.75, 0.56, 0.34, 0.26, 0.09 \(\mu\)m diameter) rotating drum impactor (8 DRUM) to ultrafine particles via fixed ultrafine after filters capable of mass and compositional analyses, and validate the mass versus FRM fine mass measurements. Breathe California of Sacramento-Emigrant Trails (BCSET) covered all direct costs for this work. We also used the opportunity to perform a number of ancillary studies, and the site hosted a small US EPA study to develop continuous ultrafine capability, 2008 – 2009.

\(^1\) Lippmann, M, Semi-continuous speciation analysis for ambient air particulate matter: An urgent need for health effects studies, J. Exposure Science and Environmental Epidemiology 19, 235 – 247 (2009)
Background

The existing federal and state aerosol monitoring efforts, primarily mass in PM$_{10}$ and PM$_{2.5}$ modes, even when supplemented by hourly mass (BAMS, TEOMs) and circa 250 24 hr PM$_{2.5}$ speciation (IMPROVE, STN) sampling sites, appear inadequate to deliver the types of data necessary to tie the statistically sound health impacts with specific causal components. The latter include at least 6 potential agents (Devlin EPA 2003): coarse mass, 2.5 to 10 µm, acidic aerosols, biological aerosols, fine transition metals – free radicals, ultra fine insoluble metals, and high temperature organics such as diesel.

The BCSET Health Effects Task Force (HETF) gained approval of the ARB to perform a full year (2007) of sampling at the 13th at T Street ARB site to evaluate the usefulness of size (9 modes < 10 µm including 2 week integrated ultrafine filters), time (3 hr), and compositionally resolved aerosols data from UC Davis DELTA Group DRUM samplers, with the goal of enhancing existing monitoring networks. In particular, we were asked to examine how well does a modified DRUM sampler with ultrafine after filter correlate with filter-based FRM PM$_{2.5}$ samplers.

1. Existing ARB data at the 13th and T Street site

The first task was to extract the existing mass data from the ARB sites at 13th and T Street from the ARB website (http://www.arb.ca.gov/ADAM). Below we show the annual 24 hr PM$_{2.5}$, 13th and T Street site for 2007.

![Figure 1 24 hr PM$_{2.5}$, 13th and T Street, annual, 2007](image-url)
Experimental Procedures

1. Sampling methodology and quality assurance
With the help of UC Davis DELTA Group and BCSET volunteers and staff, sampling was begun in January 12, 2007, and continued until December 13, 2007. Field support needs were modest (circa 1 hr every 2 weeks), supplied by BCSET HETF.

   a. DRUM sampler (Cahill et al, 1985, Raabe et al, 1988)
      The sampler used was the upgraded slotted DELTA Group 8 DRUM, operating with Apiezon-L coated Mylar substrates (Wesolowski et al, 1978), developed for the IMPROVE/EPA BRAVO study of 1999, with a number of upgrades built into the 28 new 8 DRUMS built in 2006-2007:
      i. Rugged watertight Pelican cases,
      ii. Rotation was provided by an electronic M-drive, allowing rapid conversion of sampling duration of 2, 4, 6, 12, or 24 week duration, with typical time resolution of 1, 2, 3, 6, or 12 hr duration,
      iii. Redundant flow meters based on critical orifices vacuum and stage to stage pressure drops, readable on front panel gauges,
      iv. Computer run protocol that puts 2 positive and 3 negative time signatures on each drum strip, include a 6 mm mid-run blank.

   b. Audit devices
      i. Front end Magnehelic™ low pressure drop orifice meters, calibrated by a Collins spirometer,
      ii. Externally calibrated dry gas audit unit.

The protocol chosen for the study was a 6 week duration yielding 3 hr time resolution (1 ½ hr available during analysis if needed).

From January 12 through February 20, the DRUM operated as per specification and met all quality assurance guidelines, including agreement of all flow readings within ± 5% and rotation duration matching external clock time.

Beginning on February 20, due to the Trestle fire, sampling was interrupted so that the trestle smoke could be analyzed separately. This, plus some operational problems, do not allow February 21 through August 22 data to be used for quantitative comparison. A subtle temperature –vacuum mechanical interaction required DRUM modifications to handle increasing ambient temperatures, which were completed and field tested by summer. Beginning of August 23, the DRUM ran well until the end of the study on December 13, 2007.
Figures 2 and 3 DRUM sampler in enclosure at the ARB 13th and T Street site, (top) with parallel ARB samplers (bottom)

2. Analytical methodology and quality assurance

Mass – accuracy
Accuracy for filters was established by adopting IMPROVE protocols with a Cahn 31 microbalance and Class M standards with periodic scale checks. Tare
was set before and after each measurement, and had to fall to < 5 µg for an acceptable measurement. Mass accuracy for the soft beta system was established by comparison to weighted Mylar strips and the filter protocol (above). 6 thicknesses from 0.2 to 2.2 µg/cm² were used to span the range of deposits seen by the beta gauge.

**Mass – precision**
Repeated pre and post gravimetric measurements yielded a precision for the filters of ± 0.5 µg/m³. Mass precision for the soft beta ray gauge was established by repeated measurements, done after dismounting and remounting the strip. Two examples are shown below.

![EPA New York City DRUM Study](image)

Figure 4  Precision of mass measurements for 5.0 to 2.5 µm diameter particles as part of the US EPA continuous ultrafine DRUM development.

In Figure 4, the mean mass precision was 20 µg/cm², equivalent to 0.3 µg/m³.

Another example comes from the Roseville Railyard studies. Analysis was completed for mass values every 1 ½ hours in 8 size modes for the Roseville Railyard study. Each strip was analyzed at least 2 times, (below) and the standard deviation of the data are included in the data file.
Quality Assurance Precision Test of RRAMP DRUM strips
UC Davis DELTA Group soft beta ray mass analysis
Denio DRUM #8 Stage 8 0.26 > Dp > 0.09 microns

Run #1
Run #2

Figure 5  Analysis of the very fine particle size mode at Roseville rail yard.

Here the precision was slightly better, equivalent to 0.25 \( \mu \)g/m\(^3\). Note that since the strip was remounted, the test also validates relative time precision. Any measurements where the analysis differs by more than ± 10% is independently re-run until agreement is achieved. A number of samples were analyzed by synchroton induced x-ray fluorescence.

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Table 1 S-XRF comparison, all blind tests since 1999
The S-XRF system has been tested in blind inter-comparisons since 1999, and all of these are shown above. Typically 32 elements are recorded for each analysis, all of which can be traced back to NIST primary (SRM # 1832, SRM # 1833) or secondary (Micromatter thin film) standards. Over 250,000 S-XRF analyses have been done by the DELTA Group since completion of the system in 1999.

The complete DRUM quality assurance is posted in DRUM Quality Assurance Protocols ver 1/09 on the DELTA web site, http://delta.ucdavis.edu

Results
1. Comparison with ARB mass data
January 12 – February 20

The weather in Sacramento, winter, 2007, was the driest January on record, with persistent haze, low wind velocities and strong inversions.

![Sacramento Weather 2007](image)

Figure 6 Weather in Sacramento, Winter, 2007 (the driest January on record) with approximate averaged ground based wind directions. The haze is approximated by the reduction of visibility below the nominal “perfect” airport visibility of 10 miles.
Figure 7  NOAA HYSPLIT trajectories – typical, day and night, for regional wind directions. The three different colors represent 200, 500, and 1000 m above ground level.

Figure 8 DRUM samples, winter, 2007. The dark bands are nighttime.
The effect of strong winds on Jan 12 and Jan 20 are clearly seen, while the clean band in the middle is a period without air flow introduced by the DRUM program to provide both a timing marker and an additional blank. It is removed in the final averaged data.

a. Mass values

Mass values were measured by soft beta ray transmission and attenuation for all 8 DRUM stages in 3 hr increments. In addition, the Teflon after filters were allowed to collect aerosols for a 2 week period and weighed before and after on a Cahn 31 electro-balance with IMPROVE protocols. (Malm et al, 1994)

Below in Figure 9 and 10 we compare the results of the DRUM mass values versus the ARB’s 24 hr PM$_{2.5}$ mass values (http://www.arb.ca.gov/ADAM) for the same period. Such comparisons are always difficult in that:

1. it takes 48 values for the DRUM sampler to equal one 24 PM$_{2.5}$ value for the filter work, with inherent propagation or errors, especially insensitive to the exact blank subtraction,

2. timing is exact for the filters but inexact for the DRUM, since
   a. the finest slots equal an averaging over 1 hr 15 minutes, and the coarse slots 6 hrs or more (DQAP ver 1/08), and
   b. The DRUM with absolute timing errors between 1 ½ and 3 hr can’t match the exact start and stop time for the filter, important when some parameters have strong patterns in time.
Figures 9 and 10 Mass values for the DRUM sampler (top) and ARB filters (bottom). The 2 week ultrafine filter data were added, scaled to PM$_{1.0}$ to avoid the fine tail of the soil distribution which extends down to about 1 \( \mu \)m but is not present below.

The after filter integrates over two weeks and thus this mass must be added to the DRUM stages with some assumption. We scaled to the DRUM PM1.0 mass so as to avoid the presence of fine tail of the soil mass distribution which extends to about 1 \( \mu \)m but not below. The agreement is about as good as one can expect under the inherent limitations, but show that no significant mass is lost in the process.

The result of these analyses was an average PM2.5 mass for the DRUM of 23.2 \( \pm \) 1.0 \( \mu \)g/m$^3$ versus the ARB 24 hr samples of 22.1 \( \mu \)g/m$^3$. DRUM field blank values were 0.7 \( \mu \)g/m$^3$. 
One key mass finding was that in this period, most of which was an essentially rainless, fogless period with calm winds, the driest January in history, more than half of all the mass, 12.3 µg/m³ out of 23.1 µg/m³ PM$_{2.5}$ via DRUM, (22.1 µg/m³ PM$_{2.5}$ via ARB FRM), lay in the < 0.09 µm mode.
Is this result credible? For example, if the lower cut point of the DRUM, 0.09 µm, was actually much higher than that, say 0.15 µm, mass would end up on the after filter that should have been caught on the DRUM stages, artificially raising the ultra fine mass. The conversion constant for measured mass on the filter is about 3 x greater than that on the stages. Thus, if some mass were placed on the filter that didn’t belong there, it would by converted into µg/m³ at 3 x the correct rate, resulting in total DRUM plus filter masses too high. The agreement with the ARB filters constrains this option, so the cut point is probably about right. This is supported by laboratory and theoretical studies by Marple et al (1974) and Raabe et al (1988) for the jetted and slotted DRUM. The same argument applies for bounce-down from higher stages to the filter, which is extremely low in sub micron stages.

On the other hand, the after filter is at about 1/3 of an atmosphere pressure and in an air stream cooled by expansion through the final slot. Artifact collection of semi-volatile materials is a possibility. However, this would have to be balanced by loss of material on the DRUM stages for which no evidence exists. Elemental analysis of the DRUM strips in one of the ancillary studies in the Appendices supports this conclusion.

There are potential health consequences of such a high average mass value in ultrafine particles depending on their composition.
2. Feb 20 – March 24

Sacramento Weather 2007

As mentioned above, there were a number of technical difficulties in this period, the most important of which was the loss of the Stage 8 ($0.26 > D_p > 0.09 \mu m$) Mylar foil and all samples, which also put shreds onto the after filters. An additional complication was smoke from the Trestle fire in mid March. In fact, little smoke was seen in at 13th and T Street, but impact was seen at Watt Avenue.

Note in Figure 14 below the much lower levels of PM$_{2.5}$ mass in this period as compared to January 12 through February 20.
Figure 14 Qualitative comparison between DRUM mass and ARB 24 hr filter data. Note that the very fine particles $0.26 > D_p > 0.09 \mu m$ were lost due to failure of the Mylar support film.
3. August 23 – October 2

![PM2.5 Mass at ARB's 13th and T Street Site](image)

PM2.5 Mass at ARB’s 13th and T Street Site  
September 2007 - December, 2007  
- 13th and T Street

Figure 15 ARB PM$_{2.5}$ mass for fall and winter, 2007.

![Sacramento Weather 2007](image)

Sacramento Weather 2007  
- Wind velocity  
- Visibility reduction below 10mi  
- Rainfall inches (x 10)

Figure 16 Weather for the Period III summer sampling from August 23 to Oct 2.
Figure 17  DRUM samples from the August – October sampling period. The intense bands on Stages 6 and 7 are from the Moonlight forest fire.

Figure 18  PM$_{2.5}$ mass from the ARB 13$^{th}$ and T Street site
Figure 19 DRUM PM$_{2.5}$ mass from the ARB 13$^{th}$ and T Street site. The time marker/central blank has been left in the data.

The large mass peak on September 5 and 6 was associated with downslope night winds from the Moonlight forest fire. The DRUM data averaged 8.8 $\mu$g/m$^3$, versus 10.0 $\mu$g/m$^3$ for the ARB filters.
Northerly winds drove the Moonlight Fire south through the Plumas National Forest in Northern California on September 5, 2007. According to reports from the National Forest Service, the fire had grown to 28,000 acres since its start on September 3, and mandatory evacuations were in effect on September 6. The cause of the fire was still being investigated. This image from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA’s Aqua satellite shows the fire spreading smoke over the Sacramento Valley on September 5. The area where MODIS detected actively burning fire is outlined in red.

A wind shift from the north on September 5 and 6 brought the smoke into Sacramento.
4. October 2 – November 8

![Sacramento Weather 2007](image)

Figure 21 Sacramento weather for the fall Period sampling

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Figure 22 PM$_{2.5}$ mass data from the ARB 13$^{th}$ and T Street site
Average PM$_{2.5}$ mass in this period was 18.9 µg/m$^3$ by the DRUM with afterfilters and 14.3 µg/m$^3$ by ARB filters.

5. November 8 – December 13

Figure 24  Sacramento weather for the winter, 2007 sampling period.
Figure 25  ~ PM$_{10}$ and PM$_{2.5}$ DRUM mass for the winter sampling period.

Figure 26  PM$_{2.5}$ DRUM mass and ARB filter mass for the winter sampling period.
Figure 27 PM$_{2.5}$ DRUM mass and ARB filter mass for the winter sampling period. The slope was about 10% above unity and $r^2 = 0.74$

**Conclusions**

Annual aerosol sampling by the 8 DRUM impactor at the ARB 13$^{th}$ and T Street Site has proven to be cost effective ($15,000./year) way to obtain size (9 modes including ultra fine filter), time (3 hour), and compositionally resolved (ex post facto studies at additional cost) aerosol data for health and regulatory needs while being comparable in total mass to co-located mass instrumentation.

1. A summary of results includes good agreement between ARB 24 hr filters and the sum of 49 individual DRUM stages and filter:

   - Jan - Feb   \(23.2 \pm 1.9 \, \mu g/m^3\) 12.3 uf, DRUM, \(22.1 \, \mu g/m^3\) ARB.
   - Aug – Sept. \(8.9 \pm 1.9 \, \mu g/m^3\) 7.1 uf, DRUM, \(10.2 \, \mu g/m^3\) ARB.
   - Sept - Nov \(18.9 \pm 1.9 \, \mu g/m^3\) 9.0 uf, DRUM, \(14.3 \, \mu g/m^3\) ARB.
   - Nov. – Dec. \(9.1 \pm 1.9 \, \mu g/m^3\) 2.0 uf, DRUM, \(11.6 \, \mu g/m^3\) ARB.
   - Field Blank \(0.8 \, \mu g/m^3\)

The average difference for all 150 daily mass comparisons (6,900 individual DRUM mass values) was \(1.01 \pm 0.21\). The dominant components of the DRUM uncertainty were the propagation of errors associated with establishing the background of 48 separate DRUM values per single ARB PM$_{2.5}$ filter, and the variability in ultrafine filter mass, typically $\pm 1 \, \mu g/m^3$. 
Future Work

Future work should address the uncertainties in this program. We can identify a number of useful studies:

1. Laboratory tests of the cut points of this slotted DRUM should be performed by a third party laboratory such as Aerosol Dynamics Inc. We are initiating additional in-house tests for sizing this summer, focusing on the final Stage 8 slot with its 0.09 µm cut point.

2. It would be important for the upgraded 8 DRUM to be operated side by side with a MOUDI impactor at the 13th and T Street site, especially in winter conditions. We would propose both a standard MOUDI with afterfilter and a nano-MOUDI, since they handle ultra fine particles differently. Two DRUM units with integrating uf after filters should be run for precision. All samples should be analyzed for mass.

3. Existing instrumentation for ultrafine particles by number should be operated side by side with the DRUM (and the MOUDIs?) as a way to tie the extensive information on ultrafine particles by number to ultrafine particles by mass and composition.

Note that some of these tests will be performed this summer in a USD EPA/UC DELTA Group study in Cleveland with 4 slotted DRUM impactors – 2 with continuous ultrafine stages, (see Appendix C), one indoors with uf filters, and one for organic matter with uf filters.
Appendix A

March 23, 2005

Thomas A. Cahill, Ph.D.
Breathe California of Sacramento-Emigrant Trails
909 12th Street, Suite 100
Sacramento, California 95814

Dear Dr. Cahill:

Tom,

I enjoyed meeting with you and other representatives of Breathe California of Sacramento-Emigrant Trails (Breathe California) last week. Our mutual interests and concerns are many and I look forward to a productive relationship with your organization during my tenure as Air Resources Board (ARB) Chair. I asked ARB staff to consider your proposal to collaborate on monitoring aerosol mass at the ARB 13th and T site. I am pleased to say that we can respond affirmatively to the majority of your request.

ARB is willing to contribute in-kind resources to implement Breathe California's proposal to collect twelve months of very fine and ultra fine particulate matter in Sacramento. Specifically, we will provide space, power and the requested staff support to the project. In order to effectively perform the tasks, we will need detailed operating instructions, operator training, and a twelve-month sampling schedule for both the OASIS and the Ultra Fine Filter Sampler. Please contact Debra Pogejoy, Manager, Air Monitoring North Section, at 916-327-4725, or via email at dpo@arb.ca.gov to coordinate installation and operation of these devices.

Sincerely,

Robert F. Sawyer, Ph.D.
Chair

cc: Betty Turner
Breathe California of Sacramento-Emigrant Trails

Debra Pogejoy
Air Resources Board
Appendix B: Cost and Operational Requirements

The costs and operational requirements for sampling and analysis of a one year period of DRUM operations were quantified by analysis of the effort required during this current study. They include:

a. Equipment: DRUM samplers are available from a commercial supplier at a cost currently of $8,600.

b. Field operations: Labor averaged about 2 hrs/month, including an ultra filter change every 2 weeks.

c. Supplies: The filters cost about $120./year, and a $500 annual pump replacement is recommended.

d. Analysis of the samples: mass and optical data are being re-calculated by UC Davis, with a reduction in rate to about $150.,/strip of 340 values. This means that every 6 week period costs $1500., including overhead. For an entire year, the analytical costs are about $13,500.

e. Analysis of data: This can be done by in-house staff, by external contract with a local university, or a commercial company. The level of effort should be at about 0.25 FTE in order to gain the benefit of the thousands of measurements provided annually.

Appendix C: Ancillary studies

1. Mass closure for the ultrafine filters

As part of the US EPA study, the ultrafine filters from the present study were analyzed by S-XRF for elements and Proton Elastic Scattering Analysis for hydrogen, and organic surrogate used by IMPROVE. (Malm et al, 1994). Mass closure was achieved under the assumption of minimal ultrafine nitrates. About ½ the mass was diesel and smoking car exhaust, with smoke and transition metals of unknown source.

<table>
<thead>
<tr>
<th>Major components</th>
<th>ug/m3</th>
<th>Minor components</th>
<th>ng/m3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>filter</td>
<td></td>
<td>filter</td>
</tr>
<tr>
<td>Mass (gravimetric)</td>
<td>2.04</td>
<td>Phosphorus</td>
<td>2.4</td>
</tr>
<tr>
<td>Mass (reconstructed)</td>
<td>2.15</td>
<td>Vanadium</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chromium</td>
<td>0.45</td>
</tr>
<tr>
<td>Organic</td>
<td>1.72</td>
<td>Nickel</td>
<td>3.5</td>
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<tr>
<td>Diesel PM (est.)</td>
<td>na</td>
<td>Copper</td>
<td>8.3</td>
</tr>
<tr>
<td>Ammonium Sulfates</td>
<td>0.34</td>
<td>Zinc</td>
<td>11.5</td>
</tr>
<tr>
<td>Salt</td>
<td>0.04</td>
<td>Arsenic</td>
<td>0.6</td>
</tr>
<tr>
<td>Soil</td>
<td>0.048</td>
<td>Selenium</td>
<td>0.3</td>
</tr>
<tr>
<td>K non</td>
<td>0.053</td>
<td>Bromine</td>
<td>3.7</td>
</tr>
<tr>
<td>Metals</td>
<td>0.035</td>
<td>Lead</td>
<td>4</td>
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</tbody>
</table>

Table 1 Mass reconstruction from 2 week integrated ultrafine filters, December, 2007.
2. Comparison of aerosols at Sacramento Country Day School (well removed from all freeways) and the 13th and T Street site.

As an example of this work, below we show the signature of fresh wood smoke, non soil potassium in the 0.34 to 0.26 µm size mode, for January and February, 2007.
3. **US EPA continuous ultra fine DRUM capabilities, 2008 - 2009**

The US EPA funded a small grant to develop the capability for continuous ultra fine measurements by mass and elemental composition. Mass data are shown below.

![EPA Continuous ultra-fine Study](image-url)

*EPA Continuous ultra-fine Study*
DELTA 8 DRUM, ARB 13th and T Street site

- **PM10**
- **PM2.5**
- **Ultrafine mass**

Micrograms/m³

<table>
<thead>
<tr>
<th>7</th>
<th>8</th>
<th>Micrograms/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>20</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>25</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>30</td>
<td>25</td>
<td>20</td>
</tr>
</tbody>
</table>

December

| 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 1 | 2 | 3 | 4 | 5 | 6 |

January
4. Organic analyses from DRUM samplers

At the same time the 13\textsuperscript{th} and T tests were proceeding, a study was being made of organic aerosols via paired DRUM samplers with ultrafine after filters near Watt Avenue and 540 m upwind of Watt Avenue at Sebastian Way. Organic data from ultrafine filters and DRUM stages were 4 week averages, while S-XRF elements and mass were 3 hr increments.

Hundreds of organic species were measured in 9 size modes over 4 sampling periods. They include PAHs, organic acids, sugars, and n-alkanes. An example is shown below for PAHs.

The presence of benzo[e] (and benzo[a]) pyrene in the 0.34 to 0.26 micron mode was from very local wood smoke, as confirmed by both levoglucosan and very fine potassium via S-XRF. The ultrafine organics had an admixture of wood smoke and vehicular signatures.

Note the excellent agreement between independent DRUM samplers even at low organic mass values.
Appendix D: Delta Group DRUM publications

We provide here only those publications using the slotted DRUM configuration developed for IMPROVE/YUS EPA for BRAVO and now used for all future DRUMs.

History: The Air Quality Group (AQG, 1971 – 1997) and the Detection and Evaluation in Long-range Transport of Aerosols (DELTA Group, 1997 – present) have always preferred on fundamental and scientific grounds to perform experiments with continuous sampling of size and compositionally resolved aerosols. The samplers used have varied in time (typical time resolutions have and can be varied at will):

1. Lundgren sampler 1972-1974 , thereafter 5 stages, slots, 4 hr resolution, 160 L/min
2. Multiday sampler 1973 – 1981 3 stages, slots, 24 hr resolution 35 L/min
3. DRUM samplers
   a. Jetted 8 DRUM 1985 – 1995 8 stages, jets, 3 hr resolution, 1.0 L/min
   b. DELTA 8 DRUM 1996 – 2001 8 stages, slots, 3 hr resolution 10.0 L/min
   c. DELTA 8 DRUM, 2001 – 2005 8 stages, slots, 3 hr resolution 16.7 L/min
   d. DELTA 3 DRUM, 2001 – 2005 3 stages, slots, 3 hr resolution 22.5 L/min
   e. 8 DRUM upgrade, 2005 – 2008 8 stages, slots, 3 hr resolution 16.7 L/min

Publications from DRUM samplers (slotted, 3 and 8 stage, types b through e)

Emma Pere-Trepat, Eugene Kim, Pentti Taatero, and Philp K. Hopke, Source Apportionment of time and size resolved ambient particulate matter measured with a rotating DRUM impactor, Atm. Env. (September, 2008)


Seinfeld, J.H., Carmichael, G.R., Arimoto, R, Conant, W. C., Brechtel, F. J., Bates, T. S.,
Cahill, T. A., Clarke, A.D., Flatau, B.J., Huebert, B.J., Kim, J., Markowicz, K.M.,
Masonis, S.J., Quinn, P.K., Russell, L.M., Russell, P.B., Shimizu, A., Shinozuka, Y.,
ACE-Asia: Regional Climatic and Atmospheric Chemical Effects of Asian Dust and 
Pollution, Bulletin American Meteorological Society 85 (3): 367+ MARCH 2004

Han, J.S, K.J. Moon, J.Y. Ahn, Y.D. Hong, Y.J Kim, S. Y. Rhu, Steven S. Cliff, and 
Thomas A. Cahill, Characteristics of Ion Components and Trace Elements of Fine 
Particles at Gosan, Korea in Spring Time from 2001 to 2002, Environmental Monitoring 
and Assessment 00: 1-21, 2003

Thomas A. Cahill, Steven S. Cliff, Michael Jimenez-Cruz, James F. Shackelford, Michael 
Dunlap, Michael Meier, Peter B. Kelly, Sarah Riddle, Jodye Selco, Graham Bench, 
Patrick Grant, Dawn Ueda, Kevin D. Perry, and Robert Leifer, Analysis of Aerosols from 
the World Trade Center Collapse Site, New York, October 2 to October 30, 2001. 


Reuter, John E., Cahill, Thomas A., Cliff, Steven S., Goldman, Charles R., Heyvaert, 
Alan C., Jassby, Alan D., Lindstrom, Susan, and Rizzo, Davis M., An Integrated 
Watershed Approach to Studying Ecosystem health at Lake Tahoe, CA-NV, in Managing 

V. Shutthanandan, S. Thevuthasan, R. Disselkamp, A. Stroud, A. Cavanaugh, E.M. 
Adams, D.R. Baer, L. Barrie, S.S. Cliff, T.A. Cahill. Development of PIXE, PESA and 
transmission ion microscopy capability to measure aerosols by size and time. 2001 Nuclear Instruments and Methods in Physics Research B: Beam Interactions with 
Materials and Atoms.

Graham Bench, P.G. Grant, D. Ueda, S.S. Cliff, K.D. Perry, and T. A. Cahill. The use of 
STIM and PESA to respectively measure profiles of aerosol mass and hydrogen content 
across Mylar rotating drum impactor samples. 2001 Aerosol Science and Technology 
36:642-651.

Miller, Alan E. and Thomas A. Cahill. Size and compositional analyses of biologically 
active aerosols from a CO2 and diode laser plume. 2000 International Journal of PIXE. 
Vol. 9, Nos. 3 & 4.

Perry, Kevin D., Thomas A. Cahill, Russell C. Schnell, and Joyce M. Harris. Long-range 
transport of anthropogenic aerosols to the NOAA Baseline Station at Mauna Loa 
No. D15, Pages 18,521-18,533.