

Prototype PM_{2.5} Federal Reference Method Field Studies Report

---- An EPA Staff Report ----

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July 9, 1997

ACKNOWLEDGMENTS

The Federal Reference Method (FRM) field comparison involved many field and laboratory operators from different organizations. The authors wish to thank Mr. Thomas Merrifield (now with Met One Instruments, Grants Pass, OR) of Graseby Andersen (Atlanta, GA) for his efforts in supplying the dichotomous samplers, calibrating the prototype FRMs, and providing training in the operation of FRMs at Birmingham, AL; Denver, CO; Phoenix, AZ; and Bakersfield, CA. Special thanks to the field and laboratory support of the following staff and agencies: Randy Dillard, Oscar Smith, Ann Bobbs, Roger Clark, and Jackie Walland of the Jefferson County Department of Health; Gary Kenniston, Dan Ely, Gordon Pierce, Bill Kotasek, Jim Von Feldt, and Roy Sheets of the Colorado Department of Public Health and Environment; Terry Taflinger, Clay Juniel, and Randy Redmen of the Arizona Department of Environmental Quality; Al Cota of the Pima County Department of Environmental Quality; Dave Dietrich of Air Resource Specialists; Jack Romans, Steve Rider, Debbie Bruce, Phil Powers, and Lesteris Koumis of the California Air Resources Board; and Antonio H. Miguel of Aerosol Dynamics Inc. C. Fred Rogers, Steve Kohl, and Norm Robinson of the Desert Research Institute prepared plots and data analysis summaries, and Norman Mankim assisted in producing and editing the report.

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I. INTRODUCTION

The purpose of this report is to communicate the results to date from field studies of the prototype PM_{2.5} Federal Reference Method (FRM) that have been conducted between November 1996 and May 1997. These include studies conducted at Birmingham, AL; Phoenix, AZ; Denver, CO; Bakersfield, CA; Tucson, AZ; and Azusa, CA. A common purpose of these field studies was to gain experience with and evaluate the operational and performance characteristics of the prototype FRM prior to it being accepted as the standard method for the new PM_{2.5} National Ambient Air Quality Standard (NAAQS).

The intent of a new Particulate Matter (PM) NAAQS is to protect against both long- and short-term exposure to fine particle pollution. Such exposure has been shown in epidemiological studies to be related to adverse health effects including premature deaths. Epidemiological studies employed a number of methods to measure, estimate, or infer fine particulate matter concentrations used in developing relationships to health effects. In order to provide a high quality, consistent approach for measuring fine particles, EPA has defined a method to measure the concentration of PM with aerodynamic diameter less than 2.5 µm (PM_{2.5}) that employs an air filtration type of sampler to collect particles that are subsequently weighed in the controlled environment of an analytical laboratory.

FRM samplers as described in Appendix L to 40 CFR part 50 must meet a combination of design and performance specifications. All of the sampler components that come in contact with the sampled air stream from the inlet to the filter are specified by design. This is to ensure that the particles collected by any FRM sampler, regardless of manufacturer, experience the same factors that control the fate of the particles (e.g., materials used, surface finishes and sample air flow characteristics). Design of other components of FRM samplers are left to manufacturers, so long as resulting samplers meet all of the prescribed performance specifications. Subparts A and E to 40 CFR part 53 identifies the specific tests to show conformance with all of the design and performance specification required by EPA prior to their designation of a PM_{2.5} sampler as an FRM. The field tests described in this report were designed to focus on the field-worthiness of the prototype FRM, and not intended to meet the requirements of these specific tests though they do provide some of the required information.

Design specifications of the FRM samplers include the use of an inlet that has previously been wind tunnel tested and approved for use in sampling PM₁₀. After the inlet, sample air is drawn through an inertial separator known as the WINS (Well Impactor - Ninety Six) which is designed to remove particles with aerodynamic diameter greater than 2.5 µm by impacting them on the bottom of an open topped aluminum cylindrical container. The impacting particles are trapped at the bottom of the well by the viscous effects of a silicone oil impregnated filter that covers the bottom of the well. PM_{2.5} particles follow the air stream which turns up and out of the well and is directed back down to a Teflon filter where the particles are removed

by filtration. Figure 1 is a drawing of the WINS separator components of the FRM. The WINS separator was designed by EPA specifically for use in the FRM. Samplers employing this device have not been subject to field evaluations prior to those reported on here.

Performance specifications include active monitoring of a number of operational characteristics of the sampler including sampler volumetric flow, temperature, and pressure. Unlike previous particle samplers, FRM samplers are required to maintain the temperature of the filter during and after sampling to within ± 5 °C of ambient temperature. This was specified in order to reduce the loss of volatile particulate materials and to improve the comparability of sampling regardless of such factors as whether the sampler was in direct sun or shade during and after sampling. To date, all of the FRM manufacturers have chosen to use active ventilation of the enclosure that surrounds the filter holder and WINS impactor as their method to meet the temperature performance specifications.

Design and performance specifications were released to the public (manufacturers) in early fall of 1996. As a result of a competitive procurement process, EPA Office of Research and Development (ORD) purchased 17 FRM prototype samplers from Graseby Anderson. These are referred to by the manufacturer as Reference Ambient Air Samplers (Model number RAAS2.5-1). The first four samplers, completed in early November 1996, were employed in field studies designed and managed by Desert Research Institute (DRI) staff under cooperative agreement (No. CX824291-01-1) to EPA Office of Air Quality Planning and Standards (OAQPS). The DRI-conducted studies took place at Birmingham, AL (November 1996), Denver, CO, at the Adams City site (December 1996 and January 1997), and Bakersfield, CA (January and February 1997). Six of the EPA-purchased RAAS samplers were employed in a field study in Denver, CO, at the Welby site by Research Triangle Institute (RTI) under contract to EPA ORD (No. 68-D5-0040). These samplers were used again in Azusa, CA, in a field study (March and April 1997) by Aerosol Dynamics Inc. staff under subcontract to RTI. Three RAAS samplers were loaned by EPA to the Arizona Department of Environmental Quality for field studies that they designed and carried out in Phoenix, AZ (December 1996 and January 1997), and Tucson, AZ (April and May 1997).

Except for the Denver-Welby site and Azusa field studies, all of the field studies employed additional PM_{2.5} particle samplers operated on the same schedule as the RAAS FRM samplers. In the Bakersfield study, a Partisol-FRM Model 2000 sampler from Rupprecht & Patashnick Co., Inc. was operated allowing the only comparison reported on here of FRM samplers from different manufacturers.

As indicated above, the seven field studies reported on here were sponsored by three organizations (EPA-ORD, EPA-OAQPS, and AZ-DEQ). At the Birmingham and Phoenix field studies, the Electric Power Research Institute (EPRI) independently sponsored deployment and operation of additional monitoring by scientist from the Harvard School of Public Health (HSPH) using a variety of

samplers and other methods. Samplers and analysis using IMPROVE (Interagency Monitoring of Protected Visual Environments) fine particle sampling and analysis methodologies were operated at the Denver-Adams City site, Bakersfield, and Tucson field studies. Additional organizations were also involved including state and local air quality agencies that provided field sites and operators, and Graseby Andersen, the manufacturer of the FRM samplers, who provided assistance, training, and quick turnaround fixes for problems identified in the RAAS.

Field study objectives and approaches to achieve them vary somewhat among the sponsoring organizations. However, the following two broad objectives are common to all of the field studies:

- (1) to determine the prototype FRM system field readiness and suitability; and
- (2) to determine its performance characteristics under a range of typical monitoring conditions.

Approaches employed to address the first objective involved identification of system and procedural problems and finding solutions where possible; establishing, evaluating, and refining operating procedures; and for some of the field studies, employing local agency technicians to better simulate "real world" operations and provide feedback concerning operations. The approach used to satisfy the second objective involved determining precision with three or more collocated FRM samplers operated for 20 or more sample periods (except 10 periods at Denver-Welby site); collocated operation of FRM with other PM_{2.5} samplers to characterize the degree of comparability (except at Denver-Welby and Azusa sites); and to assess the effects of various meteorological and aerosol conditions on the performance by having multiple field study sites which experienced a variety of ambient conditions.

This document reports information from the seven PM_{2.5} FRM field monitoring studies in a timely and integrated fashion. It is limited in scope to the PM_{2.5} mass concentration data developed by these programs, even though limited chemical speciation, particle size distribution, gaseous pollutant, and meteorological data are available for some of the studies. More detailed individual study reports or other publications are anticipated for some of the studies.

The report is organized into four major sections. The Introduction, Discussion, and Conclusions sections integrate information from the seven field studies; while the Field Studies section includes separate descriptions of each of the seven field studies following a brief joint description of the seven. Each individual description of the field studies includes subsections on site description, field study configuration and operation, laboratory facilities and procedures, and monitoring results. Variations in the format and level of detail of individual study descriptions are a result of having a variety of contributors.

II. FIELD STUDIES

The six different PM_{2.5} samplers used in the field studies are described in Table 1. Sampler flow rates ranged from 5 L/min to 21.5 L/min with 25- to 47-mm ringed Teflon-membrane filter substrates (Gelman Scientific, Ann Arbor, MI). The operating principle for each inlet is also identified in Table 1. These principles include direct impaction, virtual impaction, and cyclonic flow (Watson and Chow, 1993; Chow, 1995). Size-selective inlets define the particle size fraction being sampled. Variations of inlet type, sample flow rate, and sampling face velocity may result in differences in PM_{2.5} concentrations owing to the collection of different particle size fractions and different treatment of volatile aerosol components.

Field study site locations and equipment configurations are documented in Tables 2 and 3. For tests conducted in Birmingham, AL; Denver (both locations), CO; Bakersfield, CA and Azusa, CA; PM_{2.5} samples were acquired daily for 22- or 23-hour durations between noon and 10 am or 11 a.m. This sampling duration was chosen to accommodate daily sampling with instrument maintenance. Phoenix and Tucson, AZ tests collected 24-hour duration samples on an alternate- and every-third-day schedule allowing a non-test filter-change day for each sample period. As shown in Table 4, the studies collected samples for 10 (Denver-Welby site) to 26 (Denver-Adams City site) sample periods though not all samplers produced valid samples for each period.

Early in the first field test (Birmingham) it became apparent that particle build-up on the WINS impaction surface became visible in less than 24 hours of sampling. For most studies the oil impregnated filter impaction surface was replaced every fourth day. The WINS were wiped clean with absorbent tissues, rinsed with methanol, and air dried prior to installation of a clean 37-mm glass-fiber filter with 1 milliliter (ml) of nonvolatile diffusion pump oil. In the Azusa study, tests were conducted to determine the effects on the data caused by not maintaining a clean WINS impaction surface.

Birmingham, AL

Site Description:

The Birmingham field study was conducted at the North Birmingham site at 3009 28th Street, Birmingham, AL which is situated in a small valley bordered by hills to the east in a residential, commercial, and industrial area to the north of Birmingham's city center. The site is located in a small park that has residences to the north and south, a warehouse to the west, and a steel pipe manufacturing facility to the east. Adjacent streets are paved, curbed, clean, and lightly traveled. U.S. Route 31 lies 200 m west of the site and is a moderately traveled, paved and curbed commercial thoroughfare. Several large industrial operations are located to the east and northeast of the site, including steel manufacturing and coking. These contain many storage piles and are served by a dense and intensely used railroad

network. The North Birmingham site has been used for several decades to collocate and test particle sampling methods (Watson et al., 1981).

The North Birmingham site has been a National Air Monitoring Station (NAMS) site for 15 years where carbon monoxide (CO), ozone (O₃), and particulate matter (PM₁₀ and TSP) have been monitored. During the FRM field testing period between 11/04/96 and 11/23/96, the Jefferson County Department of Health also operated a Tapered Element Oscillating Microbalance (TEOM) to acquire hourly average PM₁₀ concentrations (not reported on here).

Study Configuration and Operation:

Birmingham site had three types of PM_{2.5} samplers. There were four of the Graseby Andersen RAAS units, three Graseby Andersen SA-244 Dichotomous Samplers, and two Harvard Impactors. Inlet height above the ground was about 4 meters with about 2 meter spacing between the inlets. Figure 2 shows the layout of the samplers and other instruments at the Birmingham site.

Two or more of the four RAAS units sampled on 17 of the possible 22 sample periods between 11/02/96 and 11/23/96. At least two of the three dichotomous samplers and at least one of the two Harvard Impactors operated on 21 of the possible 22 days. By design, the Harvard Impactors were operated in duplicate only four times to characterize precision for this field study. Flow rates and timers, and for the RAAS units temperature and pressure, were calibrated at the beginning of each sampling period and verified at the end of the period.

Limited availability of RAAS filter cassettes necessitated on-site loading of preweighed blank Gelman 47-mm Teflon filters into the Delrin cassette rings as well as post-sampling unloading of the filters. The procedures used to load and unload the RAAS filter cassettes in the field were very similar to those used at the DRI laboratory in Reno for the Dichotomous Sampler cassettes. These are discussed in the Laboratory Facilities and Procedures subsection below.

RAAS and Dichotomous Sampler filters were stored before and after sampling at less than 4 °C to minimize contamination and volatilization. If the sample was accidentally contaminated or dropped, this was noted in the comments section of the field data sheet. After field sampling, all filters were packed with blue ice in a cooler and shipped by overnight express courier to the DRI facilities in Reno, NV, for gravimetric analysis.

The WINS impactor was cleaned at least every four days and sometimes more frequently in these tests. The cleaning date and the appearance of the impactor surface (e.g., clean, light loading, heavy black loading, evidence of particle bounce) were noted on the field data sheet.

During cleaning, the WINS impactor assembly was removed from the inlet tube and separated to reveal the impactor well. The top of the well was removed and the used glass-fiber filter was extracted with an absorbent tissue. Oil and residue was wiped from the well with an absorbent tissue. A new 37-mm-diameter borosilicate glass-fiber filter (without binder, 1- to 1.5- μm pore size [ASTM F316-80], 300- to 500- μm thickness) was dropped into the impactor well and 1-ml drops of tetramethyltetraphenyl trisiloxane single-compound diffusion pump oil (maximum vapor pressure 2×10^{-8} mm Hg at 25 °C, viscosity 36 to 40 centistokes at 25 °C, density 1.06 to 1.07 g/cm³ at 25 °C) was poured over it (U.S. EPA, 1996a). The filter becomes transparent when it is fully wetted by the oil. The WINS was reassembled and oil was wiped from its exposed surfaces, especially those that might come into contact with the filter cassette. The WINS was then reinstalled into the sampler.

Harvard Impactors (HI) were operated independently on the same schedule as the RAAS and Dichotomous Samplers by staff from the Harvard School of Public Health. The HI (known commercially as the MST sampler) is a low flow particle sampler that uses an oiled impactor plate to minimize particle bounce and provide a sharp cut point. The PM_{2.5} HI samplers consist of an inlet, an impaction plate, and filter mounted in a plastic holder. In its standard configuration, the HI sampler flow is 10 L/min. The concentration of particles is determined from the calculated mass change on the filter by precise weighing under controlled temperature and relative humidity conditions and the total volume of air sampled (at local temperature and pressure). The design and performance of the HI sampler is described in Marple et al. (1987) and Lioy and Wainman (1988).

Laboratory Facilities and Procedures:

Teflon-membrane filters for the RAAS and Dichotomous Sampler were conditioned for at least one week in the temperature-(20°C to 23°C) and relative-humidity-(20% to 30%) controlled environment of DRIs Environmental Analysis Facility (EAF). This conditioning allows for outgassing of newly manufactured filters and minimizes spurious weight changes found for unconditioned filters (Tombach et al., 1987). Filters were individually examined over a light table to reject filters showing discoloration, pinholes, creases, or other defects. Approximately 2% of the filters in each filter lot were submitted to x-ray fluorescence (XRF) analysis for trace elements, and entire lots were rejected when any of the forty quantified elements showed detectable levels. No filter lots were rejected for contamination in this study.

Unexposed and exposed Teflon-membrane filters were equilibrated in a temperature- and relative-humidity-controlled environment for at least 24 hours prior to weighing. Filters were weighed on a Cahn 31 microbalance with $\pm 0.001 \mu\text{g}$ sensitivity. The electric charge on each filter was neutralized by exposing the filter to a polonium-210 source for 30 seconds prior to placing it on the balance pan.

The balance was calibrated with a 20.000 mg Class M weight and the tare was set prior to weighing each batch of filters. The calibration and tare were verified with standards after each ten filters were weighed. When balance readings differed from standard values by more than $\pm 5 \mu\text{g}$, the balance was recalibrated. When the difference in filter reweights exceeded $\pm 15 \mu\text{g}$, the balance was recalibrated and the previous 10 samples were reweighed. All unexposed filter weights and at least 30% of the exposed filter weights were checked by an independent technician. When an unexposed filter reweight differed from its original weight by more than $\pm 15 \mu\text{g}$, the filter was weighed again to determine its correct weight. When an exposed filter reweight differed from its original weight by more than \pm filters in the batch of 10 were reweighed. Pre- and post-weights, check weights, and reweights (when required) were recorded electronically and on data sheets associated with the corresponding filter ID code.

Filter loading and unloading equipment for the RAAS and Dichotomous Sampler filters included unpowdered latex gloves, forceps, labeling pen, gummed labels, laboratory bench paper, absorbent tissues, squeeze bottle containing methanol or isopropyl alcohol, Petri slides, weighed Teflon membrane filters, and FRM filter cassettes (support ring, support grid, and retainer ring, U.S. EPA, 1996a). The unpowdered latex gloves were worn during filter handling operations to minimize contamination. Work surfaces were cleaned with absorbent tissue and covered with laboratory bench paper. Forceps were cleaned prior to use with an methanol-dampened absorbent tissue. Damaged filters were identified and replaced from a planned supply of spares.

Prior to loading the filter cassettes, they were cleaned by wiping the support ring, the support grid, and the retaining ring with an methanol-dampened absorbent tissue. The support grid was placed into the support ring and the filter ID was written on top of the retaining ring with a fine, non-water-soluble (but alcohol-soluble) marker. Both aluminum and nylon filter cassettes were used in these tests, and the type was recorded in the comments section of the field data sheet.

The filter was removed from its Petri slide by lifting it along its ring with the forceps and placing it onto the filter holder support grid. The cassette retaining ring was pressed into the support ring so that an even fit was achieved. Each filter was examined for surface damage and replaced if holes or tears were observed. The loaded and labeled filter cassette was placed in a Petri dish and a gummed label with the filter ID was placed on the lid of the dish.

The intended sampling date was written on a Ziplock bag and the loaded Petri slides were placed in the bag and sealed. These bags were stored in a refrigerator prior to sampling, and were transported to and from the sampling site in a small cooler containing a block of blue ice. Cooling after sampling was intended to minimize the loss of ammonium nitrate and organic particles due to volatilization. A blank data sheet accompanied the filters in each bag to record sampler

identification number, sample start and end dates and times, sample flow rate readings, and comments.

Field blanks, filters that went through all handling but did not have air pulled through them, were provided for every seventh day of sampling. Field blanks were placed inside the samplers next to the chamber in which the sampled filters were situated.

During unloading, only the Petri slide with the ID corresponding to the ID marked on the filter cassette was opened to prevent mixing of filters. The filter cassette was placed flat on the bench area and the retaining ring was removed by prying it with the forceps. The forceps were worked around the filter cassette to loosen the ring. An edge of the filter was exposed by elevating the cassette support grid with a gloved index finger. The filter was then secured along its ringed edge with the forceps and moved from its cassette to its labeled Petri slide. The lid was then placed on the Petri slide and the slide was placed in ID order in a stack of all filters taken on that day that was secured with an elastic band. The sample stack was placed into a Ziplock bag with the data sheet and labeled with the filter identification number and sampling date.

Laboratory procedures for the Harvard Impactor included double weighing before and after exposure to improve the precision of the HI for method comparison studies. The mean of the two on and two off weights was used to determine the net mass. If the difference between any pair of filter weights exceeded 10 μg , a third weighing was done. This technique reduced the uncertainty of the net exposed filter mass to less than 10 μg , or the equivalent of less than 0.8 $\mu\text{g}/\text{m}^3$ PM concentration for the 10 L/min HI configuration and a 24-hour sample duration. The Teflon filters (41-mm diameter) used for measurement are weighed with an electronic microbalance (Cahn Models 21 or C-31). In order to assure consistent values for mass, the filters must be equilibrated in a room with controlled temperature ($21\text{ }^\circ\text{C} \pm 3\text{ }^\circ\text{C}$) and relative humidity ($40\% \pm 5\%$), both before and after sampling. In order to eliminate the effects of static charge, the Teflon filters were passed over a polonium-210 source (alpha rays) just before each weighing.

To assure accuracy in the measurement of HI filter mass, at the beginning of each weighing session the balance was calibrated with a standard weight that is used only for that balance. The integrity of these standard calibration weights was routinely checked to verify that they have not changed due to damage or mishandling. In order to verify that the balance calibration was not changing during the weighing session, lab blank filters were weighed before and after sets of 10 sample filters. If the lab blank weight differed by more than \pm was reweighed. In addition, after all the sets of sample filters for the weighing session were done, one filter from each set, designated as a quality control filter, was reweighed.

All Harvard School of Public Health run-integrated samplers (except 20 L/min HI) had a limited number of field blank and replicate (collocated) samples collected for

this study. Field blanks were handled and setup as regular samples; the only difference was that there was no flow. HI limits of detection (LODs) based on 3 times the standard deviation of the field blanks from this study are $1.9 \mu\text{g}/\text{m}^3$ for the 4-L/min HI, $0.8 \mu\text{g}/\text{m}^3$ for the 10-L/min HI, and $0.4 \mu\text{g}/\text{m}^3$ for the 20-L/min HI.

The Teflon filters used for these samplers were prepared at Harvard School of Public Health and shipped to the sampling site. Post-exposure weights were done at HSPH; there were no expected losses of larger particles from the HI samples.

Monitoring Results:

Table 5 contains a summary of the monitoring results for the Birmingham site. It shows that ambient $\text{PM}_{2.5}$ concentrations were measured from about $5 \mu\text{g}/\text{m}^3$ to $30 \mu\text{g}/\text{m}^3$, with an average of about $18 \mu\text{g}/\text{m}^3$ to $20 \mu\text{g}/\text{m}^3$ depending on the sampler type. Collocated precision was computed based on the method defined by U.S. EPA (1996b) for $\text{PM}_{2.5}$. At the Birmingham site, the collocated precision values were $1.13 \mu\text{g}/\text{m}^3$ (6.2%) for the RAAS unit, $1.04 \mu\text{g}/\text{m}^3$ (6.2%) for the dichotomous sampler, and $0.21 \mu\text{g}/\text{m}^3$ (1.0%) for the Harvard samplers.

Temporal variations of the $\text{PM}_{2.5}$ concentrations at Birmingham are shown in Figure 3. Note that the three samplers measured the same concentrations within one or two precision intervals. Scatter plots of the data are shown in Figure 4. The regression statistics shown in the figure are by ordinary, unweighted linear regression.

$\text{PM}_{2.5}$ comparisons following the procedures defined by Mathai et al. (1990) using all available data for each pair of samplers are summarized in Table 6. For each pairwise comparison, one sampler is designated as the X sampler and the other as the Y sampler. The table shows the variance-weighted regression slope and intercept for each sample pair, along with their standard errors. These statistics for Birmingham are quite similar to those of unweighted ordinary linear regressions presented in Figure 4. For each comparison, the X-sampler PM_{10} measurement was the independent variable and the Y-sampler $\text{PM}_{2.5}$ measurement was the dependent variable.

When the slope equals unity to within three standard errors, the intercept is equal to zero within three standard errors, and the correlation coefficient is greater than 0.9, the selection of independent and dependent variables is often considered to be statistically equivalent (Berkson, 1950; Madansky, 1959; Kendall, 1951; 1952). [Note: This is not EPA's criteria for equivalent sampler determination.] If the correlation coefficient is greater than 0.9 but the slope and intercept criteria are not met, the compared measurements are said to be predictable from the independent variable. By these criteria the RAAS sampler data is shown to be equivalent to both the Dichotomous Sampler and Harvard Impactor.

Table 6 also presents the average ratios and standard deviation of Y to X and the percent distribution of the data pairs whose difference (X minus Y) is less than 1σ , between 1σ and 2σ , between 2σ and 3σ , and greater than 3σ . Here, σ is the measurement uncertainty of X-Y, which is the square root of the sum of the squared uncertainties ($\sigma_x^2 + \sigma_y^2$), where σ_x and σ_y are the PM_{2.5} measurement uncertainties for the X and Y samplers, respectively. The individual sampler uncertainties were estimated from replicate analyses for each sampler. Table 6 shows that all pair comparisons lie within $\pm 2\sigma$ for the RAAS versus Dichotomous, and 94% of the RAAS versus Harvard comparisons are within $\pm 2\sigma$ for Birmingham.

As shown in Table 6, the average Y/X ratio is equal to unity within two standard deviations of the average. Table 6 also gives the average of the paired differences (X-Y) between the X and Y sampler; the collocated precision, which is the standard deviation of the paired differences; and the root mean squared (RMS) precision (the square root of the mean squared precision for the X and Y samplers). The average differences and collocated precision can be used to test the statistical hypothesis that the difference between samplers X and Y is zero. Statistical equivalence can be established when the RMS precision is less than $5 \mu\text{g}/\text{m}^3$ or 7% of the PM_{2.5} mass, whichever is greater (Mathai et al., 1990). By this criteria the difference between the RAAS and Dichotomous sampler data and between the RAAS and Harvard sampler data are not significantly different than zero for the Birmingham study.

Denver (Adams City), CO

Site Description:

Adams City is about 12 km northeast of Denver's central business district. Samplers were located on the single story roof of the county health center about 50 m north of moderately traveled East 72nd St. and about 100 m east of moderately traveled York St. Both are curbed, paved, clean roads. Highly traveled SR 224 is 300 m north of the site and I-76 is about 300 m south of the site. A ball field and county buildings are south of the site, with light industry and office buildings to the east and west. A parking lot and garages are to the immediate north. Large refineries and a coal-fired power station, with associated rail and truck traffic, are situated within 3 km southwest of the site. Adams City is also along the outflow and backflow trajectory that includes emissions from the Denver metropolitan area (Watson et al., 1988) owing to its proximity to the N. Platte River drainage.

Adams City is an important population-exposure monitoring site. There are several public schools in the immediate vicinity, and some of the highest PM₁₀ events in the Denver area have been recorded at this location. During the FRM field testing period between 12/11/96 and 01/07/97, the Colorado Air Pollution Control Division conducted daily PM₁₀ sampling (both high-volume and dichotomous samplers) on the regulatory midnight-to-midnight schedule at this site.

Study Configuration and Operation:

Four RAAS units and three IMPROVE channel-A samplers were operated at the Denver-Adams City site. Data from the Dichotomous Sampler operated by the state was not included in the analysis because their midnight start/stop time schedule was not compatible with the mid-day sample changing schedule used for the other samplers. The layout of the samplers at the Denver-Adams City site is similar to that shown in Figure 2 except that the IMPROVE samplers were operated instead of the Dichotomous Samplers. Inlet height above the ground was about 4 meters with about a 2 meter spacing between sampler inlets.

Of a total possible of 26 sampling periods (no sampling was conducted on New Years Eve and Day) all four of the RAAS operated for 24 periods and at least 3 operated for each sample period. The IMPROVE samplers started on the second day of the study and all three produced data for the remaining 25 sample periods.

The RAAS units were operated in the same way at the Denver-Adams City site as at the Birmingham study which is described above.

The three IMPROVE channel-A samplers were operated using standard IMPROVE monitoring protocol with the exception that sampling was conducted daily instead of twice weekly. IMPROVE sampler flow control is by a critical orifice which maintains a constant flow so long as the pressure drop across the orifice is sufficient and filter loading is not so great that it affects the flow. Two vacuum gauges are checked and documented on the data sheet before and after sampling to identify potential system leaks and to ensure the pump is providing sufficient pressure across the orifice and to determine initial and final flow rates. Initial sample flow was set at 23.0 L/min. Average IMPROVE flow during the three FRM field studies was 21.5 L/min.

For the IMPROVE samplers, Teflon filters, pre-loaded into 25-mm filter holder cassettes that are capped and in resealable plastic bags are transported to and from the field study site in insulated shipping containers designed for that purpose. The shipping container also transports field log sheets that the operator uses to document sample date, elapsed sample time, readings from the vacuum gauges, and maximum and minimum temperatures during the sampling.

Laboratory Facilities and Procedures:

RAAS filters for the Denver-Adams City site were processed at the DRI laboratory in Reno, NV, in the same way as for the Birmingham study.

IMPROVE samples were processed using standard IMPROVE protocols by the Air Quality Group at the University of California at Davis (UCD). Gelman 25-mm Teflon filters were purchased by UCD from a single production lot with approximately 1% used for acceptance testing procedures which included visual inspection for holes

or other irregularities and elemental analysis to ensure an artifact-free blank for the subsequent sample analysis.

Pre- and post-sampling gravimetric analysis of the IMPROVE filters was performed using a Cahn 31 Electrobalance. Polonium anti-static strips were used to reduce electrostatic effects in the weighing cavity and on individual filters. A segregated laboratory area was used to control human traffic and to stabilize the temperature of the weighing environment. The area was cleaned with a high efficiency HEPA vacuum daily and tacky floor covering was installed to minimize dust artifact. The output of the balance is entered into the computer database directly when the technician indicated to the computer that an acceptable gravimetric analysis was made.

The balance was cleaned and calibrated twice daily and was recalibrated at any time that the balance failed a "zero" test that was performed after every five samples during the day. Calibration was conducted using a 200.000 mg Class M standard and a 50.000 mg standard which must be within $\pm 2 \mu\text{g}$ for a successful calibration. The stability of the mass on sampled filters was tested by multiple weighing of randomly designated filters as control filters. Control filters were weighed twice a day and reweighed a month later after having been stored in a filter cassette.

Monitoring Results:

Table 5 contains a summary of the monitoring results for the Denver-Adams City site. It shows a range of $\text{PM}_{2.5}$ concentrations from about $3 \mu\text{g}/\text{m}^3$ to $21 \mu\text{g}/\text{m}^3$, with an average of about $11 \mu\text{g}/\text{m}^3$ to $12 \mu\text{g}/\text{m}^3$ depending on the sampler type. At the Denver-Adams City site, the collocated precision values were $0.49 \mu\text{g}/\text{m}^3$ (5.4%) for the RAAS unit, and $0.96 \mu\text{g}/\text{m}^3$ (11.3%) for the IMPROVE sampler.

Temporal variations of the $\text{PM}_{2.5}$ concentrations at Denver-Adams City are shown in Figure 5. Scatter plots of the data are shown in Figure 6. The regression statistics shown in the figure are by ordinary, unweighted linear regression. The two samplers measured the same concentrations within one or two precision intervals.

$\text{PM}_{2.5}$ comparisons using all available data for each pair of samplers are summarized in Table 6. These statistics for Adams City are quite similar to those of unweighted ordinary linear regressions presented in Figure 6. The slope (1.02 ± 0.05) and intercept ($0.64 \pm 0.61 \mu\text{g}/\text{m}^3$) meet the criteria to consider the RAAS and IMPROVE data sets statistically equivalent (Berkson, 1950; Madansky, 1959; Kendall, 1951; 1952). Table 6 shows that all of the pair comparisons lie within $\pm 2\sigma$ for the RAAS versus IMPROVE data sets for Adams City. As shown in Table 6, the average Y/X ratio (1.11 ± 0.20) is equal to unity within one standard deviations of the average, and the difference ($0.87 \pm 1.09 \mu\text{g}/\text{m}^3$) is equal to zero within one standard deviation.

Bakersfield, CA

Site Description:

Bakersfield is one of the major urban centers in California's San Joaquin Valley. The site at 5558 California Ave., Bakersfield, CA, which is located in a commercial area of the city. The site is a National Air Monitoring Site for PM₁₀ and is classified as Neighborhood Scale for High Concentrations of PM₁₀. Site elevation is 120 meters above mean sea level. Traffic is heavy in the area due to office buildings and shopping centers. The site is in the vicinity of an oil refinery, railroad tracks, and a major highway. During the FRM field testing period between 01/21/97 and 02/14/97, the California Air Resources Board monitored toxics, chromium VI, ozone, oxides of nitrogen, carbon monoxide, sulfur dioxide, hydrocarbons, visibility, coefficient of haze, wind speed, wind direction, temperature, relative humidity, time of wetness, and solar radiation at this site. In addition to the channel-A IMPROVE samplers reported on below, one channel-B IMPROVE sampler which employs a denuder and nylon filter to collect particulate nitrate was employed as part of the intercomparison study. However, the nitrate data were not available to be reported on in this document.

Study Configuration and Operation:

Bakersfield site had four types of PM_{2.5} samplers: three RAAS units, one Partisol-FRM Model 2000, one Dichotomous Sampler, and three channel-A IMPROVE samplers. The California Air Resources Board (ARB) provided all of the servicing and gravimetric analysis for the Dichotomous Sampler. The sampler inlets were about 6 meters above ground level and approximately 2 meters above the roof. The distance between the roof parapet and the sampler inlets was about 10 meters and the spacing between sampler inlets was approximately 2 meters. Figure 7 shows the layout of the samplers during the study.

At least two of the RAAS units operated for 24 sample periods and all three ran for 22 sample periods. Two IMPROVE units operated for 23 sample periods and all three operated for 22 sample periods. The ARB Dichotomous sampler operated for 22 sample periods and the Partisol-FRM collected 14 samples starting 01/28/97. At the conclusion of the main study a short special study was run at this site for seven days from 03/11/97 to 03/19/97 to see the effects on the mass concentrations of disabling, on one of the RAAS units, the active ventilation fan used to maintain temperature of the filter within 5 °C of ambient. All three RAAS units and IMPROVE samplers were operated for this special study.

Laboratory Facilities and Procedures:

DRI processed and weighed the filters for the RAAS and Partisol-FRM samplers in the same manner as described for the Birmingham study (described above).

Similarly, UCD used the same procedures for the Bakersfield study as described for the Denver-Adams City study (described above).

ARB weighed the Dichotomous Sampler filters using a Sartorius M3P microbalance with a minimum resolution of 0.001 mg and a precision of ± 0.001 mg. Prior to weighing filters, the balance was zeroed and then calibrated using 100-mg Ainsworth Class S standard weights. Pre- and post-sampling weighing of filters follows the same general procedures. All filters were visually inspected for defects or irregularities that may interfere with sampling or mass analyses.

The balance and filters were equilibrated for a minimum of 24 hours at a relative humidity of $40\% \pm 5\%$ and temperature of $23.0\text{ }^{\circ}\text{C} \pm 3.0\text{ }^{\circ}\text{C}$. Just prior to weighing, filters were individually placed on a polonium (Nuclear Products "Static Master") anti-static device for 30 seconds to eliminate static charge of the filter. Then each filter was placed on the balance pan, and the balance chamber door was closed. The balance indicates equilibrium by the appearance of a bubble after which the operator waited an additional 30 seconds prior to transmitting the weight information from the balance to the computer file. The balance zero was checked after every second filter and a duplicate filter was weighed after every ten filters. Duplicate weights must be within $20\text{ }\mu\text{g}$ of the original to be acceptable.

Weighed pre-sampled filters were then loaded into the sampler support rings and enclosed in Petri dishes for packaging and shipping to the field, while post-sampled filters were saved in sectioned archive boxes for possible future X-ray fluorescence analysis.

Monitoring Results:

Preliminary results for the ARB operated Dichotomous Sampler in Bakersfield (presented at the Western and Eastern sessions of the National $\text{PM}_{2.5}$ Monitoring Workshop) were found to have been incorrectly calculated. In their preliminary report ARB used total sampler flow in place of the fine particle filter flow to calculate $\text{PM}_{2.5}$ concentrations and they did not realize that data from all other samplers were reported for actual (as opposed to standard) temperature and pressure conditions. Corrected concentrations are presented in this report.

Table 5 contains a summary of the monitoring results for the Bakersfield site. It shows that the $\text{PM}_{2.5}$ concentrations ranged from about $6\text{ }\mu\text{g}/\text{m}^3$ to $52\text{ }\mu\text{g}/\text{m}^3$, with an average of about $24\text{ }\mu\text{g}/\text{m}^3$ to $32\text{ }\mu\text{g}/\text{m}^3$ depending on the sampler type and time period. For the 23 data pairs during the main part of the study with both samplers, the collocated precision was $0.43\text{ }\mu\text{g}/\text{m}^3$ (1.8%) for the RAAS units and $2.7\text{ }\mu\text{g}/\text{m}^3$ (10.8%) for the IMPROVE samplers during the main study. During the special study conducted after the main study, the RAAS units precision changed very little to $0.62\text{ }\mu\text{g}/\text{m}^3$ (2.9%) while the IMPROVE sampler precision improved to $1.6\text{ }\mu\text{g}/\text{m}^3$ (6.8%). The effects of having the ventilation fan for one of the RAAS units disabled during the special study have not yet been evaluated, but are not likely to have

been very great based upon the good precision ($0.62 \mu\text{g}/\text{m}^3$) for the RAAS during the special study period.

Temporal variations of the $\text{PM}_{2.5}$ concentrations for the Bakersfield study are shown in Figure 8. Scatter plots of the data are shown in Figure 9. With the exception of one outlier (02/09/97) the RAAS and Partosol FRM data are very nearly identical. From the scatter plots, the IMPROVE sampler data is shown to be somewhat lower than the RAAS data for the 23 data pairs of the original study period. However, for the 7 data pairs of the special study the values were nearly identical. From Table 6 the average difference ($1.4 \pm 3.1 \mu\text{g}/\text{m}^3$) between the IMPROVE and RAAS is not significantly different than zero, nor is the average ratio (0.98 ± 0.11) significantly different from 1.0.

As in the Birmingham study, the Dichotomous Sampler data is somewhat higher than the RAAS data for Bakersfield. Still the average difference ($1.7 \pm 1.7 \mu\text{g}/\text{m}^3$) is not significantly different from zero and the average ratio (0.95 ± 0.04) is not significantly different from 1.0.

Denver (Welby), CO

Site Description:

The Denver-Welby site is one of three principle sampling sites of the State of Colorado's Northern Front Range Air Quality Study. The site is located in northeast Denver, approximately one mile from the Denver-Adams City site. It is at the corner of East 78th Drive and Steele Street in a low-lying area just north of the confluence of the South Platte River and Clear Creek. Sampling was conducted in an open field in a sparsely populated rural area approximately 15 meters west of a bend in the South Platte River.

Study Configuration and Operation:

Six RAAS units were operated on a platform 3.1 meters above ground level, putting the inlets 4.8 meters above ground level. Inlets were spaced between 1.6 and 2.1 meters apart. Five of the six RAAS operated for 10 sampler periods and all six operated for eight of the sample periods.

Initial calibration of the RAAS units was hampered by adverse weather conditions. Due to highly fluctuating winds with gusts up to 27 m/sec (60 mph), calibration of the sampler's pressure transducers could not be performed in the field per the manufacturer's recommended procedures. To enable calibration of the transducers, the exhaust and cooling fan vent covers first had to be blocked to minimize pressure fluctuations within the instrument housing. Even so, stable pressure values, as indicated by the microprocessor count, could not be routinely attained. To complete the pressure transducer calibrations, it was necessary for the operator to manually

accept each indicated reading as “stable.” This modified procedure was not believed to significantly affect the accuracy of subsequent pressure measurements.

The highly fluctuating winds also precluded use of the single-ended Intermountain Laboratories Orifice for calibration of the RAAS flow rates. Although the available Gilian Gilibrator and BIOS DryCal flow calibrators were less affected by the wind, their observed inconsistent performance at the low ambient temperatures made them unacceptable for accurate flow calibrations. Per the RAAS sampler’s operating manual, flow calibrations were conducted using a NIST traceable dry gas meter. No significant problems were encountered using this technique.

Additional difficulties were also encountered while conducting the leak check of each sampler. These were subsequently identified as a software related problem that the manufacturer has since corrected. No physical changes in the sampler’s design or construction will be necessary to address this problem.

No problems were encountered during field calibration of any of the RAAS sampler’s ambient, filter, or dry gas meter temperature thermocouples. As will be discussed, however, three of the RAAS samplers were later identified to inadvertently contain non-temperature compensated circuitry for measuring dry gas meter temperatures. This resulted in a slight bias in measured air volumes for these three samplers resulting in a slight bias in calculated mass concentration for these three instruments on colder days.

Filter weighing was done in a hotel room near the monitoring site using a methodology described in the Laboratory Facilities and Procedures subsection below. Routine procedures for daily sampling were as follows. The work day began with calibration of the Cahn microbalance and weighing of filters to be used during that day’s run. Weighing conditions, sample filter initial weights, lab blank and field blank initial weights, and the balance’s response to the two Class 1 calibration weights were all recorded on a filter data sheet. Field filter blanks and sample filters were all loaded in Delrin cassettes and the cassettes placed in pre-labeled tins. Sample filters and field blanks were then transported upright to the sampling site.

Upon arriving at the site, field personnel would inspect each of the samplers to ensure that each was functioning correctly. Approximately 10 minutes prior to scheduled sampler shutdown, a written record was made of each sampler’s indicated ambient temperature, ambient pressure, and volumetric flow rate. The actual ambient temperature and ambient pressure were then measured and recorded by the field technician.

Once each sampler had ended its sampling run (typically at 10 am MST), the field technician would retrieve the field blanks and each of the sample filters. The WINS impactor of each sampler was then disassembled and all of its internal surfaces carefully inspected for the presence of oil or foreign deposits. Surfaces containing

microdrops of oils were typically cleaned with Kimwipes prior to reassembly and reinstallation of each WINS. The summary information from each sampler was then inspected and used primarily to ensure that each of the samplers was operating correctly.

Following downloading of the data, new sample filters were installed in each of the samplers. The field technician would then program each of the samplers to start simultaneously (typically at 12 pm MST) and operate for 22 hours. Experience showed that the scheduled 2-hour non-sampling period was sufficient to allow sampler changeover between successive runs as well as minor sampler maintenance. Once the new run began, the field technician would ensure that each of the samplers appeared to be functioning correctly. Approximately 10 minutes into the sampling run, a written record was made of each sampler's indicated ambient temperature, ambient pressure, and volumetric flow rate. The actual ambient temperature and ambient pressure were then measured and recorded by the field technician. Site conditions were also recorded on the sampling sheet.

Retrieved filters were then transported back to the conditioning environment and exposed for at least 24-hour prior to final weighing. The laboratory technician then conducted a weighing session for weighing the previous set of 24-hour equilibrated field samples. As during all weighing sessions, weighing conditions, sample filter initial weights, lab blank and field blank initial weights, and the balance's response to the Class 1 calibration weights were all recorded on a filter data sheet. The PM_{2.5} concentration for each sampler was then calculated along with the coefficient of variation for the six replicate samplers.

The flow systems of each of the RAAS samplers were calibrated in the field prior to use. Since routine flow checks were not performed during the study, the daily accuracy of the systems cannot be determined. Upon their return to RTP, however, four of the flow systems were recalibrated under laboratory conditions. The remaining two RAAS samplers were unavailable at the time the final flow checks were conducted. Results showed that the response of the flow systems was remarkably stable over time. The RTP calibrations of three of the samplers were identical to that of the Denver calibrations while the remaining sampler differed by only 0.01 cc/click.

Once the field study was concluded, analysis of field data revealed that dry gas meter temperatures for units 0002, 0005, and 0006 typically averaged about 20 °C higher than ambient temperatures. By comparison, dry gas meter temperatures for samplers 0007, 0009, and 0010 averaged only a few degrees centigrade above the measured ambient temperature. Further diagnosis of the problem revealed that the circuitry measuring dry gas meter temperatures in samplers 0002, 0005, and 0006 was not temperature compensated and thus provided an incorrect measure of actual volumetric flow rate. Based on the noted temperature bias one would predict that actual volumetric flow rates in samplers 0002, 0005, and 0006 were approximately 7% higher than indicated by the instruments.

Post-site analysis of collected field data also revealed that the RAAS samplers did not measure ambient temperature correctly when exposed to low temperatures. Specifically, all six of the samplers indicated a minimum ambient temperature of approximately -5 °C even when the temperature dropped substantially below that value. Post-site inspection revealed that the sampler's ambient temperature circuitry was not properly compensated for ambient temperature. Comparison of the RAAS's indicated temperatures with a collocated reference thermometer revealed that the maximum temperature deviation occurred on 12/17/96 when a 10-°C measurement bias occurred. An absolute bias in measured flow rate of approximately 4% would be predicted at this temperature differential. Because all the RAAS samplers behaved similarly, however, the lack of properly compensated ambient temperature circuitry did not affect the precision of the RAAS flow systems.

Laboratory Facilities and Procedures:

A Cahn C-44 electronic microbalance was used for all filter weighing during the course of this study. Setup, calibration, and use of the Cahn C-44 balance for weighing PM_{2.5} filters is described by the RTI Standard Operating Procedures for Filter Weighing. Calibration of the Cahn C-44 relies on two internal stainless steel weights which are automatically placed on the balance arm during the calibration cycle. As a check of the balance's inherent precision, an ANSI Class 1, 200-mg capacity, stainless steel calibration weight was weighed at RTP ten successive times. Results indicated a mean mass of 199.994 mg and a standard deviation of 0.0013 mg (1.3 µg).

In preparation for the field study, 190 Gelman Teflo filters were conditioned for a minimum of 24 hours (22 °C and 37% RH) in the EPA Annex Building at Research Triangle Park, NC. Filters were stored in individual, prelabeled plastic Petri dishes with the dish lids slightly open to expose the filters to the conditioning environment.

A weighing session was initiated by first measuring the room's temperature and relative humidity using a Omega RH411 thermo-hygrometer. This data was recorded along with the operator's name and the date and time. The Cahn balance was then zeroed and calibrated following techniques provided in its operating manual. Following the initial balance calibration, the 200-mg and 2-mg Class 1 calibration weights were weighed and recorded.

Each of the filters was first charge-neutralized by laying it on top of two side-by-side polonium-210 sources for a minimum of 60 seconds. Ensuring that the balance read 0.000 mg, the operator then opened the door to the balance chamber, carefully placed the filter onto the center of the balance pan, and closed the chamber door. Once the balance indicated that a stable reading was obtained, the operator set a stopwatch for a 60-second countdown. At the end of the countdown, the filter's indicated weight was recorded on the data sheet. The filter was removed and placed in its respective Petri dish. The balance was zeroed and calibrated every

Quality controls for the field study included the use of three filter laboratory blanks for each test. Laboratory blanks were conditioned and weighed in the same manner as the actual filter samples but were not loaded in the Delrin cassettes nor did they leave the weighing room. For 24-hour measurement periods, measured mass changes of the 30 lab blanks ranged from -12 μg to +11 μg . On average, however, mean mass changes for the 30 lab blanks was measured to be only 0.2 μg with a standard deviation of 3 μg . These results indicate that negligible $\text{PM}_{2.5}$ measurement uncertainty is associated with equilibration, handling, and weighing of the Teflo filters under these test conditions.

Site quality control checks also included the use of three filter field blanks for each test. Field blanks were conditioned and weighed under conditions identical to those of the lab blanks but were loaded in Delrin cassettes, the cassettes loaded in prelabelled metallic tins, and the tins transported to the field site. Each cassette was then removed from its protective tin, briefly loaded into a sampler, returned to its protective tin, and the tin stored in a sampler during the test run. Following the run, the cassettes were returned to the weighing room and the field blanks reconditioned for 24 hours prior to weighing. Field blanks thus served as an indicator of measurement uncertainty in the absence of aerosol collection. Based on the on-site weighing, field blank mass changes ranged from -5 μg to +13 μg with an average of 3 μg and a standard deviation of 4.4 μg . Subsequent reweighs of the field blanks at RTP indicated that mass changes ranged from -12 μg to +11 μg with a mean mass change of -0.2 μg and a standard deviation of 4.6 μg . Based on a provisional definition of mass detection limit as the absolute value of the measured mean plus 10 times the standard deviation of field blanks, both site weighing and

RTP weighing of field blanks resulted in a detection limit of approximately 46 µg. For 24-hour sampling at a nominal flow rate of 1 m³/hr, this value equates to a PM_{2.5} detection limit of approximately 2 µg/m³.

Upon returning to RTP, 26 Teflo filters were weighed which were not used during the Denver field study. None of these filters gained weight, and the weight loss ranged from 0 µg to 7 µg. Mean weight change was -3 µg with a standard deviation of 2 µg. These measurements indicate that loss of filter material during round-trip transport was negligible.

Filters used to collect aerosol were also reweighed upon returning to RTP. Despite returning to a more humid conditioning environment, collected aerosol mass was measured to be about 4% less than that measured in Denver. PM_{2.5} concentrations calculated based on RTP weighing, therefore, averaged about 4% less than those calculated using the Denver weighing. Reasons for this change in collected aerosol mass are unclear at this time.

Monitoring Results:

Table 5 contains a summary of the monitoring data for the Denver-Welby site. Data for the six RAAS have been divided into two groups representing the samplers with and without proper temperature compensated electronics. Average PM_{2.5} concentrations for the two groups are different by about 1 µg/m³ (11.4 µg/m³ and 10.4 µg/m³). Daily concentrations ranged from about 1 µg/m³ to 20 µg/m³. Collocated precision is 0.36 µg/m³ (4.8%).

As seen in Table 6 the two groups of RAAS units produce data that are highly related and in fact meet all of the statistical criteria for equivalence, in spite of a small bias caused by the incorrect flow for the group of three RAAS units without temperature compensated electronics. Figure 10 shows a time plot of the two groups of RAAS units. Days with the greatest difference between the two groups were the coldest days.

Phoenix, AZ

Site Description:

The City of Phoenix Water Well Site is located at 4530 North 17th Ave, Phoenix, AZ. This site has a typical ambient neighborhood-scale PM exposure density for the urbanized metropolitan area and is the most heavily instrumented site in the existing Phoenix Long-Term PM/Urban Haze Monitoring Network. Ambient fine particle loadings in the Phoenix metropolitan area are dominated by the mobile source emissions category, consisting of primary particulate emissions (carbon and re-entrained crustal material) with wintertime episodes of secondary aerosols (ammonium nitrate). This location was chosen for ease of access and existing PM_{2.5} / PM₁₀ data records (including elemental composition), as well as additional

collocated optical and particle measurement devices already in use at the site. The seven-week time frame chosen for the testing protocol corresponds to the normal season for the occurrences of the worst urban hazes and associated PM_{2.5} loadings, assuming minimal passages of storm fronts from the west and northwest.

Study Configuration and Operation:

Four different types of PM_{2.5} samplers were operated at the Phoenix site. These include three RAAS units, a Graseby Andersen Model 251M Dichotomous Sampler, two Air Metrics "Mini-Vols" which are battery-operated low-flow (5 L/min) samplers that use a PM_{2.5} impaction inlet, and a Harvard Impactor.

Sampling was conducted by the Arizona Department of Environmental Quality (ADEQ) operators every other day and excluded the Christmas and New Year holidays for a maximum of 24 sample periods between 12/06/96 and 01/27/97. The Dichotomous Sampler collected samples for all 24 periods, as did one of the RAAS units. Two of the RAAS units collected 23 samples and the two Air Metrics collected 20 samples each. The Harvard Impactor operating on an everyday sampling schedule collected 21 samples from 12/10/96 to 01/01/97. A second collocated HI collected four samples during the study to use for calculating precision. Unfortunately the difference in sampling days resulted in only 10 days where the HI data can be compared with data from the other samplers.

Laboratory Facilities and Procedures:

The pre-sample and post-sample mass of the manual method Teflon filters are measured on a Sartorius M3P Microbalance in the ADEQ Air Quality Filter Laboratory. Microbalance operation and filter handling/processing procedures are based on documentation from the microbalance manufacturer, Desert Research Institute (DRI) and the EPA Quality Assurance Handbook. These procedures have been integrated into and documented in the Standard Operating Procedures for the Air Quality Filter Lab and the ADEQ Quality Assurance Manual. From the on-site sampler flow rate checks and the quality control checks of the microbalance, the uncertainty of flow rate and mass measurements are integrated and the mass loadings' uncertainties propagated for the individual samplers and the groups of sampler models during the study period using a methodology provided by the DRI.

Harvard laboratory procedures for the Phoenix study are the same as described for the Birmingham study (above).

Monitoring Results:

Table 5 contains a summary of the monitoring results for the Phoenix study. PM_{2.5} concentrations ranged from about 3 µg/m³ to 38 µg/m³ depending on which sampler's data is used. The average concentration is about 19.1 µg/m³, 17.8 µg/m³ or 20.3 µg/m³ respectively from the Dichotomous Sampler, RAAS, and Air Metrics

sampler. RAAS and Air Metrics sampler precision are $0.4 \mu\text{g}/\text{m}^3$ (2.8%) and $3.0 \mu\text{g}/\text{m}^3$ (16.9%) respectively. For the 10 sample periods that are coincident for the Harvard and RAAS samplers, the Harvard-measured average $\text{PM}_{2.5}$ concentration was $21.5 \mu\text{g}/\text{m}^3$.

Figures 11 and 12 are a time plot and scatter plots of the $\text{PM}_{2.5}$ data for Phoenix. From these and the pairwise data comparison in Table 6 it is clear that data from the various samplers were highly correlated and measured nearly the same concentrations most of the time. The average differences ($1.4 \pm 1.2 \mu\text{g}/\text{m}^3$, $1.7 \pm 2.4 \mu\text{g}/\text{m}^3$, and $0.1 \pm 0.7 \mu\text{g}/\text{m}^3$) between the RAAS and Dichotomous Sampler, between the RAAS and Air Metrics, and between the RAAS and Harvard sampler are not significantly different from zero. Similarly the average ratios (1.07 ± 0.06 , 1.18 ± 0.29 , and 1.01 ± 0.06) are not significantly different than 1.0. Unlike in the Birmingham and Bakersfield studies, the Dichotomous sampler data tend to be somewhat higher than the RAAS data for the Phoenix study. However, the Harvard Impactor and RAAS samplers produced nearly identical data in Phoenix.

Tucson, AZ

Site Description:

The site is at the University of Arizona Respiratory Science Laboratory, at 1435 North Fremont Street, Tucson AZ. This is the central site for the Tucson urban area and has a typical ambient neighborhood-scale PM emissions density for the urbanized metropolitan area. It is the most heavily instrumented site in the existing Tucson Long-Term PM/Urban Haze Monitoring Network. Ambient fine particle loadings in the Tucson metropolitan area are predominantly in the mobile source emissions category, consisting of primary particulate emissions (carbon and re-entrained crustal material), along with episodes of contribution from secondary aerosols (ammonium nitrate and sulfate). This location was chosen for ease of access and existing $\text{PM}_{2.5}$ / PM_{10} data records (including elemental composition), as well as additional collocated optical and particle measurement devices already in use at the site. The nine-week time frame chosen for the testing protocol corresponds to a time of year with variable meteorology, characterized by passages of both dry and wet cold fronts with associated elevated wind speeds, interspersed with multi-day periods of stable conditions.

Study Configuration and Operation:

Data from four different $\text{PM}_{2.5}$ samplers were compared by the Arizona Air Quality Division and the Pima County Department of Environmental Quality in this study. There were two RAAS units, one Dichotomous Sampler, two Air Metrics "Mini-Vols", and one channel-A IMPROVE sampler.

Each sampler collected midnight-to-midnight 24-hour samples every third day. The two RAAS and the Dichotomous Sampler produced data for each of the possible 22

sample periods, the IMPROVE sampler produced 21 samples of which three were voided due to sample period run time problems (04/24/97 and 04/28/97) and to serious misalignment of the sample deposit on the filter. The two Air Metric samplers operated for only 12 and 9 days with only 7 days with both samplers operating and with a total of 14 days were one or both operated.

Unlike the other six field studies described in this report, the Tucson study was operated by a site technician as additional and unassisted duties to his normal work load of maintaining other monitoring sites. The every-third-day sampling schedule was utilized to make it possible to find the time required to conduct the field operations required by this study.

Laboratory Facilities and Procedures:

The Arizona Department of Environmental Quality procedures described earlier for the Phoenix study were used in the Tucson study for the RAAS, Dichotomous, and Air Metrics samplers. The IMPROVE samples were analyzed by the Air Quality Group at the University of California using techniques described for the Denver-Adams City study.

Monitoring Results:

Table 5 contain summary statistics for the $PM_{2.5}$ concentrations measured for the Tucson study. Tucson experienced the lowest average concentrations of all of the seven FRM field studies, with an average concentration of about $6 \mu\text{g}/\text{m}^3$ to $7 \mu\text{g}/\text{m}^3$ and a range from about $3 \mu\text{g}/\text{m}^3$ to $12 \mu\text{g}/\text{m}^3$. Collocated precision for the RAAS and Air Metrics samplers are $0.95 \mu\text{g}/\text{m}^3$ (14%) and $3.93 \mu\text{g}/\text{m}^3$ (48%) respectively. Tucson study RAAS precision at about $1 \mu\text{g}/\text{m}^3$ is about the same as at the first field study (Birmingham). However, the much lower $PM_{2.5}$ concentrations in Tucson resulted in a much higher relative precision than in Birmingham (14% compared to Birmingham's 6.2%). Poor Air Metrics sampler precision and the number of voided data (due to battery charger problems) seriously reduce the value of these data in subsequent comparisons to data from other samplers.

Temporal variations are shown in Figure 13. Agreement between samplers appears to degrade after the tenth sample point (04/25/97) and continues to be poor until the last few sample periods.

The pairwise comparison of the different samplers is shown in Table 6, and the scatter plots are in Figure 14. Of all of the seven studies, the correlation statistics (i.e., correlation coefficients and slopes of the regression lines) intercomparing the various sampler types in the Tucson study are clearly much poorer. The correlation coefficient for data from the two RAAS samplers (not shown in the table) is only 0.58, which though better than for paired data of dissimilar types of samplers at Tucson is much lower than the correlation coefficients for dissimilar types of samplers at all other sites (see Table 6). Removal of three apparent outliers on

consecutive sample periods (05/16/97, 05/19/97, and 05/22/97) considerably improves the correlation coefficient between data from the two RAAS units to 0.88. However, further analysis of the Tucson data is needed to justify identification of these data as outliers.

Azusa, CA

Site Description:

All measurements were conducted at the Azusa Station of the Southern California Air Quality Monitoring District, located at 130 N. Loren Ave, Azusa, California. This site is about 20 miles northeast of downtown Los Angeles, at the northeastern edge of the San Gabriel Valley, at the foot of the San Gabriel Mountain. The immediate area is suburban with some light industry.

Study Configuration and Operation:

Aerosol Dynamics Incorporated (ADI), a subcontractor of Research Triangle Institute (RTI), operated the Azusa study using six RAAS units. Sampling began the week of 03/24/97 and ended 05/23/97. Samplers were deployed on the roof of a one-story building (about 4 meters), with the sampler inlets separated by 2 meters.

Unlike the earlier field tests, the Azusa study was designed to investigate several specific operational issues. These include the effects on measured $PM_{2.5}$ concentration of permitting the buildup of deposited materials in the WINS separator and of delayed retrieval of filters from the samplers after sampling, as well as differences that might result from operating on the standard midnight to midnight schedule as opposed to the field study test schedule starting and ending at mid-morning.

Four types of tests were conducted. For Tests A and B all six samplers were operated simultaneously on a 22-hour mid-morning to mid-morning schedule, as done in previous testing. This schedule allows all samplers to be operated every day, and permits more data to be collected using the single day FRM. Test A was done to assess precision and equivalency of the samplers. The samplers were operated by the ADI field technician for Tests A1 to A6, and were operated by the South Coast Air Quality Management District (SCAQMD) station operator for Tests A7 to A9.

Test B compared performance of the sampler with cleaned, and uncleaned impactors. In this test, two of the samplers were run with the WINS that were cleaned daily, two samplers started with clean impactors but were allowed to get dirtier, and two samplers started with dirty impactors (with 6 days of previous sampling) that got dirtier yet. These tests were conducted by the ADI field technician at the conclusion of Test #A6. Samplers were cleaned at the conclusion

of these tests, and then turned over to the SCAQMD operator for the remaining testing (beginning with Test #A7).

For Tests C and D the samplers were operated by the SCAQMD station operator and sampling was done for 24 hours commencing at midnight in order to evaluate the samplers under monitoring conditions. For Test C three samplers were operated side-by-side on a daily, 24-hour sampling schedule, and samples were retrieved the next workday following the end of sampling. Additionally, filters were weighed by the SCAQMD as well as by RTI, to provide evaluation under actual monitoring conditions. Test C was done with consecutive days of operation. Test D examined the effect of sample retrieval time on sample integrity. All six samplers were run side-by-side for 24 hours starting Sunday midnight. Two of the samples were retrieved on Tuesday, two on Wednesday, and the remaining two on Friday.

Logistical arrangements and development of the protocol were handled by Aerosol Dynamics Inc. The samplers, substrates, weighing and initial field checks were done by Research Triangle Institute. Before testing began, RTI provided training of both SCAQMD and ADI field personnel on the sampler operations. They also verified sampler performance on-site through leak checks and flow calibrations. Field operations were handled by Aerosol Dynamics with the support of the SCAQMD. Samples were analyzed for mass by Research Triangle Institute, with duplicate weights provided for some tests by the SCAQMD. The first set of tests were conducted by Aerosol Dynamics field personnel, and the latter "monitoring mode" tests were conducted by SCAQMD district personnel.

At the outset of the experiment all of the sampler inlets were cleaned. The PM₁₀ dichotomous inlet was taken apart and cleaned with water. The PM_{2.5} WINS impactor was also cleaned with water, and a new, oiled impaction surface installed in each sampler. All samplers were leak tested after cleaning and reassembly. The flows on all samplers were calibrated against a dry test meter under the direction of RTI.

Samplers were operated according to the written standard operating procedures. Dynamic blanks were obtained for each day of operations by installation of the filter in the sampler, and running for 30 seconds. Samplers were leak-tested and flows were verified with an orifice meter on alternate days. At the end of each sampling period, sample volumes and temperatures were recorded manually, and the five-minute data recorded by the FRM microprocessor were downloaded to a personal computer.

Filter handling was done on-site at an indoor desktop at the site. Immediately after sample cassettes were removed from the sampler, the Teflon filters were unloaded into Petri dishes, and stored in a refrigerator on site. At the completion of a set of runs, filter samples shipped in blue ice via overnight courier to RTI for analysis. For C-series runs, samples first went to the SCAQMD for weighing prior to shipment to

RTI. Samples were stored on site and shipped in insulated containers at about 4 °C (blue ice temperature).

Laboratory Facilities and Procedures:

RTI procedures for pre- and post-sample weighing of the filters at EPA laboratory facilities in Research Triangle Park, NC are the same as those described for on-site weighing for the Denver-Welby site study, with the exception of having a temperature and humidity controlled environment. All filters were brought into equilibration at a relative humidity of 37% ± 3% and temperature of °C for a minimum of 24 hours.

Monitoring Results:

Table 5 shows the summary statistics for the Azusa study. PM_{2.5} concentrations ranged from about 3 µg/m³ to 42 µg/m³ during the various special studies performed as part of the Azusa study. Collocated precision was equal to or better than 0.38 µg/m³ (2.4%) which is the precision during the A test period for which all samplers were periodically cleaned on the same schedule and were run by ADI staff for the first six of the nine sample periods.

Figure 15 is the time plot for the Azusa PM_{2.5} concentration data. It shows that during the B test period, the three groups samplers (WINS periodically cleaned - B1, WINS starting clean but not cleaned during the test - B2, and starting with 5 days of deposits in the WINS - B3) produced data that departed in concentration through the study. Measured PM_{2.5} concentrations were systematically lower in the RAAS units with more than five days of sampling without WINS servicing. This can also be seen in Table 5 where the average values for B1, B2, and B3 decrease by about 0.5 µg/m³ between B1 and B2, and between B2 and B3. A preliminary assessment of the results for tests C (timer started sampling at midnight) and D (delayed filter retrieval from the samplers) showed no significant effects, though a more thorough assessment will be reported elsewhere.

III. DISCUSSION

This section of the report presents discussions of operational issues identified during the field intercomparison studies, comparisons of the results from the seven field studies, and provides thoughts on future evaluation work that should be done with regards to the PM_{2.5} FRM sampler.

Operational Issues:

A number of concerns related to the design and operation of the prototype PM_{2.5} FRM were identified in the course of conducting the field studies described above. Most of these have already resulted in system or procedural changes that have

eliminated or mitigated the problems. The following is a brief description of some of the more noteworthy issues presented roughly in the order in which they were identified.

The first filters produced by the RAAS in the Birmingham study were found to have a mottled appearance with what seemed to be few irregular spots on nearly every filter, as though a few small drops of liquid had made their way to the filter during the sampling. This raised serious concerns that the silicone oil used in the WINS impactor had splashed out of the impactor well. After extensive examination and testing this proved not to be the case. Microscopic examination of the filter followed by a series of experiments conclusively showed that the spots were the result of minor irregularities in the manufacturing of the perforated metal support disk part of the filter cassette that backs up the filter. This was confirmed by the observation that each individual support disk would produce the same irregular spot pattern each time. A redesign of the support disk that is incorporated into the final EPA specifications solved the problem.

During the efforts to investigate the spotting pattern on the filters, the WINS impactor deposits were carefully observed. Particles with sizes between 10 μm and 2.5 μm are removed from the sampled air stream by inertial impaction on the oil coated glass-fiber filter at the bottom of the WINS. At a point just below the impactor jet, these particles produce a spot that grows into a cone-shaped deposit in a day or two of sampling. The particles are apparently held in place by the silicone oil which is drawn into the deposited particles by capillary action. By the third and fourth days, the deposit can have a very slender needle point at the top of the cone. At least on one occasion the needle became unstable and broke into several pieces, a few of which reached the filter. No other incident of this type was reported at any of the field studies.

The simple solution to this problem is to service the WINS (clean and renew the oil-impregnated impaction filter) before the deposit grows to the point of being unstable. Except for the Azusa study, where the rate of WINS maintenance was being studied, the procedures used were to service the WINS at least every four days. Field servicing of the WINS is not recommended because it is somewhat cumbersome, involving messy oils and particle deposits, solvents to clean the sampler surfaces, and awkward methods to precisely measure the specified amount of fresh oil used by the impactor. A better operational solution, not available during the field studies, involves having multiple WINS impactors that are serviced in a laboratory setting and brought to the field site and installed during normal filter change times by the field technician. This issue is still a problem for future sequential filter change samplers if they employ a single WINS for more than 3 or 4 filters, since such a sampler would require a special trip to the field for WINS servicing, defeating the convenience of automatic filter changes. Efforts are underway to mitigate this problem by a change to the inlet or inertial separator. Such solutions would not effect the FRM, but could be utilized by samplers certified by EPA as equivalent to the FRM in accordance with 40 CFR part 53.

Early in the Birmingham study, a blowing rain storm resulted in rain water passing through the SA246 PM₁₀ inlet, partially filling the WINS and wetting the filter. One of the samplers stopped operating and none of the filters were suitable for analysis. At the Denver-Welby site study, three inches of snow fall resulted in snow making its way into the SA246 PM₁₀ inlet (12/16/96) though the sampler continued to operate. Upon disassembly, the operators found that there was a frost layer in the WINS and on the filter and its housing. Sampler collocated precision for this sample period was not unusual though the measured concentrations may have been affected. The ability of precipitation to pass through the SA246 PM₁₀ inlet originally specified for the prototype FRM sampler is a serious shortcoming that EPA has addressed by modifications to the design specifications for the sampler inlet.

In nearly all of the field studies operators noted that the active ventilation of the sampler box needed to maintain temperature of the filter near ambient temperature results in significant dust buildup in the sampler box. While only a nuisance during the relatively short field test, this could present more serious problems in the long run for the precision-machined parts and electronics that are in the box unless a vigorous cleaning schedule is adopted. Other approaches that should be considered involve filtering the ventilation air upon entering the sampler box. Manufacturers are free to address this problem without EPA direction, since the ventilation addresses a performance as opposed to a design specification. Adherence to a proper cleaning schedule will be part of an effective quality assurance program and is addressed in EPA quality assurance guidance.

In the Azusa study, the effects on the data of various cleaning schedules for the WINS was directly studied and found to be important. As indicated in the discussion above, an early concern with the cleaning of the WINS was to avoid the possibility of having part of the impactor deposit breaking off and making its way to the filter, thus giving a falsely high measurement of PM_{2.5}. What was found in Azusa was that a dirty WINS impactor tends to produce a falsely low measurement of PM_{2.5}. In as little as five days without cleaning the WINS, the FRM measured concentration is about a 0.5 µg/m³ less than would be measured with a recently serviced FRM. This discrepancy increases to 1 to 2 µg/m³ after 10 to 12 days of sampling without cleaning the WINS. The response of the sampler to even greater periods without cleaning the WINS was not tested.

One explanation of the problem is that the deposit being built up on the impaction surface is in effect changing the critical dimensions of the WINS, resulting in a lowering of the particle size cutpoint significantly below the nominal 2.5 µm diameter. The relationship between number of days without cleaning the WINS and the concentration discrepancy would be expected to vary depending on the concentrations of coarse particles (10-µm to 2.5-µm diameter particles) that make up the deposit in the WINS, as well as the concentrations of particles between the nominal 2.5-µm cutpoint and the lower, actual cutpoint. The same approaches discussed above for mitigating this issue of WINS deposit buildup apply here also.

However, the effect of reducing the measured concentration as a result of the lack of maintenance is perhaps a more serious problem, since some might believe that being able to reduce the measured concentration would be an incentive for poor maintenance practices.

Comparison of Results:

One of the most striking results from all of the field intercomparison, except Tucson, is the very good precision of the FRM. Though most of the data came from a single manufacturer's version of the FRM (i.e., Graseby Andersen's RAAS), it is encouraging to see in the Bakersfield study, that a single FRM from another manufacturer (R&P's Partisol-FRM Model 2000) produced data that compared well with the three collocated RAAS units.

Precision determined by collocated sampling data incorporates the uncertainty of each component of the monitoring and analyses method used to obtain a mass concentration value. The most important of these are thought to be consistency in particle selection (by size and composition) and retention on the filter, flow rate and sample period timing consistency, integrity of the blank and sampled filter during transport to and from the laboratory and field site, and weighing consistency. For any specific ambient aerosol condition, sampler design, production, operation, and maintenance are controlling factors for the consistency of particle selection and retention on the filter and for flow rate consistency. Insuring the integrity of the filter during transport primarily involves avoiding contamination and high temperatures. Weighing consistency is determined by laboratory procedures, facilities, and the skill of the technician.

For cases with good collocated precision all of these factors must be satisfactorily under control. However poor precision, as in the case of the Tucson study, requires an examination of each of the factors that influence system performance in order to determine which are responsible for the poor precision. Though such an assessment has not yet been completed for the Tucson study, there were two features which distinguished Tucson from the other six field studies which should be examined. The $PM_{2.5}$ concentrations tended to be lower for the Tucson study, which means that the weighing precision may be a big factor. The expected ability to weigh filters to better than $\pm 20 \mu\text{g}$ translates to about $\pm 1 \mu\text{g}/\text{m}^3$ concentration uncertainty. This is a relatively large fractional variation when the ambient concentration is from $3 \mu\text{g}/\text{m}^3$ to $10 \mu\text{g}/\text{m}^3$. The field technician operating the Tucson samplers was working alone and had a full work-load of other duties. This might be expected to have limited his time and the care he could apply to operating the samplers for this study.

Another striking feature of the intercomparison studies is the level of agreement between the data from the FRM and other types of samplers, such as the Dichotomous, IMPROVE, and Harvard Impactor samplers. Accounting for the combined precision of the various sampler, the paired collocated data are not

significantly different between the various samplers. Similarly the average ratios of paired data are not significantly different from 1.0.

Though these tests would seem to indicate that the different sampler types are indistinguishable, that is not completely true. There is a small bias between data from some of the samplers in these tests. The amount of difference may be smaller than two or three times the measurement uncertainty as is the case in these studies and yet betray a bias by the consistency of one being always or nearly always higher than the other. Two truly identical systems would produce data where the probability of one being higher than the other is 50% (like a coin flip). The probability of having many more than half of one systems data higher than another is small (e.g., for 20 coin flips the probability of 15 heads is less than 4%). Though limited to only 14 days and disregarding an apparent outlier, this type of stringent test for identifying small biases, indicates that the RAAS and Partisol-FRM 2000 versions of the FRM are identical.

The degree of data comparability between data from the various types of samplers, though not identical, is still remarkable considering that in most cases different samplers also had weight analysis done by different laboratories and somewhat different procedures. Five of the six different laboratories (DRI, Harvard, UCD, CARB, and AZ-DEQ) generated data that compared favorably to data from one or more of the other laboratories. RTI was not involved in studies with other laboratories, however for the Denver-Welby study they setup a temporary laboratory in a hotel room near the field site that produced data with precision comparable to that of the best full-time laboratory. The ability to reliably make pre- and post-sampling filter weight measurements is critical to the overall success of a PM_{2.5} monitoring program. With the very small masses that are involved, this cannot be considered a trivial pursuit. However, the fact that all six laboratories performed well in these studies is encouragement that other organizations can establish the capability to accurately weigh FRM samples.

Future Activities:

Additional assessment of the results from the seven field studies is needed. This is particularly true for the most recently completed field studies (Tucson and Azusa) from which some data was only available from 07/01/97. The results and discussion in this report of all seven of the studies, but especially these more recent two, should be considered preliminary. Additional analyses by the investigators involved in these studies are likely to augment our understanding of the operational characteristics of the FRM sampler and its comparability to other PM_{2.5} monitoring methods.

The Tucson study in particular should be further examined to assess the reasons for the poor precision and comparability between different samplers. If necessary additional measurements should be made to help to understand what the problems were and how they can be avoided in future monitoring.

Chemical analysis of filters collected in these studies could be very helpful in understanding the differences between the various samplers. Some compositional analysis of filter samples collected in these studies has already been conducted. Additional chemical analyses was included in the design of some of the studies and for other studies it remains to be decided whether compositional analyses will be conducted. Assessment of the compositional comparability of samples from various types of instruments will be useful in understanding small differences between the data sets. If the differences are solely the result of differences in sampler flow calculations, the composition can be expected to be the same. However, if the differences are caused by differences in the sampler's size segregation at the nominal 2.5- μm particle diameter, then the relative amount of crustal material will be different. Nitrate and perhaps organic carbon particulate concentrations may be useful in comparing the relative loss of volatile particulate components on filters by the various samplers and the post-sampling transport and handling of the sample. A plan to analyze representative filter samples from each of the studies should be developed and implemented, and the compositional data should be assessed as outlined above.

Additional test with specific objectives similar to those for the Azusa field study should be designed and conducted. Tests with the Azusa study objectives (i.e., effects of WINS cleaning schedule, unattended operation, and delayed sample retrieval) should be repeated in other locations to experience different extremes of aerosol and meteorological conditions. Another objective that should be tested is the effects of sample handling and transport conditions on sample integrity. The relationship between the particle sizing of the WINS and the amount of deposit on the impaction surface should be determined in a hybrid field/laboratory study. This study should be repeated when a new sampler inlet is designed that reduces the amount of material collected as deposit in the WINS. The effectiveness of modifications to the inlet to control the passage of precipitation into the sampler should also be tested in the field.

Conclusions

Two manufacturers' versions of the prototype FRM were successfully field tested in seven studies with four other $\text{PM}_{2.5}$ samplers under a variety of ambient conditions.

FRM performed well in six of the seven studies (i.e., not in Tucson) with typical collocated precision of about $0.5 \mu\text{g}/\text{m}^3$ corresponding to about 3% at $15 \mu\text{g}/\text{m}^3$.

Additional analyses data from these field studies, especially the two most recently completed field studies (Azusa and Tucson) should be conducted to more thoroughly assess the operational characteristics of the prototype FRM and its comparability to other $\text{PM}_{2.5}$ samplers.

FRM data is comparable to data from the other PM_{2.5} samplers having results generally within about 2 µg/m³.

Field testing was successful in identifying a number of problems that have been address by changes in procedure or specification.

Though additional field studies will be useful in better characterizing the performance characteristics of the FRM and refining procedures, the test results to date are sufficient to confidently predict the success of the FRM as a means to measure PM_{2.5} mass concentration.

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Table 1
FRM Field Testing Equipment

<u>Instrument Type</u>	<u>Inlet</u>	<u>Filter Diameter</u>	<u>Flow Rate (L/min)</u>
RAAS	SA-246B / WINS (Well Impactor Ninety-Six)	47 mm	16.67
Partisol-FRM	SA-246B / WINS	47 mm	16.67
Dichotomous	SA-246B / virtual impactor	37 mm	16.67
IMPROVE	AIHL cyclone	25 mm	21.5
Harvard	Glass impactor	41 mm	10
Air Metrics	Nylon impactor	37 mm	5

Table 2
Locations of Federal Reference Method (FRM) Field Testing Sites

<u>Site Location</u>	<u>Air Quality Instrument</u>	<u>Operator/ Contact</u>
Birmingham site 3009 – 28th St. Birmingham, AL	Dichotomous sampler Reference Ambient Aerosol Sampler (RAAS)	Randy Dillard Jefferson County Health Dept. 1400 6th Ave. South Birmingham, AL 35233 (205) 930-1281
	Harvard Impactor	George Allen Dept. of Environmental Health Harvard School of Public Health 665 Huntington Ave. Boston, MA 02115 (617) 432-1946
Denver-Adams City site 4301 East 72nd Ave. Adams City, CO	Reference Ambient Aerosol Sampler (RAAS) IMPROVE sampler	Dan Ely and Gary Kenniston Colorado Air Pollution Control Div. 4300 Cherry Creek Dr. South Denver, CO 80222 (303) 692-3228
Bakersfield site 5558 California Ave., Suite 460 Bakersfield, CA 93303	Dichotomous sampler IMPROVE sampler Reference Ambient Aerosol Sampler (RAAS) Partisol-FRM sampler	Peter Ouchida California Air Resources Board P.O. Box 2815 Sacramento, CA 95814 (916) 322-3719

Table 2 (continued)
Locations of Federal Reference Method (FRM) Field Testing Sites

<u>Site Location</u>	<u>Air Quality Instrument</u>	<u>Operator/ Contact</u>
Denver-Welby site corner of E. 78th Dr. and Steele St. Denver, CO	Reference Ambient Aerosol Sampler (RAAS)	Robert W. Vanderpool Research Triangle Institute P.O. Box 12194 Research Triangle Park, NC (919) 541-7877
Phoenix site 4530 N. 17th Ave. Phoenix, AZ	Dichotomous sampler Reference Ambient Aerosol Sampler (RAAS) Air Metrics Minivol sampler	Thomas Moore Air Quality Division Arizona Dept. of Environmental Quality 3033 N. Central Ave. Phoenix, AZ 85004 (602) 207-2353
Tucson site University of Arizona Respiratory Science Laboratory 1435 N. Fremont St. Tucson, AZ	Dichotomous sampler IMPROVE sampler Reference Ambient Aerosol Sampler (RAAS) Air Metrics Minivol sampler	Thomas Moore Air Quality Division Arizona Dept. of Environmental Quality 3033 N. Central Ave. Phoenix, AZ 85004 (602) 207-2353
Azusa site 130 N. Loren Ave. Azusa, CA	Reference Ambient Aerosol Sampler (RAAS)	Susanne Hering Aerosol Dynamics Inc. 2329 Fourth St. Berkeley, CA 94710 (510) 649-9360

Table 3
FRM Field Testing Site Configurations

<u>Site Name</u>	<u>Air Quality Instrument Make/Model</u>	<u>No. of Units</u>	<u>Inlet Height Above Ground (m)</u>	<u>Sampler Spacing (m)</u>
Birmingham	Graseby Andersen (Atlanta, GA) Reference Ambient Aerosol Sampler (RAAS)	3	4	2
	Graseby Andersen (Atlanta, GA) SA-244 dichotomous sampler	3		
	Harvard Impactor (Harvard University, Boston, MA)	2		
Denver-Adams City	Graseby Andersen (Atlanta, GA) Reference Ambient Aerosol Sampler (RAAS)	3	4	2
	Interagency Monitoring of Protected Visual Environments (IMPROVE) sampler	3		
Bakersfield	Graseby Andersen (Atlanta, GA) Reference Ambient Aerosol Sampler (RAAS)	3	4	2
	Rupprecht & Patashnick (Albany, NY) Partisol-FRM sampler	1		
	Graseby Andersen (Atlanta, GA) SA-244 dichotomous sampler	1		
	Interagency Monitoring of Protected Visual Environments (IMPROVE) sampler	3		
Denver-Welby	Graseby Andersen (Atlanta, GA) Reference Ambient Aerosol Sampler (RAAS)	6	5	2
Phoenix	Graseby Andersen (Atlanta, GA) SA-244 dichotomous sampler	1	3	2
	Graseby Andersen (Atlanta, GA) Reference Ambient Aerosol Sampler (RAAS)	2		
	Air Metrics (Springfield, OR) Minivol sampler	2		
	Harvard Impactor (Harvard University, Boston, MA)	1		
Tucson	Graseby Andersen (Atlanta, GA) SA-244 dichotomous sampler	1	5	2
	Graseby Andersen (Atlanta, GA) Reference Ambient Aerosol Sampler (RAAS)	2		
	Interagency Monitoring of Protected Visual Environments (IMPROVE) sampler	1		
	Air Metrics (Springfield, OR) Minivol sampler	2		
Azusa	Graseby Andersen (Atlanta, GA) Reference Ambient Aerosol Sampler (RAAS)	6	5	2

Table 4
FRM Field Testing Sampling Configurations

<u>Site</u>	<u>Testing Period</u>	<u>Sampling Duration and Frequency</u>	<u>Total No. of Sample Sets</u>
Birmingham, AL	11/04/96 to 11/23/96	22 hours/day from 1200 EST to next day 1000 EST on a daily basis	22
Denver-Adams City, CO	12/11/96 to 01/07/97	23 hours/day from 1200 CST to next day 1100 CST on a daily basis	26
Bakersfield, CA	01/27/97 to 02/14/97	22 hours/day from 1200 PST to next day 1000 PST on a daily basis	24
	03/11/97 to 03/19/97	22 hours/day from 1200 PST to next day 1000 PST on a daily basis	7
Denver-Welby, CO	12/10/96 to 12/22/96	22 hours/day from 1200 MST to next day on a daily basis	10
Phoenix, AZ	12/06/96 to 01/27/97	24 hours/day starting at approx. 1000 MST every other day	24
Tucson, AZ	03/29/97 to 05/31/97	24 hours/day starting at midnight every third day	22
Azusa, CA	03/25/97 to 03/30/97, 04/08/97 to 04/10/97	22 hours/day from approx. 1000 PDT to next day (6 collocated samplers, equal treatment)	9
	03/31/97 to 04/05/97	22 hours/day from ~1000 PDT to next day (6 collocated samplers, varying cleanliness of impactor)	6
	04/14/97 to 04/20/97	24 hours/day starting at midnight (6 collocated samplers, equal treatment)	6
	04/28/97, 05/05/97, and 05/19/97	24 hours/day starting at midnight (6 collocated samplers, varying retrieval time)	3

Table 5
Summary of Federal Reference Method Comparison Data

<u>Sampler</u>	<u>Average PM_{2.5} Concentration (Avg ± Std Dev) (µg/m³)</u>	<u>Number in Average</u>	<u>Coefficient of Variation^b (%)</u>	<u>Concentration Range (µg/m³)</u>	<u>Collocated Precision (µg/m³)^c</u>	<u>Collocated Precision (% of Average)^c</u>
Birmingham Site: 11/04/96 to 11/23/96						
RAAS	19.8 ± 7.9	16	40	6.5 to 33.4	1.13	6.19
Dichotomous	17.8 ± 7.2	16	40	5.5 to 29.9	1.04	6.21
Harvard Impactor	18.1 ± 7.6	16	42	5.3 to 31.0	0.21	1.01
Denver-Adams City Site: 12/11/96 to 01/07/97						
RAAS	11.3 ± 6.1	25	54	2.8 to 20.7	0.49	5.38
IMPROVE	12.2 ± 6.3	25	52	3.1 to 21.3	0.96	11.31
Bakersfield Site: 01/21/97 to 03/19/97						
RAAS	32.4 ± 10.5	14 ^d	32	18.9 to 52.1	0.46	1.50
Partisol ^a	32.3 ± 10.6	14 ^d	33	18.6 to 52.2	N/A	N/A
Dichotomous	30.3 ± 9.2	14 ^d	30	19.1 to 48.9	N/A	N/A
RAAS	29.2 ± 11.7	22 ^d	40	6.3 to 51.8	0.44	1.78
Dichotomous	27.5 ± 10.4	22 ^d	38	6.0 to 48.9	N/A	N/A
RAAS	27.6 ± 12.6	23 ^d	46	6.3 to 51.8	0.43	1.75
IMPROVE	26.9 ± 10.4	23 ^d	39	6.6 to 49.6	2.73	10.84
RAAS	24.7 ± 11.0	7 ^e	45	10.8 to 41.3	0.62	2.91
IMPROVE	24.5 ± 11.0	7 ^e	45	10.8 to 41.7	1.56	6.79
Denver-Welby Site: 12/12/96 to 12/21/96						
RAAS (without temperature compensation)	11.4 ± 6.3	10	56	1.5 to 21.5	0.39	5.42
RAAS (with temperature compensation)	10.4 ± 5.8	10	55	1.2 to 19.8	0.36	4.83

Table 5 (continued)
Summary of Federal Reference Method Comparison Data

<u>Sampler</u>	<u>Average PM_{2.5} Concentration (Avg ± Std Dev) (µg/m³)</u>	<u>Number in Average</u>	<u>Coefficient of Variation^b (%)</u>	<u>Concentration Range (µg/m³)</u>	<u>Collocated Precision (µg/m³)^c</u>	<u>Collocated Precision (% of Average)^c</u>
Phoenix Site: 12/06/96 to 01/27/97^f						
RAAS	17.8 ± 9.2	24	52	3.3 to 33.9	0.42	2.77
Dichotomous	19.1 ± 10.1	24	53	3.7 to 37.8	NA	NA
Air Metrics	20.3 ± 9.2	20	45	6.0 to 35.3	2.98	16.91
Harvard Impactor	21.5 ± 9.9	10	46	5.3 to 35.4	NA	NA
Tucson Site: 03/29/97 to 05/31/97^f						
RAAS	6.8 ± 1.9	22	28	4.1 to 10.4	0.95	14.03
Dichotomous	6.2 ± 2.0	22	32	2.7 to 11.8	NA	NA
IMPROVE	6.9 ± 1.7	19	24	3.9 to 11.1	NA	NA
Air Metrics	8.7 ± 6.3	14	72	1.1 to 20.3	3.93	48.00
Azusa Site: 03/25/97 to 05/19/97						
RAAS A (03/25/97-03/30/97, 04/08/97-04/10/97)	18.6 ± 7.2	9	39	6.0 to 32.1	0.38	2.40
RAAS B1 (03/31/97-04/05/97)	8.8 ± 4.0	6	45	3.4 to 12.9	0.14	1.69
RAAS B2	8.4 ± 3.7	6	44	3.1 to 12.4	0.11	1.01
RAAS B3	7.9 ± 3.5	6	45	2.9 to 11.8	0.09	1.07
RAAS C (04/16/97-04/20/97)	27.6 ± 9.2	6	33	19.5 to 42.0	0.36	1.85
RAAS D (04/28/97-05/19/97)	18.8 ± 3.9	3	21	14.3 ± 21.5	0.99	5.32

^a Partisol sampler data are available only from the period 01/28/97 to 02/13/97 at Bakersfield.

^b Coefficient of variation in percent is the standard deviation divided by the average PM_{2.5} concentration times 100.

^c Root mean squared (RMS) collocated precision = $\sqrt{\frac{\sum_{i=1}^n (R_i - \bar{R})^2}{n-1}}$ (Mathai et al., 1990) = $\sqrt{\frac{\sum_{i=1}^n R_i^2 - \frac{1}{n} \left(\sum_{i=1}^n R_i\right)^2}{n-1}}$ (U.S. EPA, 1996b).

^d 01/21/97 to 02/13/97 main study period.

^e 03/11/97 to 03/19/97 special study period to evaluate the effect on mass concentration by chamber temperature.

^f No blank correction.

**Table 6
Pairwise Comparisons of FRM Sampler Field Testing Results**

X-Sampler ^a	Y-Sampler ^a	Slope ^b	Slope Uncertainty	Intercept ^c ($\mu\text{g}/\text{m}^3$)	Intercept Uncertainty ($\mu\text{g}/\text{m}^3$)	Correlation Coefficient ^d	Number of Pairs	Average Ratio	Std. Dev. of Ratio ^e	Percent Distribution ^f				Average Difference ^g ($\mu\text{g}/\text{m}^3$)	Precisions ($\mu\text{g}/\text{m}^3$)		
										< 1 σ	1-2 σ	2-3 σ	> 3 σ		Collocated ^h	RMSE-Y ⁱ	RMSE-X ⁱ
Birmingham, AL																	
RAAS	DICHOT	0.90	0.05	-0.03	1.04	0.989	16	0.90	0.06	69	31	0	0	-2.01	1.17	1.11	1.18
DICHOT	RAAS	1.09	0.07	0.41	1.13	0.989	16	1.12	0.07	69	31	0	0	2.01	1.17	1.18	1.11
RAAS	Harvard	0.94	0.06	-0.55	1.07	0.978	16	0.91	0.08	69	25	6	0	-1.68	1.37	1.14	1.18
Harvard	RAAS	1.02	0.06	1.34	1.06	0.978	16	1.11	0.10	69	25	6	0	1.68	1.37	1.18	1.14
Denver-Adams City, CO																	
RAAS	IMPROVE	1.02	0.05	0.64	0.61	0.984	25	1.11	0.20	80	20	0	0	0.87	1.09	1.01	1.00
IMPROVE	RAAS	0.95	0.04	-0.27	0.61	0.984	25	0.92	0.11	80	20	0	0	-0.87	1.09	1.00	1.01
Bakersfield, CA																	
RAAS	Partisol	1.00	0.06	-0.14	1.83	0.998	14	1.00	0.02	100	0	0	0	-0.13	0.51	1.70	1.70
Partisol	RAAS	1.00	0.06	0.26	1.81	0.998	14	1.01	0.02	100	0	0	0	0.13	0.51	1.70	1.70
RAAS	DICHOT	0.90	0.04	1.32	0.96	0.994	22	0.95	0.04	91	9	0	0	-1.71	1.71	1.49	1.65
DICHOT	RAAS	1.10	0.05	-1.19	1.11	0.994	22	1.05	0.05	91	9	0	0	1.71	1.71	1.65	1.49
RAAS ^k	IMPROVE ^k	0.84	0.03	3.16	0.84	0.966	23	0.98	0.11	78	13	9	0	-1.40	3.07	1.52	1.63
IMPROVE ^k	RAAS ^k	1.12	0.05	-2.04	1.08	0.966	23	1.04	0.11	78	13	9	0	1.40	3.07	1.63	1.52
RAAS ^l	IMPROVE ^l	0.98	0.07	0.33	1.59	0.999	7	1.00	0.02	100	0	0	0	-0.17	0.42	1.40	1.41
IMPROVE ^l	RAAS ^l	1.02	0.07	-0.31	1.65	0.999	7	1.00	0.02	100	0	0	0	0.17	0.42	1.41	1.40
Denver-Welby, CO																	
RAASNT ^j	RAASWT ^j	0.92	0.07	0.02	0.93	0.998	10	0.91	0.06	100	0	0	0	-0.91	0.58	1.00	1.01
RAASWT ^j	RAASNT ^j	1.09	0.09	0.01	1.01	0.998	10	1.10	0.081	100	0	0	0	0.91	0.58	1.01	1.00
Phoenix, AZ																	
RAAS	DICHOT	1.10	0.04	-0.41	0.74	0.996	24	1.07	0.06	88	13	0	0	1.35	1.24	1.22	1.17
DICHOT	RAAS	0.90	0.04	0.48	0.66	0.996	24	0.94	0.05	88	13	0	0	-1.35	1.24	1.17	1.22
RAAS	Air Metrics	0.90	0.04	3.24	0.74	0.956	20	1.18	0.29	70	15	10	5	1.70	2.43	1.23	1.19
Air Metrics	RAAS	1.01	0.05	-1.89	0.88	0.956	20	0.89	0.17	70	20	5	5	-1.70	2.43	1.19	1.23
RAAS	Harvard	0.98	0.06	0.54	1.15	0.998	10	1.01	0.06	100	0	0	0	0.11	0.70	1.28	1.28
Harvard	RAAS	1.02	0.06	-0.46	1.20	0.998	10	0.99	0.05	100	0	0	0	-0.11	0.70	1.28	1.28

Table 6 (continued)
Pairwise Comparisons of FRM Sampler Field Testing Results

X-Sampler ^a	Y-Sampler ^a	Slope ^b	Slope Uncertainty	Intercept ^c ($\mu\text{g}/\text{m}^3$)	Intercept Uncertainty ($\mu\text{g}/\text{m}^3$)	Correlation Coefficient ^d	Number of Pairs	Average Ratio	Std. Dev. of Ratio ^e	Percent Distribution ^f				Average Difference ^g ($\mu\text{g}/\text{m}^3$)	Precisions ($\mu\text{g}/\text{m}^3$)		
										< 1 σ	1-2 σ	2-3 σ	> 3 σ		Collocated ^h	RMSE-Y ⁱ	RMSE-X ^j
Tucson, AZ																	
RAAS	Air Metrics	0.99	0.20	1.87	1.40	0.32	14	1.30	1.07	21	43	7	29	1.79	5.65	1.00	1.00
Air Metrics	RAAS	0.10	0.05	6.02	0.48	0.32	14	1.71	1.85	21	43	7	29	-1.79	5.65	1.00	1.00
DICHOT	RAAS	0.30	0.11	4.92	0.74	0.31	22	1.16	0.37	77	14	5	5	0.59	2.25	1.00	1.00
RAAS	DICHOT	0.32	0.12	4.01	0.84	0.31	22	0.97	0.41	77	14	5	5	-0.59	2.25	1.00	1.00
RAAS	IMPROVE	0.36	0.14	4.43	1.01	0.37	19	1.06	0.33	63	32	5	0	0.02	1.87	1.00	1.00
IMPROVE	RAAS	0.39	0.15	4.20	1.06	0.37	19	1.03	0.28	63	32	5	0	-0.02	1.87	1.00	1.00

^a RAAS=Reference Ambient Air Sampler; DICHOT=dichotomous sampler; Harvard=Harvard Impactor; IMPROVE=Interagency Monitoring of Protected Environments sampler; Partisol=Partisol-FRM sampler, and Air Metrics=Air Metrics Minivol sampler.

^b Variance-weighted regression slope with standard error.

^c Variance-weighted regression intercept with standard error.

^d Correlation coefficient.

^e Average of Y/X and standard deviation of this ratio.

^f Percentage of data pairs falling into the specified precision intervals, where each precision interval is equal to root mean square (RMS) of the sum of the squared precisions of the X and Y samplers.

^g Average of X minus Y.

^h Collocated precision or standard deviation of X minus Y.

ⁱ RMS precision of the difference between X and Y, the root mean square (RMS) of the sum of the squared precisions of X and Y.

^j RAASNT=RAAS without temperature compensation. RAASWT=RAAS with temperature compensation.

^k 01/21/97 to 02/13/97.

^l 03/11/97 to 03/19/97.

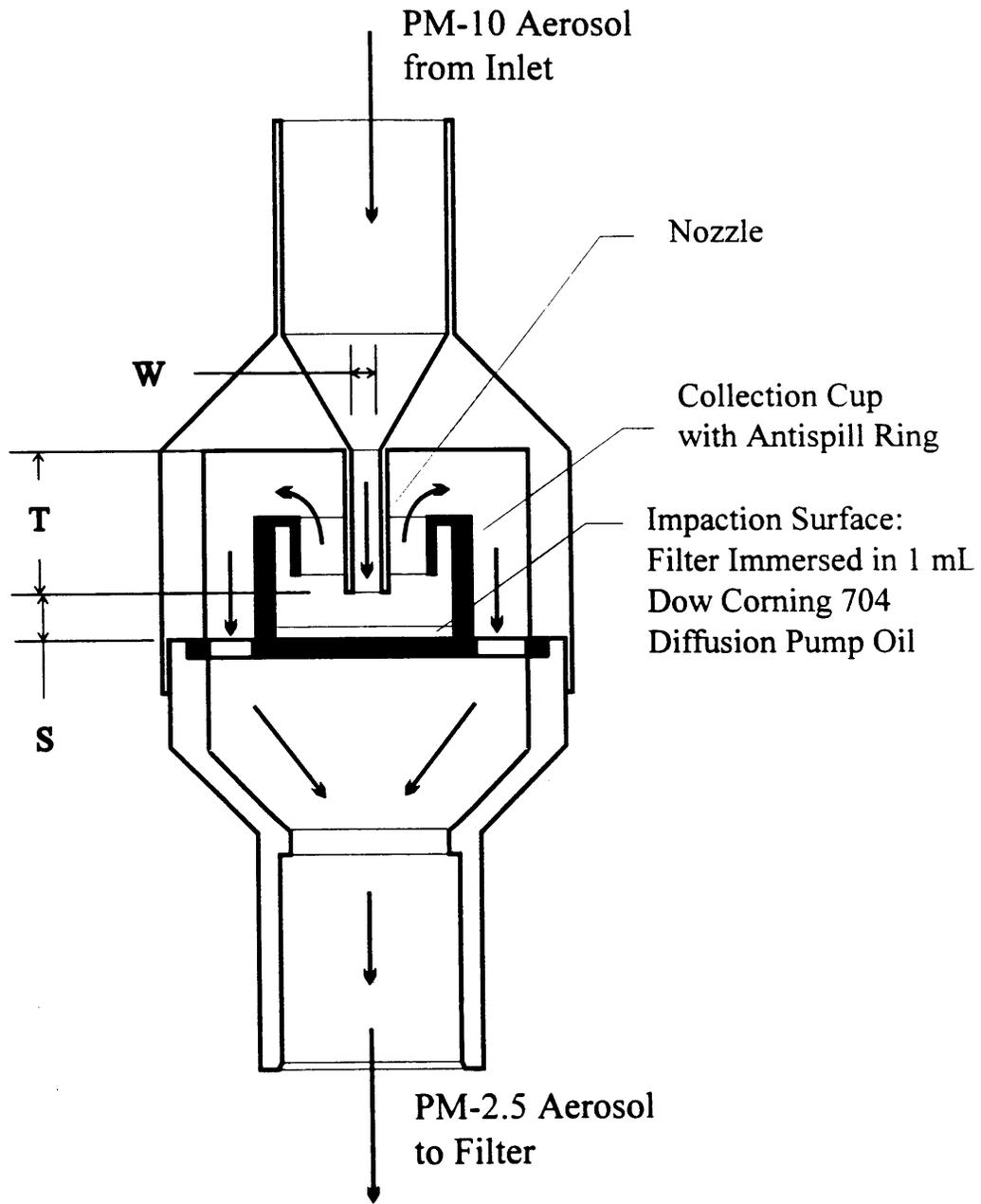


Figure 1. WINS impactor.

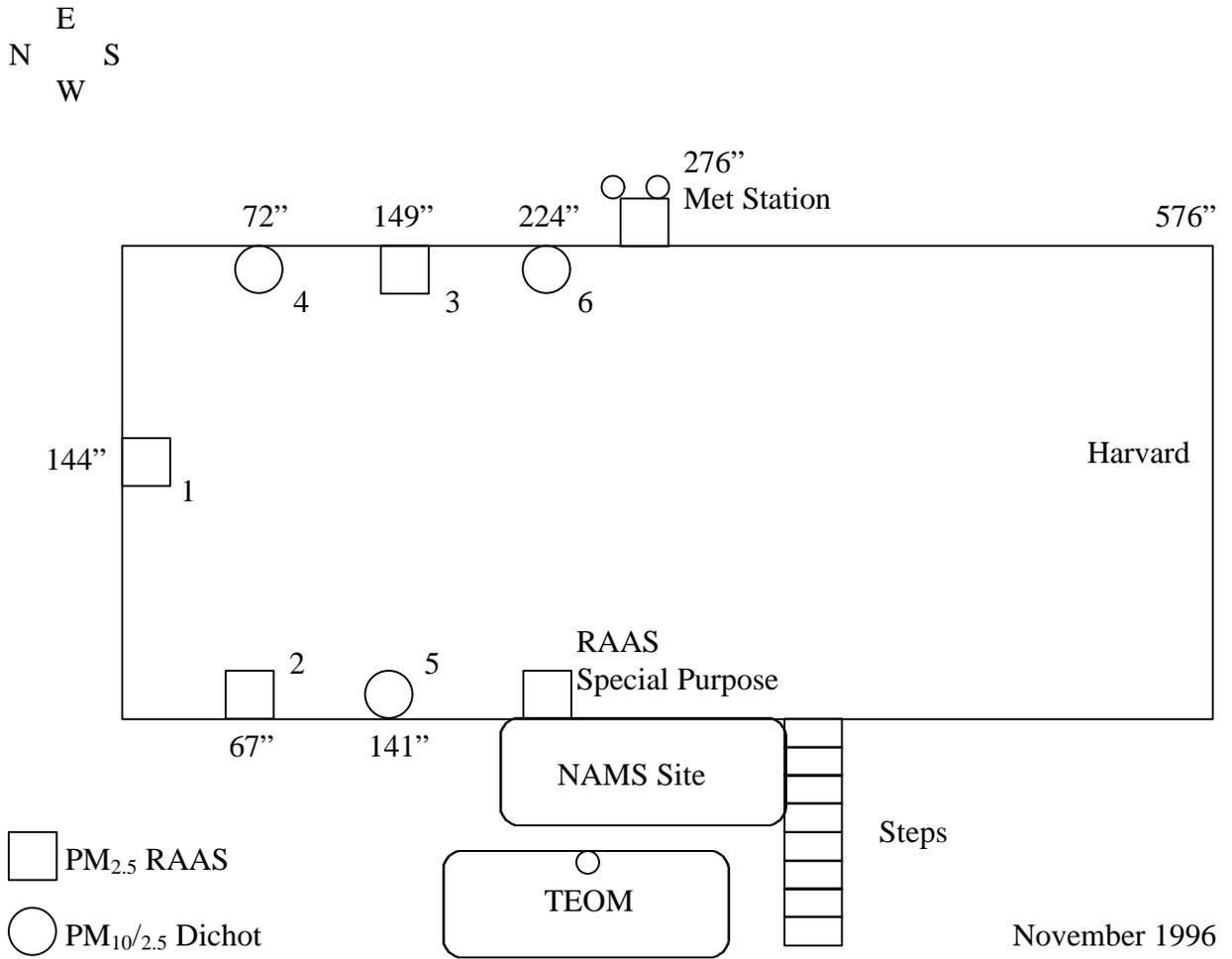


Figure 2. Layout of the field testing samplers at the Birmingham site.

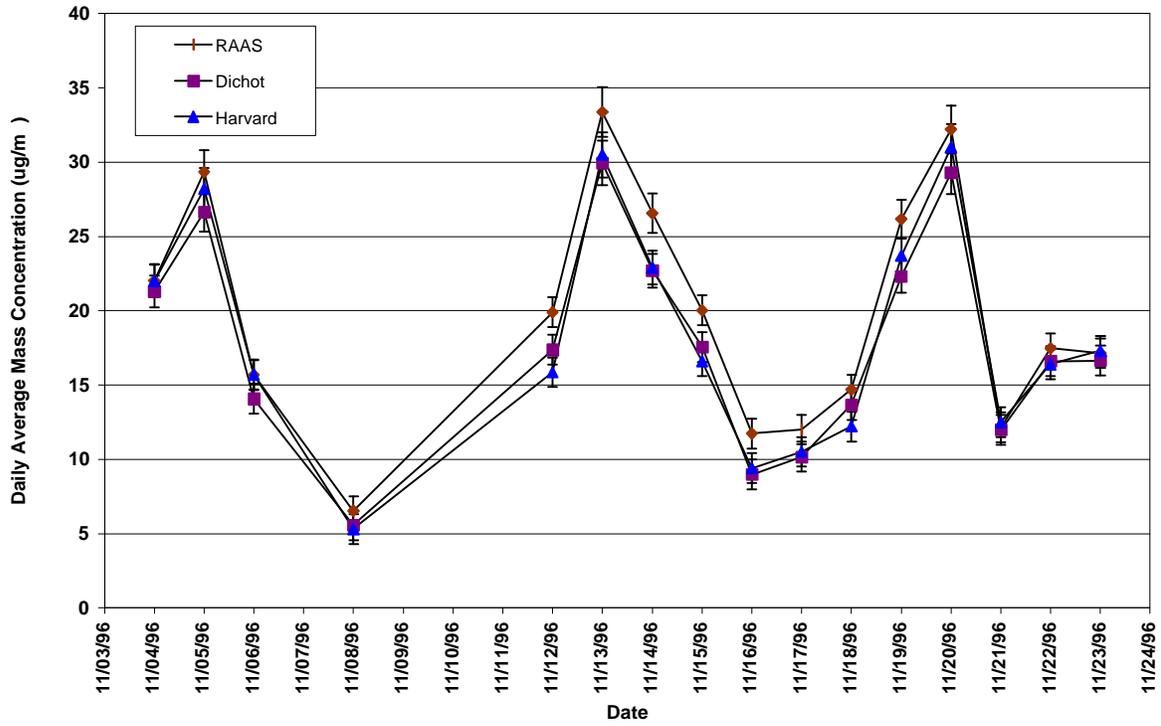


Figure 3. Temporal variations of PM_{2.5} concentrations at the Birmingham site between 11/04/96 and 11/24/96.

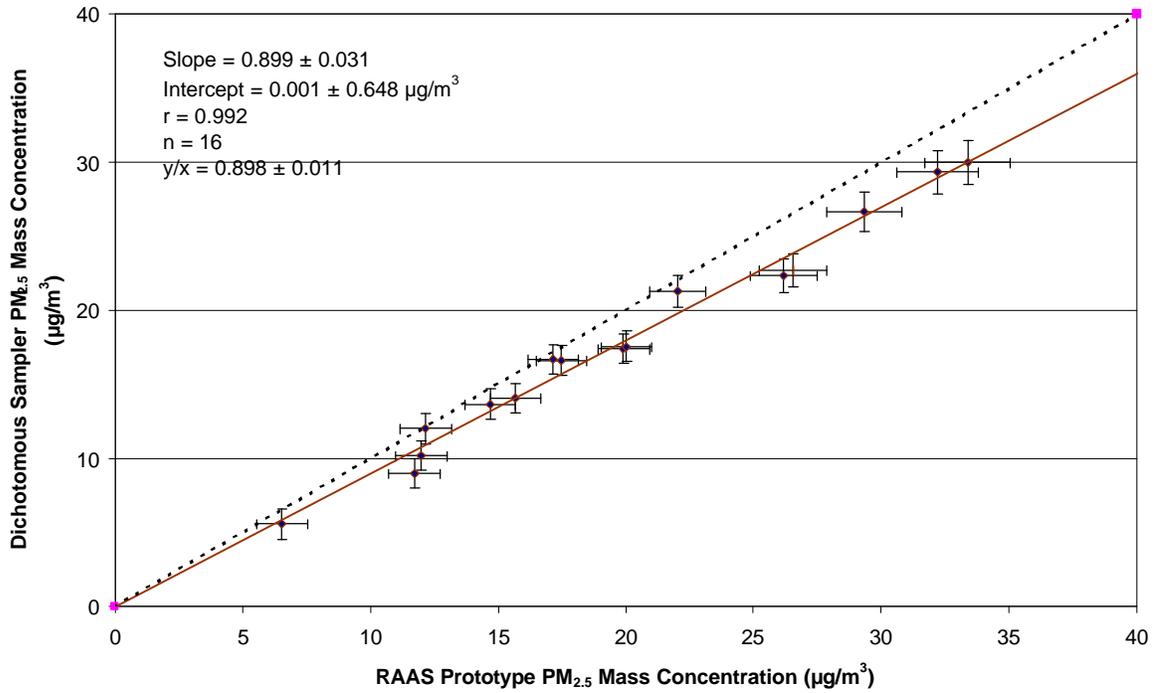


Figure 4a. Comparison of Dichotomous vs. RAAS $\text{PM}_{2.5}$ mass concentrations at the Birmingham site between 11/04/96 and 11/23/96.

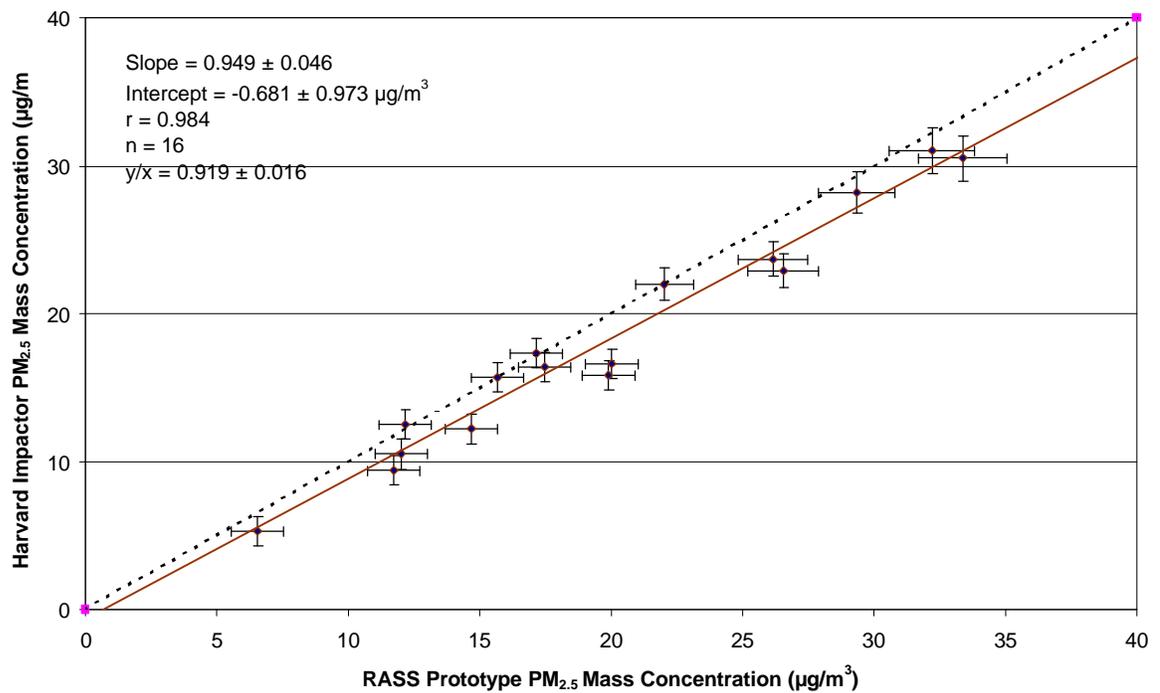


Figure 4b. Comparison of Harvard Impactor vs. RAAS $\text{PM}_{2.5}$ mass concentrations at the Birmingham site between 11/04/96 and 11/23/96.

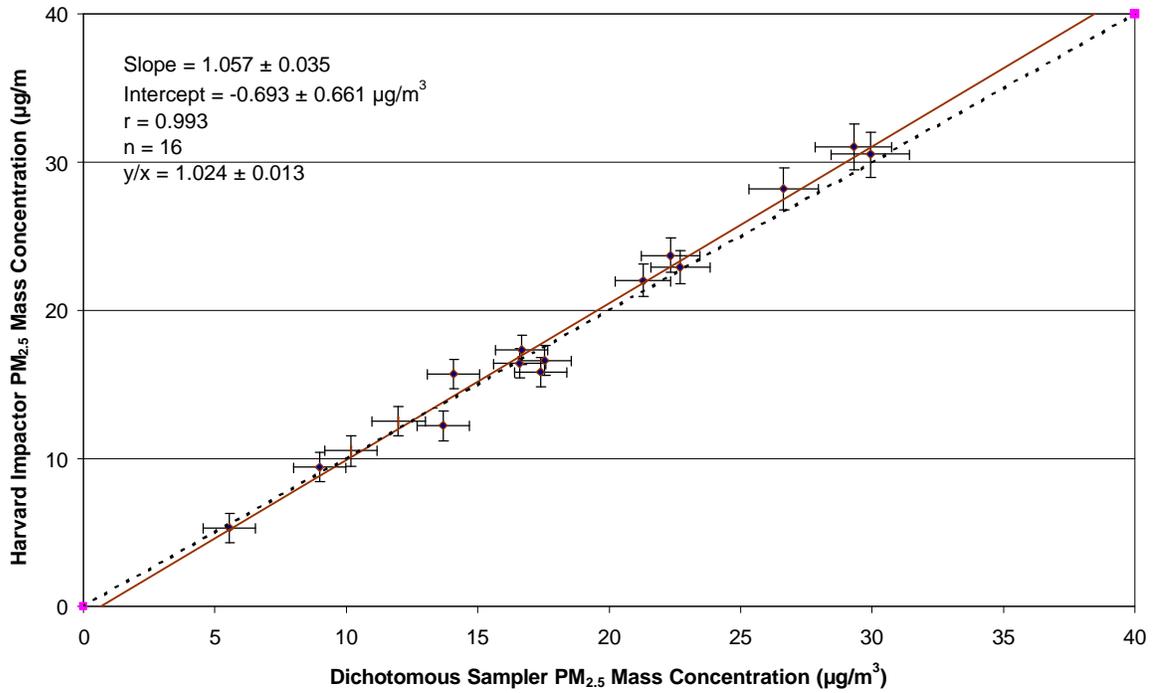


Figure 4c. Comparison of Harvard Impactor vs. Dichotomous PM_{2.5} mass concentrations at the Birmingham site between 11/04/96 and 11/23/96.

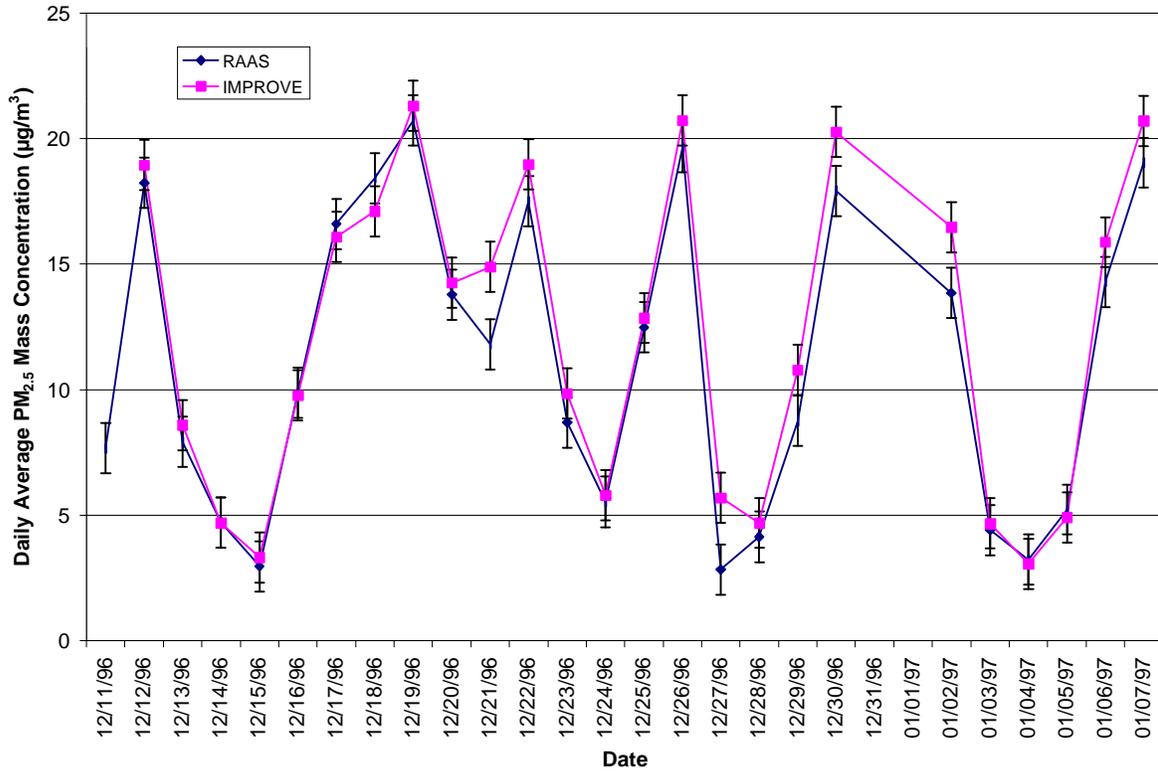


Figure 5. Temporal variations of PM_{2.5} concentrations at the Denver-Adams City site between 12/11/96 and 01/07/97.

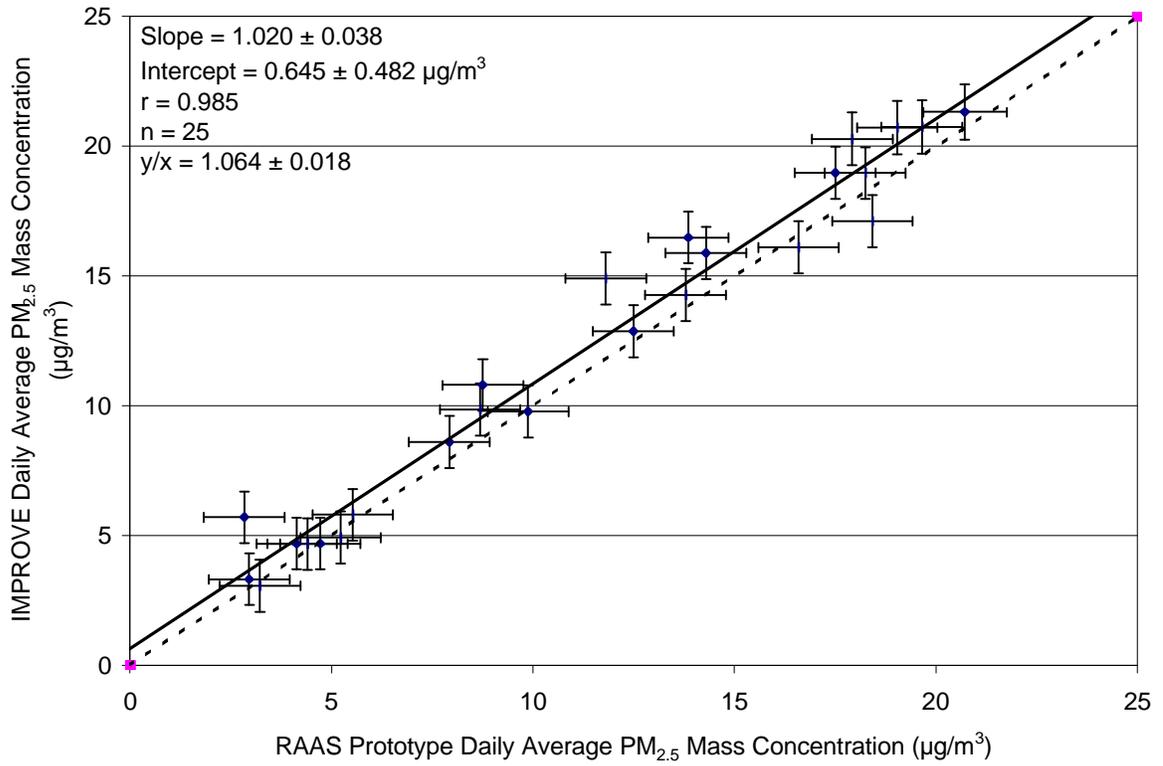
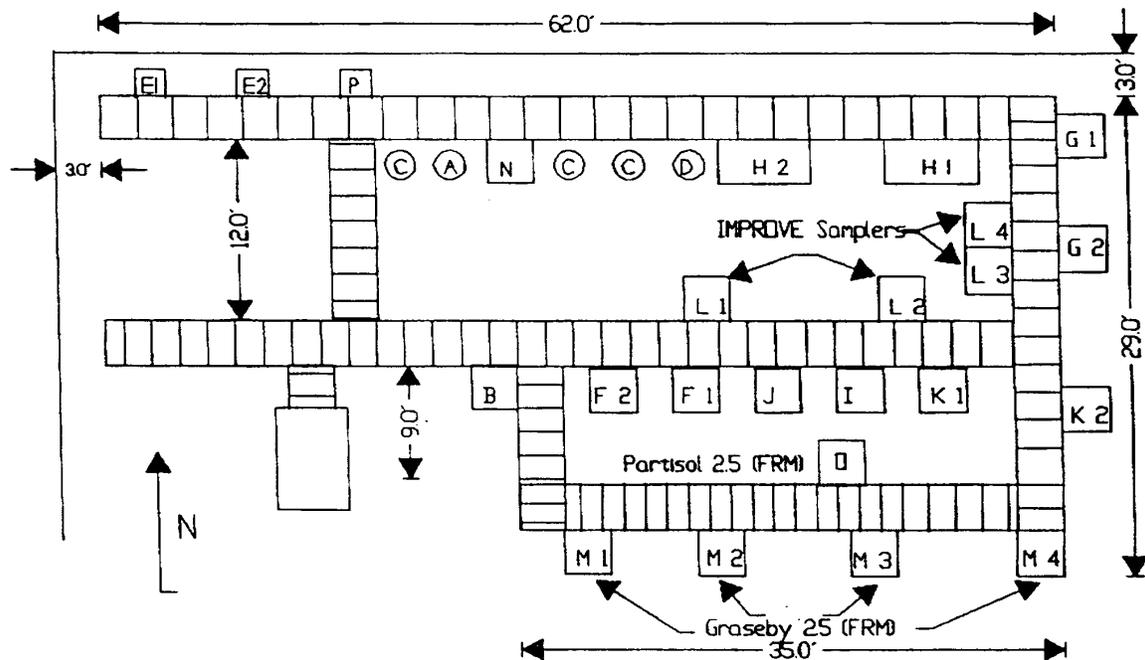


Figure 6. Comparison of $\text{PM}_{2.5}$ mass concentrations at the Denver-Adams City site between 12/11/96 and 01/07/97.



- | | | | |
|----|------------------------------------|----|-----------------------------------|
| A | Station Sample Probe | K1 | Dry Deposition Sampler |
| B | Meteorological Mast | K2 | Dry Deposition (modified) |
| C | TEOM Sample Probe | L1 | IMPROVE Sampler – Red |
| D | Carbon Analyzer Probe | L2 | IMPROVE Sampler – Yellow |
| E1 | Hi-Vol PM ₁₀ Primary | L3 | IMPROVE Sampler – Green |
| E2 | Hi-Vol PM ₁₀ Collocated | L4 | IMPROVE Sampler – Nitrate |
| F1 | Hi-Vol TSP Primary | M1 | Graseby 2.5 (FRM) #1 |
| F2 | Hi-Vol TSP Collocated | M2 | Graseby 2.5 (FRM) #2 |
| G1 | Dichot Sampler Primary | M3 | Graseby 2.5 (FRM) #3 |
| G2 | Dichot Sampler Collocated | M4 | Graseby 2.5 (FRM) #4 |
| H1 | Xontech 920 Primary | N | Partisol PM ₁₀ Sampler |
| H2 | Xontech 920 Collocated | O | Partisol PM _{2.5} (FRM) |
| I | Precipitation Collector | P | Spare Platform |
| J | Rain Gauge | | |

Figure 7. Bakersfield site rooftop sampler placement.

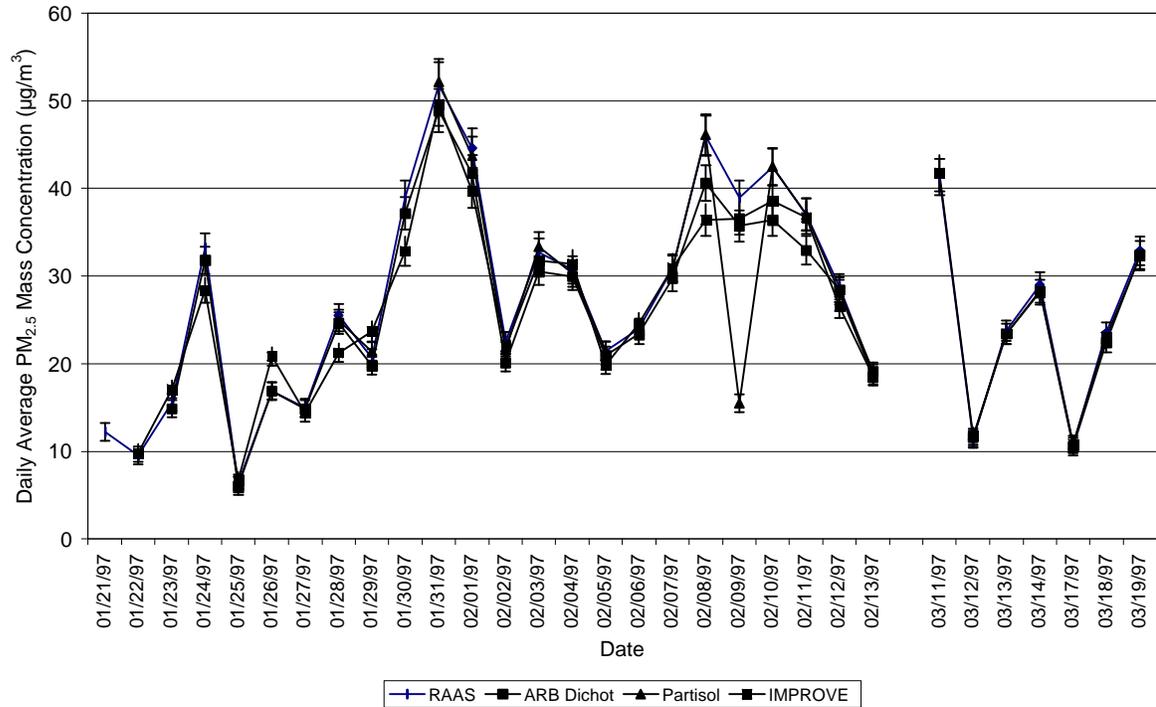


Figure 8. Temporal variations of PM_{2.5} concentrations at the Bakersfield site between 01/21/97 and 03/19/97.

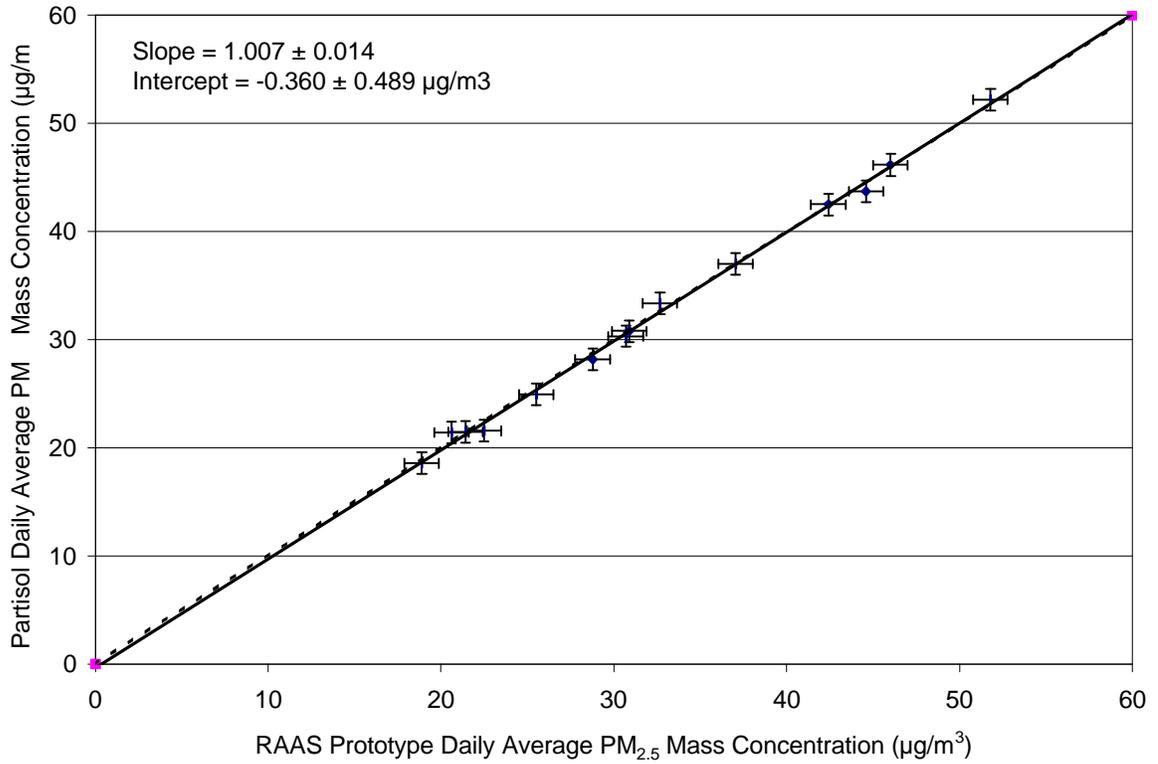


Figure 9a. Comparison of Partisol vs. RAAS PM_{2.5} mass concentrations at the Bakersfield site.

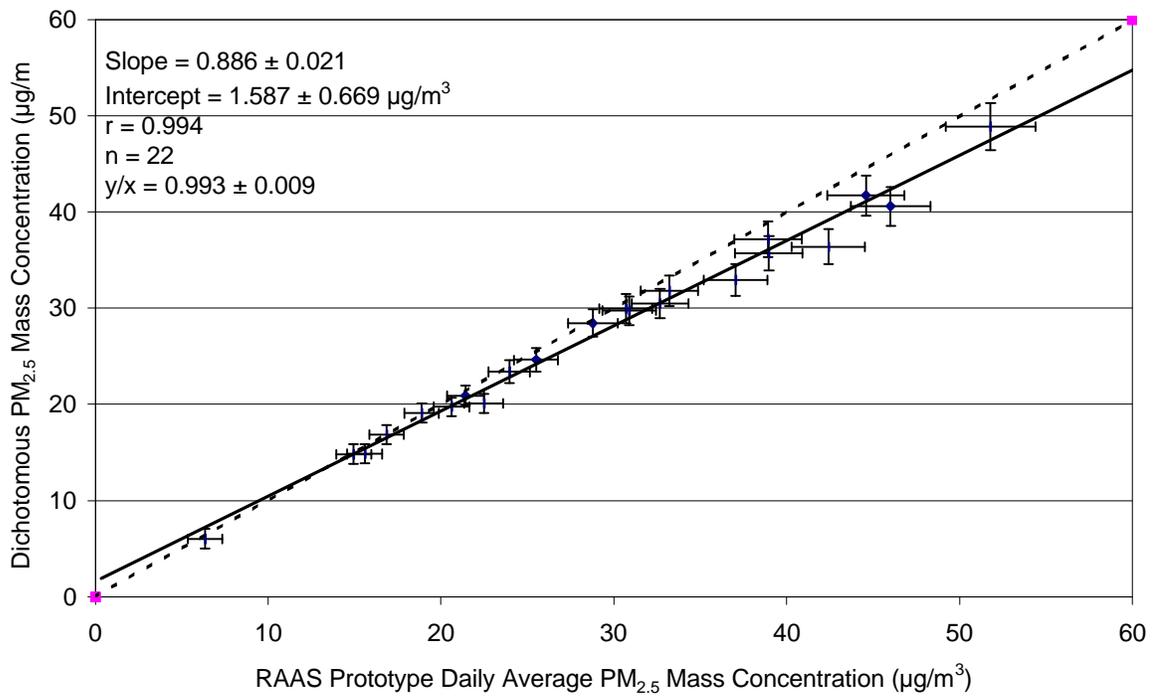


Figure 9b. Comparison of Dichotomous vs. RAAS PM_{2.5} mass concentrations at the Bakersfield site.

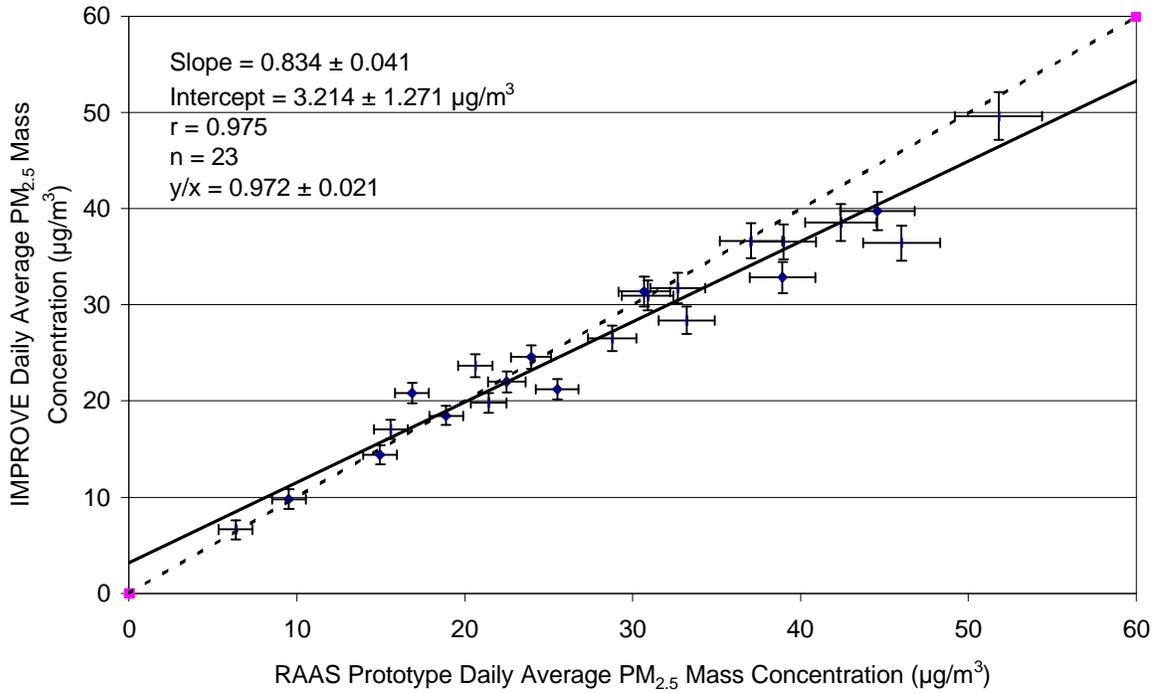


Figure 9c. Comparison of IMPROVE vs. RAAS $\text{PM}_{2.5}$ mass concentrations at the Bakersfield site during the main study period.

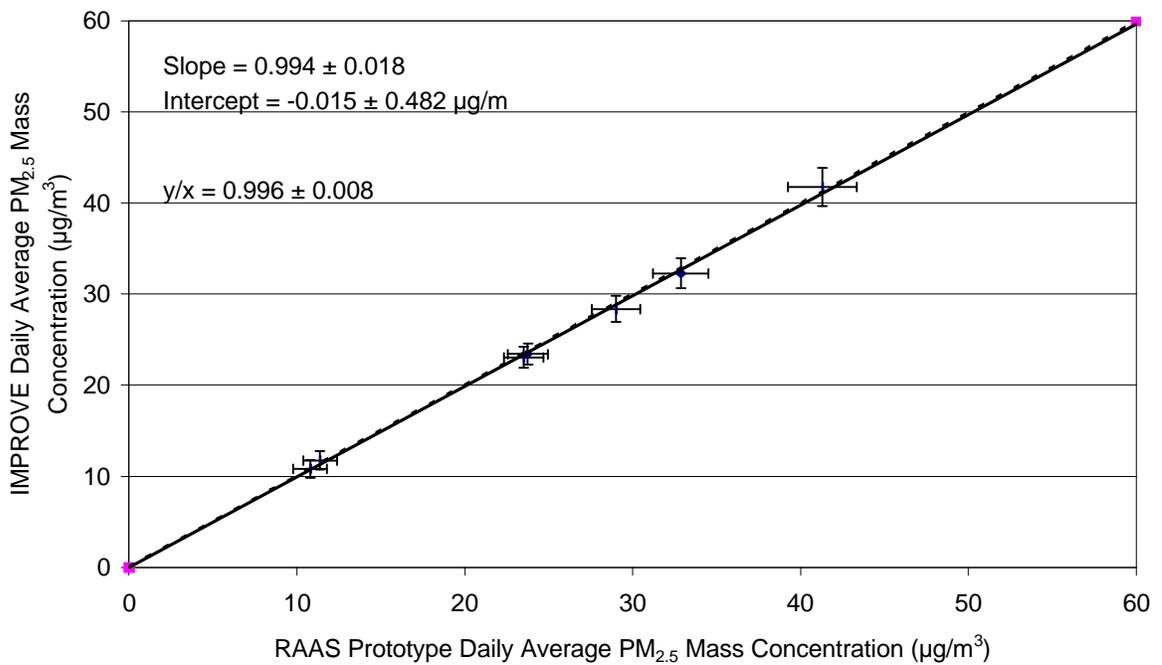


Figure 9d. Comparison of IMPROVE vs. RAAS $\text{PM}_{2.5}$ concentrations at the Bakersfield site during the special study period.

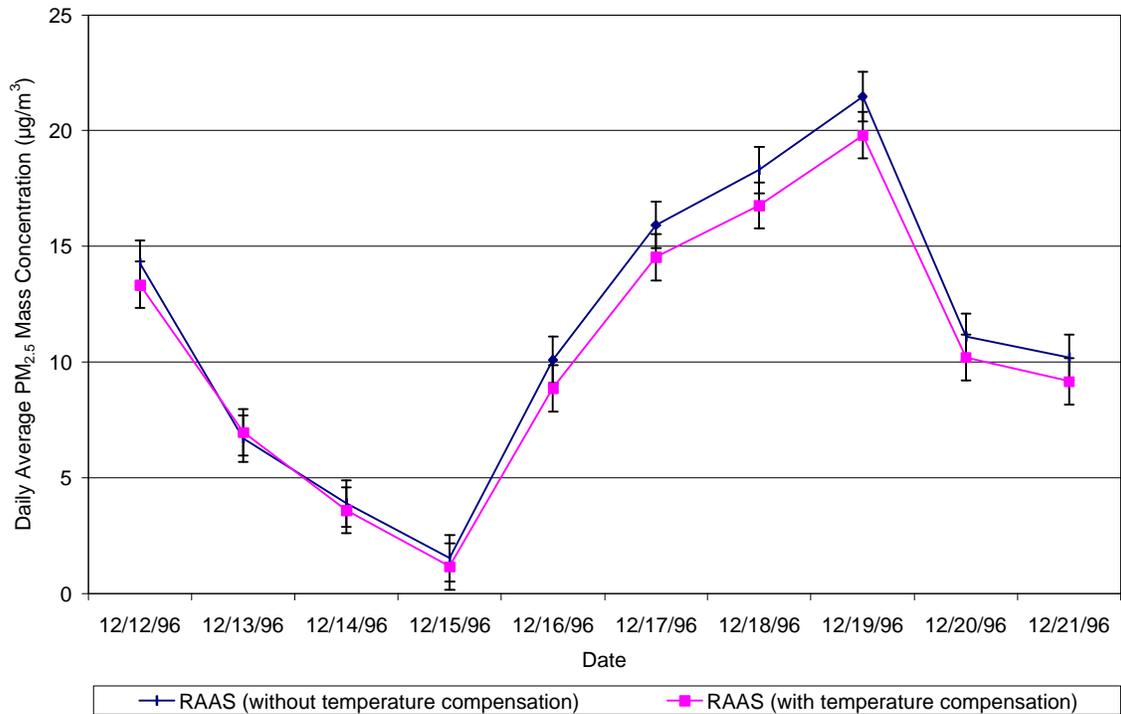


Figure 10. Temporal variations of PM_{2.5} concentrations at the Denver-Welby site between 12/12/96 and 12/21/96.

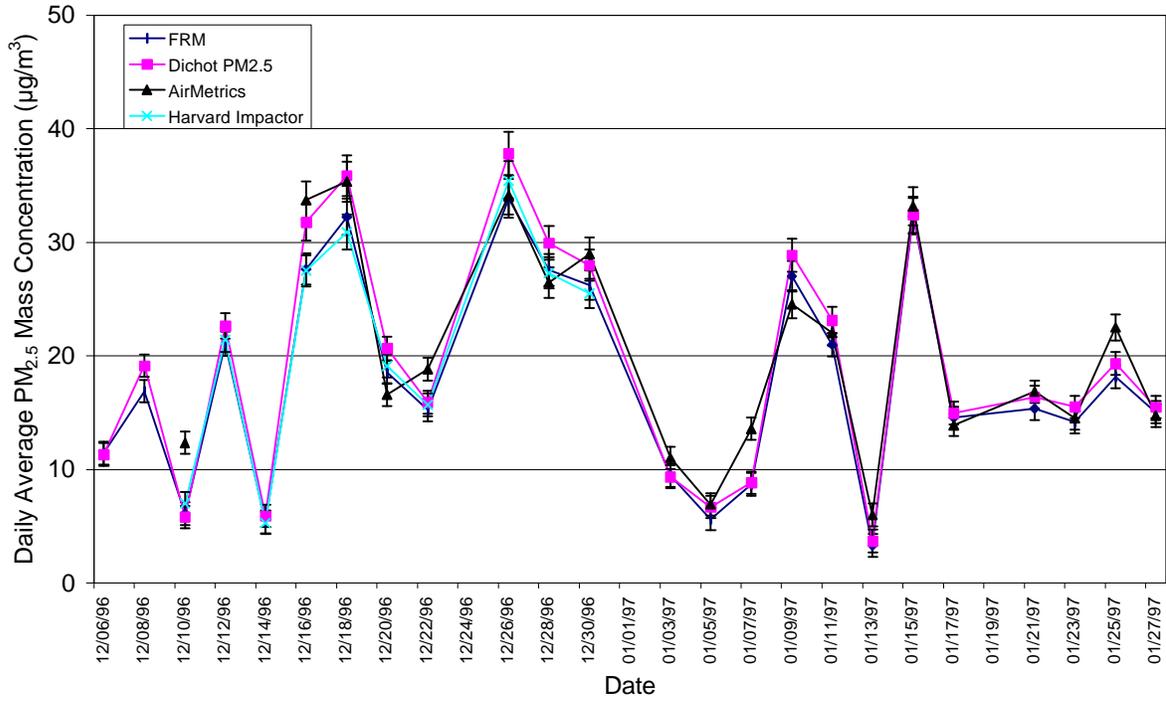


Figure 11. Temporal variations of PM_{2.5} concentrations at the Phoenix site between 12/06/96 and 01/27/97.

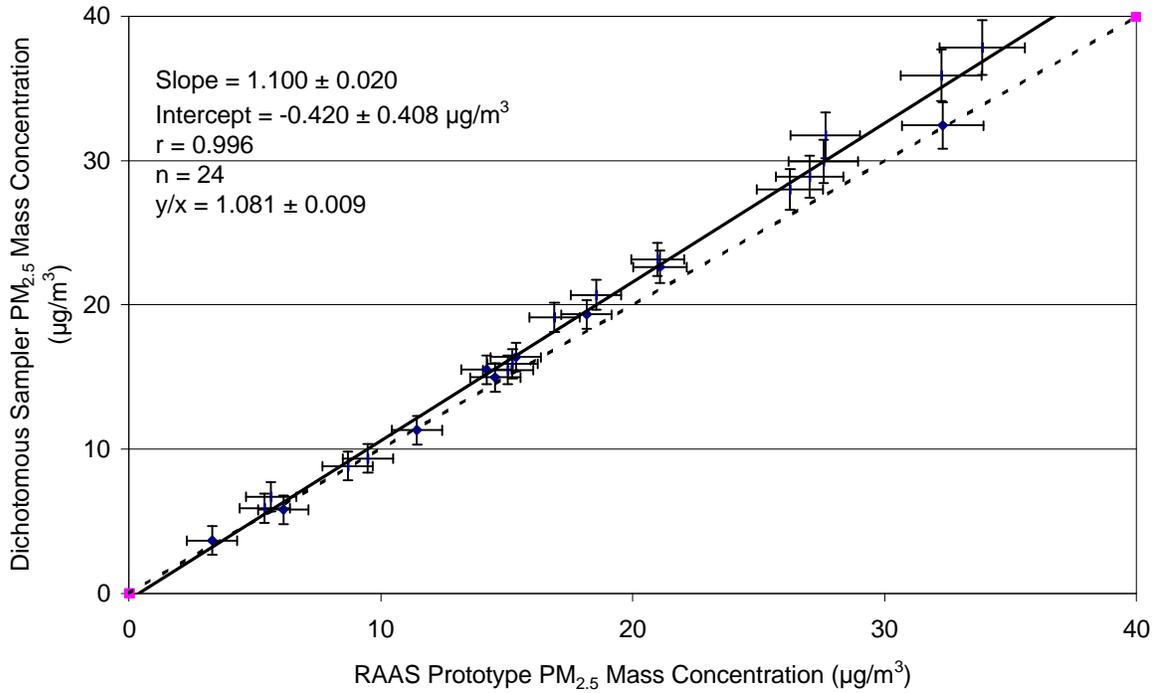


Figure 12a. Comparison of Dichotomous vs. RAAS PM_{2.5} mass concentrations at the Phoenix site.

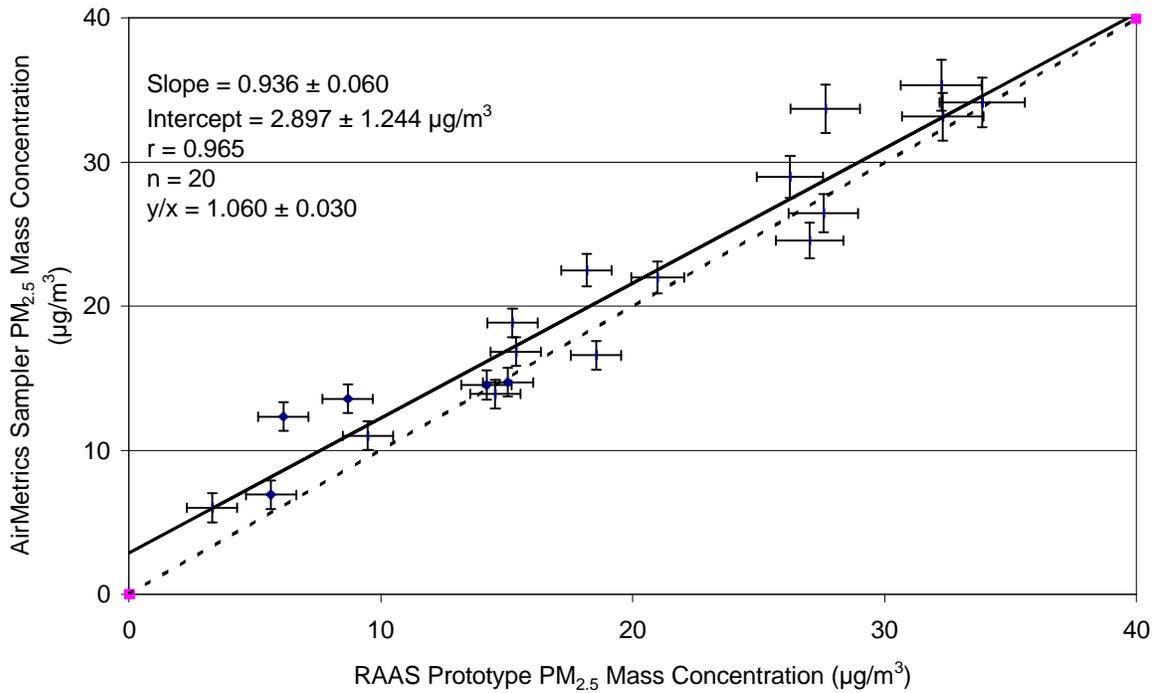


Figure 12b. Comparison of Air Metrics vs. RAAS PM_{2.5} mass concentrations at the Phoenix site.

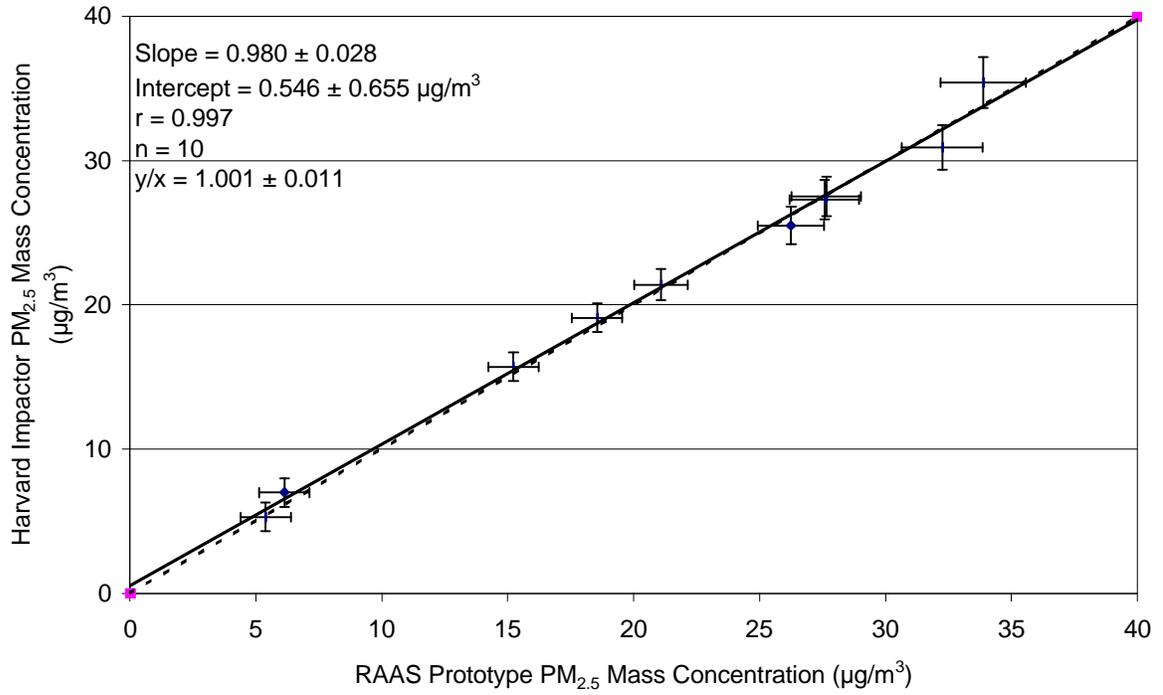


Figure 12c. Comparison of Harvard Impactor vs. RAAS $PM_{2.5}$ mass concentrations at the Phoenix site.

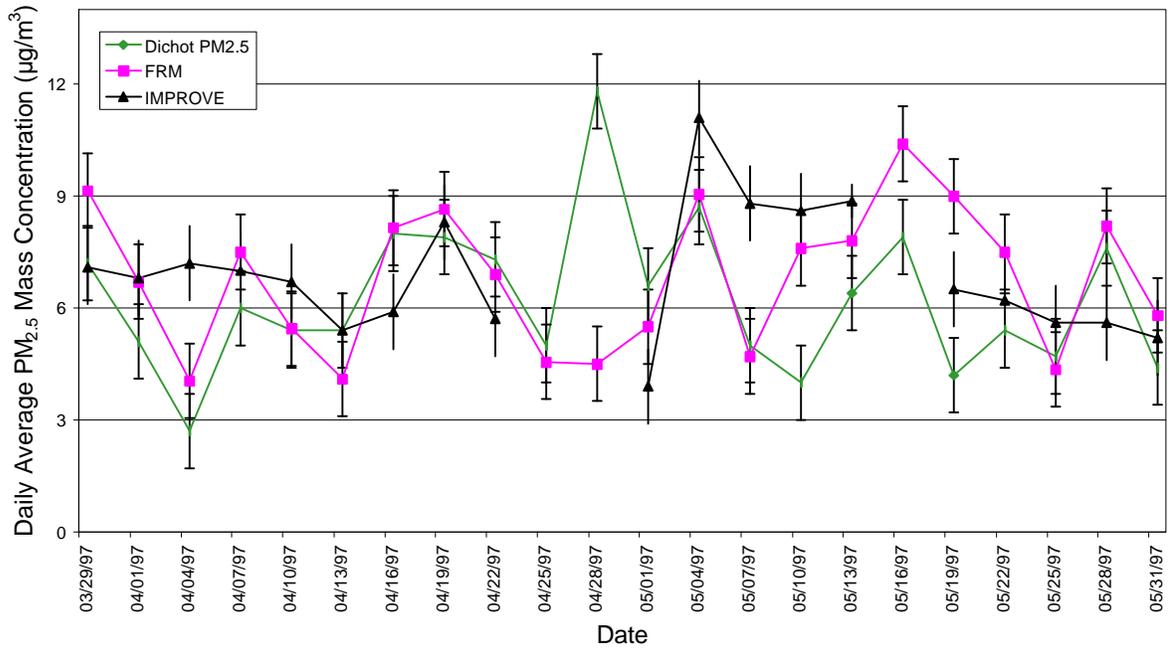


Figure 13. Temporal variations of PM_{2.5} concentrations at the Tucson site between 03/29/97 and 05/31/97.

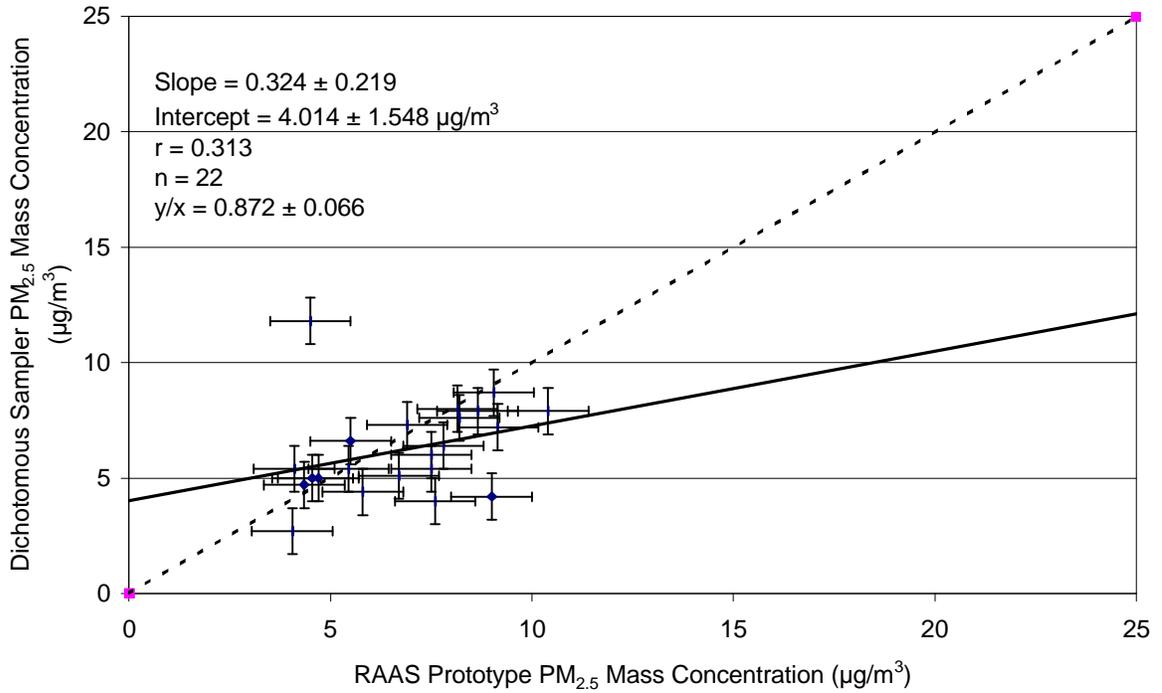


Figure 14a. Comparison of Dichotomous vs. RAAS PM_{2.5} mass concentrations at the Tucson site.

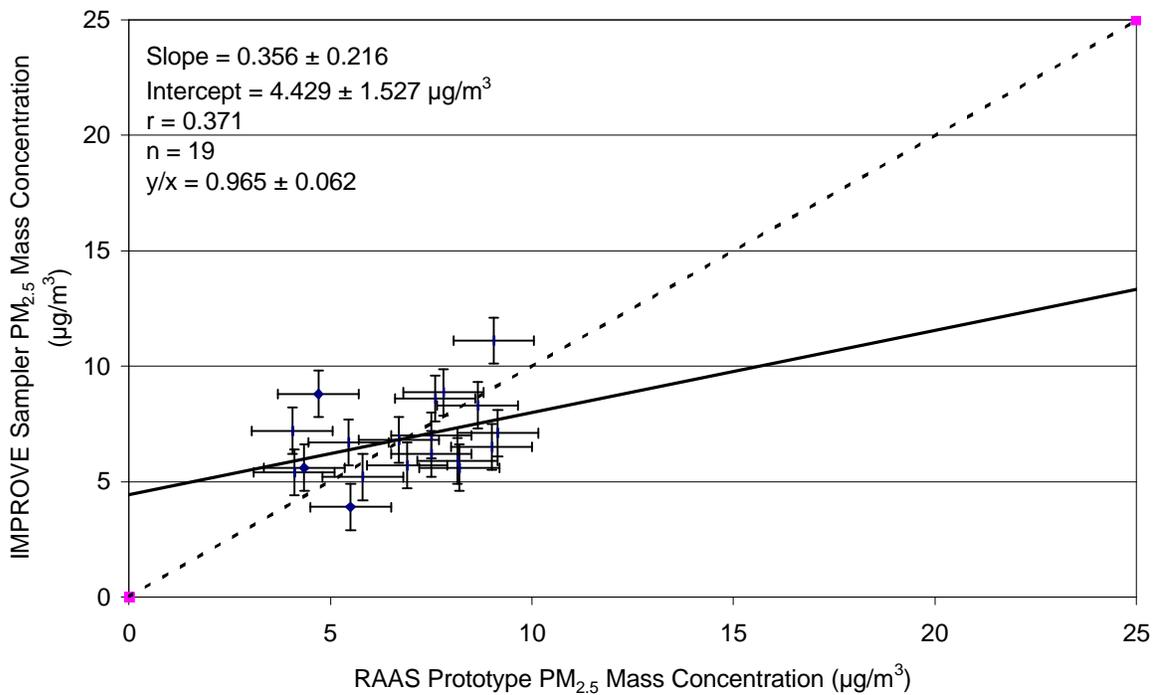


Figure 14b. Comparison of IMPROVE vs. RAAS PM_{2.5} mass concentrations at the Tucson site.

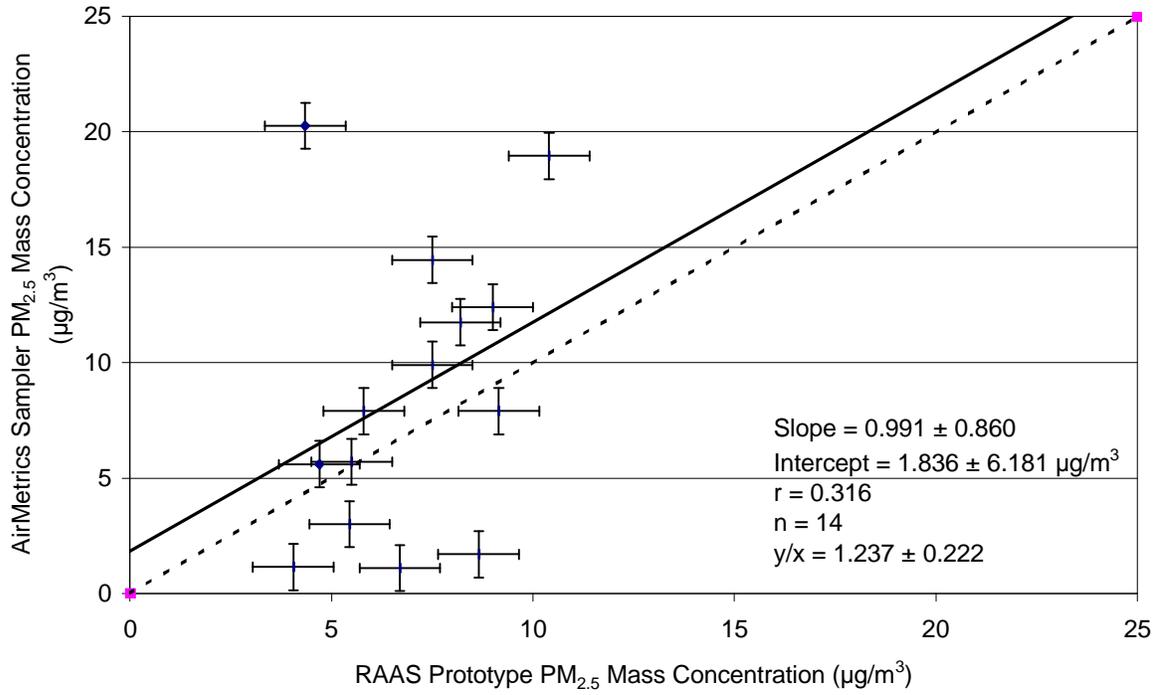


Figure 14c. Comparison of Air Metrics vs. RAAS PM_{2.5} mass concentrations at the Tucson site.

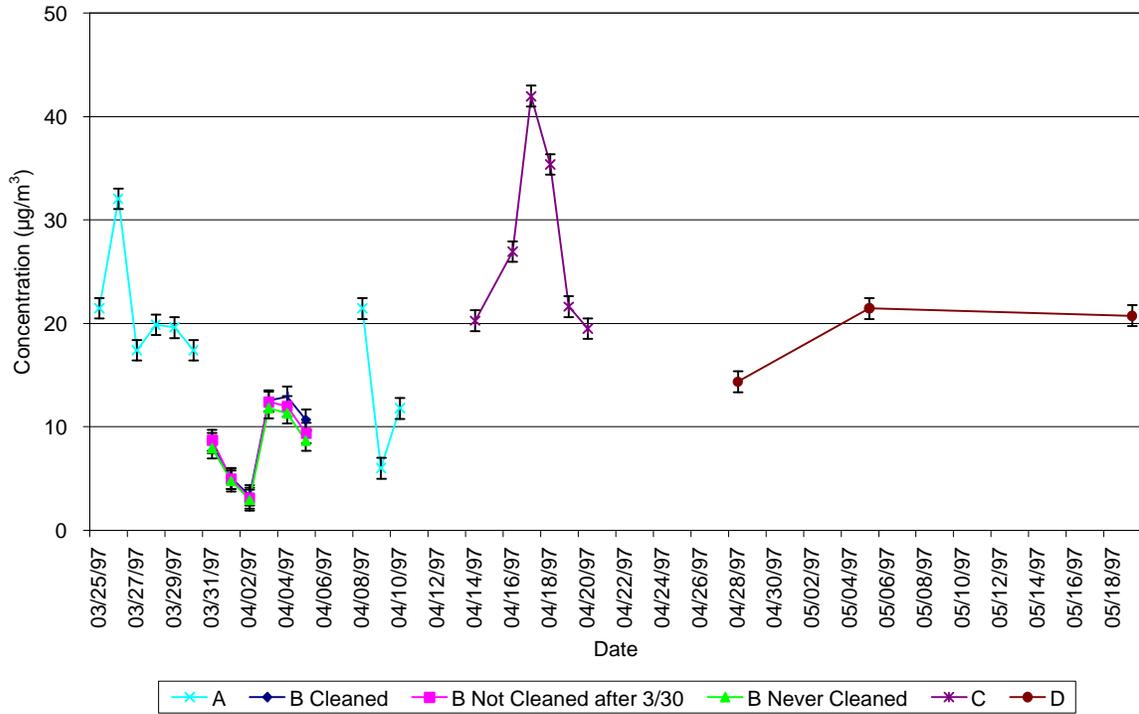


Figure 15a. Temporal variations of PM_{2.5} concentrations at the Azusa site between 03/25/97 and 05/19/97.

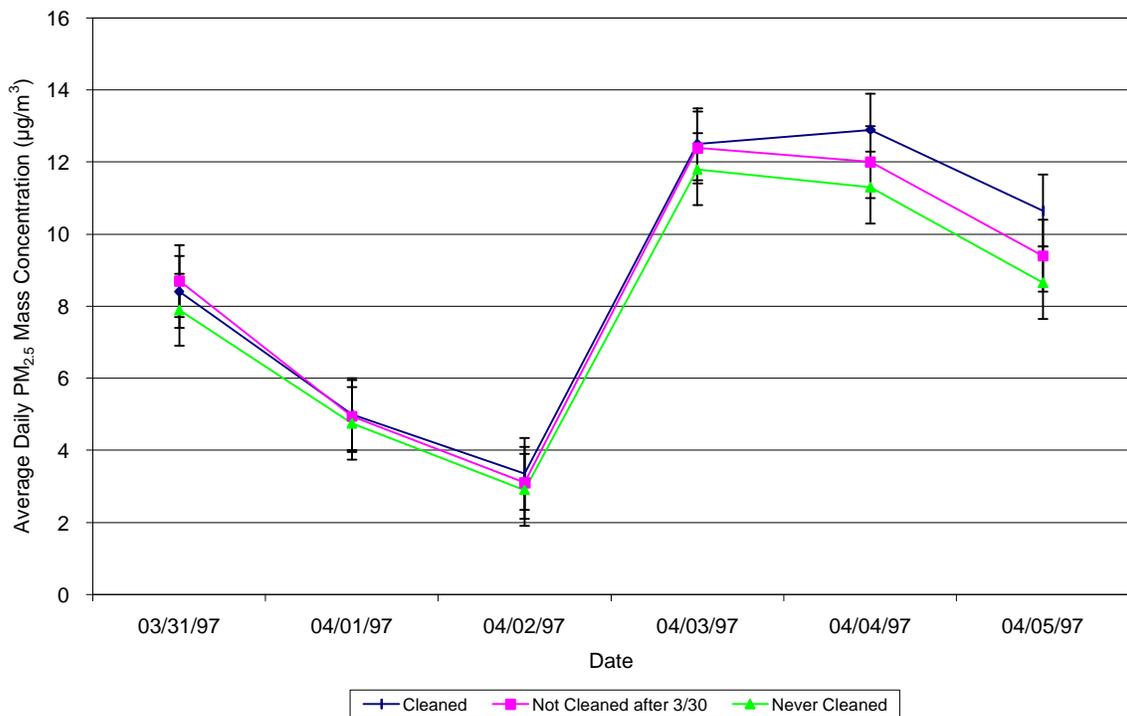


Figure 15b. Temporal variations of PM_{2.5} concentrations at the Azusa site during Test B between 03/31/97 and 04/05/97.