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COMPARISON OF THE ARB CONTINUOUS PM 2.5 MONITORING NETWORK TO THE PM 2.5 FEDERAL REFERENCE METHOD NETWORK

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TABLE OF CONTENTS

COMPARISON OF THE ARB CONTINUOUS PM 2.5 MONITORING NETWORK TO THE PM 2.5 FEDERAL REFERENCE METHOD NETWORK

LIST OF TABLES

COMPARISON OF THE ARB CONTINUOUS PM 2.5 MONITORING NETWORK TO THE PM 2.5 FEDERAL REFERENCE METHOD NETWORK

LIST OF GRAPHS

LIST OF GRAPHS CONTINUED

EXECUTIVE SUMMARY

This report examines the performance of Air Resources Board (ARB) operated PM2.5 Beta Attenuation Monitors (BAM) in terms of comparability to the federal PM2.5 reference method (FRM), inter-unit precision, and data capture rates. The ARB operates seventeen Met One BAM-1020 monitors at thirteen separate locations. Of these thirteen locations, nine have parallel PM2.5 Federal Reference Method (FRM) samplers, and four have collocated BAM-1020 monitors.

Data collected over a one year period (June 2004 through May 2005) from thirteen Met One, BAM-1020 monitors were compared through linear regression analysis to the primary PM2.5 FRM samplers at nine locations. The average coefficient of correlation squared (r^2) for these nine sites over this period was 0.948, with individual sites ranging from 0.867 to 0.989. The average slope was 1.08, with individual sites ranging from 1.00 to 1.23. The average intercept was 2.0 $\mu g/m^3$, with individual sites ranging from 0.0 $\mu g/m^3$ to 3.7 $\mu g/m^3$.

Paired, collocated, BAM-1020 monitors were similarly analyzed by linear regression, resulting in high correlation (0.923 to 0.987 r^2) and near unity slopes (0.96 to 1.02) indicating good precision. BAM-1020 precision is greater for 24-hour averaged data than for hourly data due to the random noise inherent in single, hourly measurements which is smoothed over longer averaging times. Examination of hourly, paired data yielded an annual average Coefficient of Variation of 16% for concentrations greater than 6 ug/m3.

Data capture for the annual period (June 2004 through May 2005) averaged 92% and ranged from 74% to 99% for individual BAM-1020 monitors.

IMPLICATIONS

This report is different from previous method comparisons because it uses only data-for-record from field deployed monitors collected over a one year period. It is in effect, a “real world” method comparison of the PM2.5 FRM and BAM-1020 monitors which are both California Approved Samplers (CAS). Both monitors can be used for State regulatory purposes.

Though generally in very good agreement, the differences are most pronounced when evaluating annual average concentrations. At five of the nine sites, the BAM-1020 annual average (June-May) concentrations were at least 20% higher (difference/mean) than FRM averages for the same time period (and calculated with the same sampling days). This finding suggests that though the BAM-1020 provides significantly more and better time-resolved information than an FRM, caution should be exercised when mixing data from the two methods (the BAM-1020 and the FRM).

BACKGROUND

In 1997, the United States Environmental Protection Agency (U.S. EPA) promulgated new National Ambient Air Quality Standards for particulate matter with aerometric diameters less than 2.5 micrometers (PM2.5). The federal 24 hour standard is 65 $\mu g/m^3$ and the annual standard is 15 $\mu g/m^3$, both not to be exceeded. As a result, the ARB deployed a network of filter based FRM samplers to measure PM2.5 at 81 locations throughout California.

The FRM sampler is designed to collect 24-hour integrated samples on a filter for subsequent gravimetric analysis. However, the ARB recognized the need to collect continuous PM2.5 data to characterize ambient particulate concentrations in real-time. In 1998, the ARB began the task to evaluate all known commercial and pre-commercial continuous PM2.5 monitoring technologies. The decision to purchase and deploy the Met One BAM-1020 monitor was based on the results of a PM2.5 instrument comparison project titled “Instrument Intercomparison Study, Bakersfield, CA 1998-1999” under contract with the University of California, Davis. The Met One BAM-1020 was selected because it displayed the best precision and accuracy results of all candidate technologies.

In 2002, the ARB adopted a state ambient air quality standard for PM2.5 of 12 ug/m^3 calculated as an annual arithmetic mean and not to be exceeded. In addition, a second study performed under the direction of the Monitoring and Laboratory Division, Quality Management Branch, during the months of October 15, 2001 through January 31, 2002, promulgated the CAS for the BAM-1020 and two other continuous PM2.5 monitors. The CAS designation means that data collected with these samplers can legally be used for designating areas as attainment or non-attainment of the state PM2.5 standard.

Presently the BAM-1020 monitors operated by the ARB are used for a variety of purposes including Air Quality Index (AQI) forecasting and Agricultural Burn decisions and provide better understanding of temporal PM fluctuations, transport and events. They are also being used to characterize indoor and outdoor PM2.5 exposure. As mentioned above, BAM-1020 data can also be used for state standard designation.

BAM-1020 THEORY OF OPERATION

The BAM-1020 monitor is a semi-continuous mass monitor that determines particle mass concentration. A pump pulls air through a PM2.5 size selective sharp cut cyclone and deposits the sampled particles on a glass filter tape. A small carbon-14 (^{14}C) element emits a constant source of high-energy electrons (beta rays) that is directed at the sampled particles deposited on the filter tape. A photomultiplier tube (PMT) detects the beta rays which pass through the tape. The loss of beta rays due to absorption by the collected particles is detected by the PMT. The calculated mass is proportional to beta ray absorption. Though other time intervals are available, the BAM-1020 is configured to report hourly averaged mass per volume ($\mu g/m^3$) concentration data. Flow through the BAM is volumetrically controlled with ambient temperature and pressure compensation.

Between January 2004 and May 2004, all ARB BAM-1020 monitors were modified with the BX-827 Smart Heater kit. For this reason, the annual period for this report began June 2004. The Smart Heater kit replaces a 30 watt heat tape with a 200 watt computer-program controlled heating element. When the internal air stream meets or exceeds 45% relative humidity (RH), the Smart Heater heats the sample stream until the RH drops below 45%. This upgrade has reduced filter tape hole punching while increasing valid BAM-1020 data capture.

PM2.5 FRM SAMPLER THEORY OF OPERATION

The PM2.5 FRM sampler is a filter based method. A pump pulls air though either a size selective Wells Impactor Ninety-Six (WINS) or sharp cut cyclone. Particles in the sampled air stream are deposited on a 47 millimeter diameter Teflon filter. Flow through the FRM is volumetrically controlled with ambient temperature and pressure compensation. Each sample is a composite 24-hour sample, collected from midnight to the following midnight. The PM2.5 filters are weighed in a temperature and humidity controlled environment. The mass difference from the pre and post filter weight and the measured sample volume are used to calculate concentration on a mass per volume ($\mu g/m^3$) basis.

DATA COLLECTION

The 2004 BAM-1020 and FRM comparison data set was collected from June 2004 through May 2005, for reasons previously stated.

The BAM-1020 monitors were operated in accordance with the ARB's Air Quality Surveillance Branch (AQSB) standard operation procedure, SOP 400, *Met-One Instruments Beta Attenuation Mass Monitor (BAM-1020).* The BAM-1020 SOP is designed to adhere to PM2.5 FRM quality control criteria where applicable, such as inlet flow rate, inlet maintenance and the monthly check schedule.

The FRM samplers were operated in accordance with the ARB's Air Quality Surveillance Branch (AQSB) standard operation procedures SOP 403*, Rupprecht & Patashnick Model 2000 Single Channel Sampler,* and SOP 404, *Rupprecht & Patashnick, Model 2025 Sequential Air Sampler*.

PM2.5 FRM samplers were configured for everyday sampling at the Fresno, Bakersfield, and Sacramento sites. PM2.5 FRM samplers at the Calexico, Modesto, and Visalia were configured to sample every third day. PM2.5 Samplers at the Chico, Roseville, and Yuba City were configured to sample every sixth day. All collocated FRM samplers were configured for sampling every sixth day.

The Fresno, Bakersfield, Sacramento, Calexico, Modesto and Visalia sites used the Rupprecht & Patashnick, Model 2025 Sequential Air Sampler, while the Chico, Roseville and Yuba City sites used the Rupprecht & Patashnick Model 2000 Single Sampler.

DATA VALIDATION CRITERIA

For the purposes of this comparison study, staff used the following validation criteria to ensure that each BAM-1020 24-hour average data point matched its corresponding PM2.5 FRM sampler value:

1) Valid 24-hour data point: Each BAM-1020 24-hour average was comprised of exactly 24 valid one-hour data points. If any one-hour BAM-1020 data point was missing or invalid during the day, the 24-hour average BAM-1020 point for that day was not used.

2) BAM-1020 flow and leak check: Each BAM-1020 must pass semi monthly flow and leak checks. The BAM-1020 flow check criteria is 16.67 LPM +/- 4% (16.00 to 17.34 LPM), and BAM-1020 leak check criteria must be less than 1.0 LPM. Flow checks were performed with the PM2.5 Sharp Cut Cyclone in place, and leak checks were performed in accordance with the manufacturer's operating manual. If a leak check or flow check failed to meet the required specifications, data was invalidated back to the last valid flow or leak check.

3) Total Volume (Qtot), Error Codes and Negative Values: The Qtot value (hourly volume sampled) must be between 0.830 and 0.837 m^3. The station operator downloads and stores the internal BAM-1020 datalogger files at least once each month to be used for data validation purposes. These files contain mass concentrations, Qtot and error codes for each hour. Error codes were examined and data invalidated as needed. Any negative BAM-1020 data values were corrected to zero.

FRM data were validated per U.S. EPA regulatory criteria described in 40 CFR Part 50 Appendix A and 40 CFR Part 58 Appendix L.

DATA ANALYSIS

Comparability to PM2.5 FRM

Two statistical analyses were used to assess the comparability of the BAM-1020 to the FRM. First was a standard linear regression method which calculated slope, intercept and coefficient of correlation squared (r^2). Regressions were performed to compare paired BAM-1020 and PM2.5 FRM data points collected on the same day, at the same location. At sites with collocated FRM samplers, only data from the primary FRM sampler was used in the analysis. The last row of Table 1 contains the results achieved when all matched data pairs, from all sites, are grouped together and regressed as a single data set.

Data capture rates are also included in Table 1. Data capture is calculated by dividing the number of hourly measurements by the total number of possible hourly measurements within the annual timeframe (June 2004 – May 2005). The overall data capture was 92% for all BAM-1020 monitors and ranged from 74% to 99%. For comparison, the U.S. EPA data quality objectives require a minimum of 75% data capture.

	Annual Regression Results & Data Capture June 2004 – May 2005				
Site	**Slope**	**Intercept**	**r^2**	**% Data Capture**	**n**
Bakersfield Primary BAM	1.00	2.4	0.957	86	236
Bakersfield Collocated BAM	1.02	0.0	0.956	74	200
Chico Primary BAM	1.08	3.2	0.982	95	49
Chico Collocated BAM	1.05	2.3	0.989	98	50
Sacramento Primary BAM	1.06	2.1	0.971	99	301
Sacramento Collocated BAM	1.05	2.7	0.953	99	296
Calexico Primary BAM	1.21	1.6	0.936	98	96
Calexico Collocated BAM	1.23	1.5	0.893	98	97
Fresno BAM	1.04	3.6	0.955	86	232
Modesto BAM	1.08	1.1	0.980	99	113
Roseville BAM	1.12	3.7	0.930	80	44
Yuba City BAM	1.10	0.3	0.867	93	43
Visalia BAM	1.04	1.5	0.953	92	81
Overall BAM/FRM	1.03	2.4	0.949	92	1838

Table 1. BAM-1020/FRM Regression Results and BAM-1020 Data Capture.

Figures 1 through 13 are the site-specific plots of the BAM-1020 to FRM comparisons. Figure 14 is the composite BAM-1020/FRM comparison. The regression line shown on each graph represents the theoretical best fit for all matched data points.

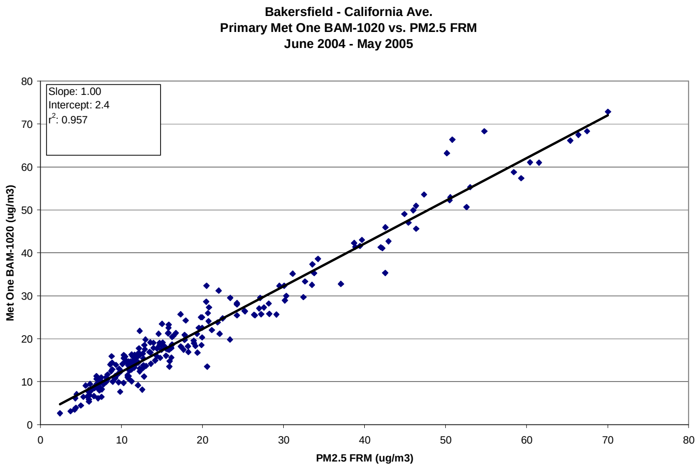

Figure 1. Bakersfield Primary BAM-1020 vs. FRM.

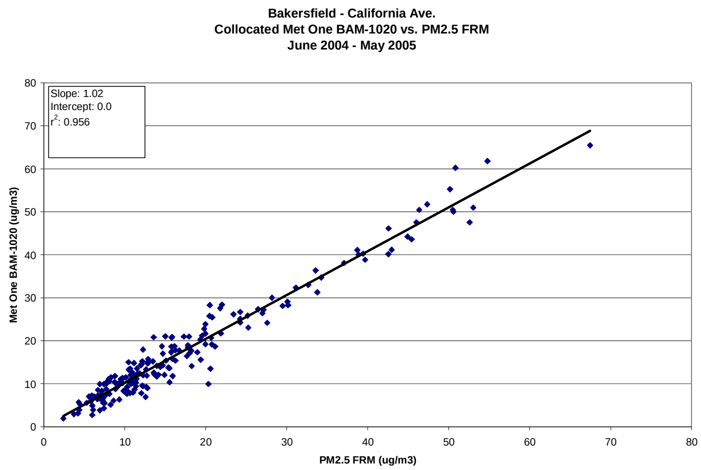

Figure 2. Bakersfield Collocated BAM-1020 vs. FRM.

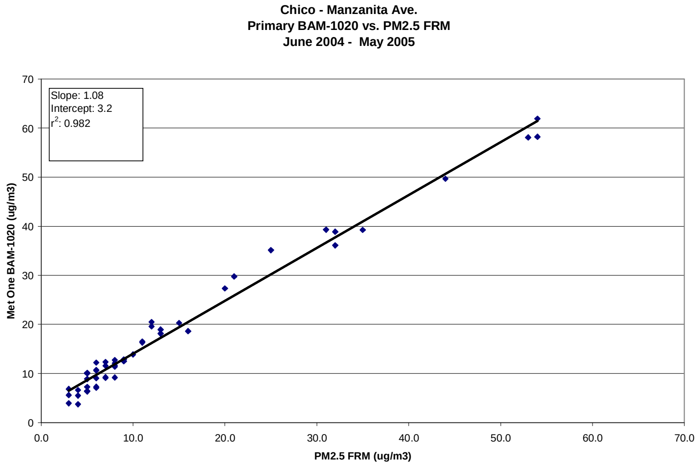

Figure 3. Chico Primary BAM-1020 vs. FRM.

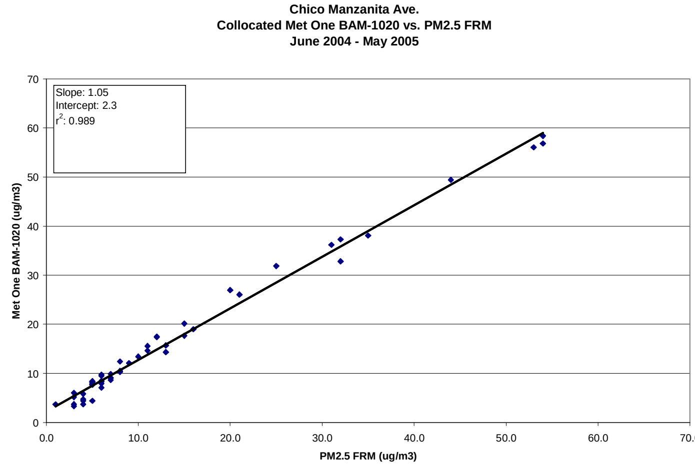

Figure 4. Chico Collocated BAM-1020 vs. FRM.

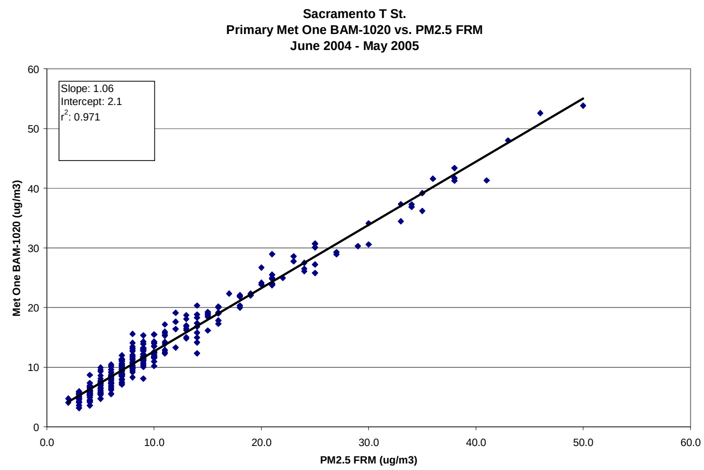

Figure 5. Sacramento Primary BAM-1020 vs. FRM.

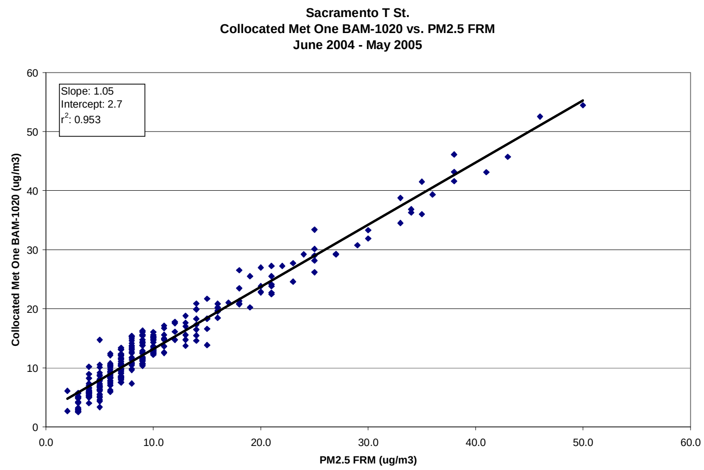

Figure 6. Sacramento Collocated BAM-1020 vs. FRM.

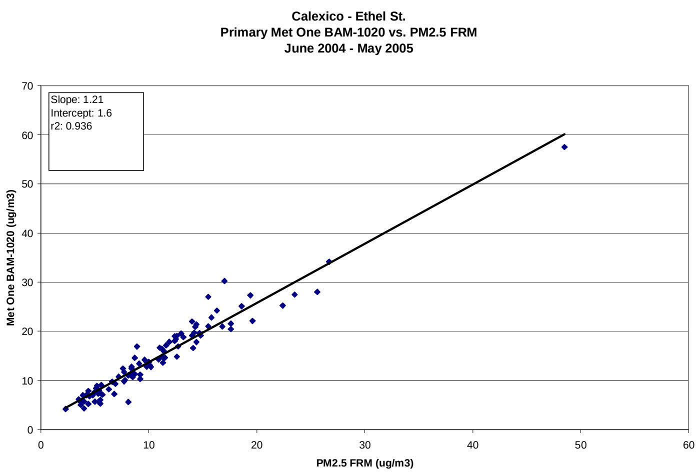

Figure 7. Calexico Primary BAM-1020 vs. FRM.

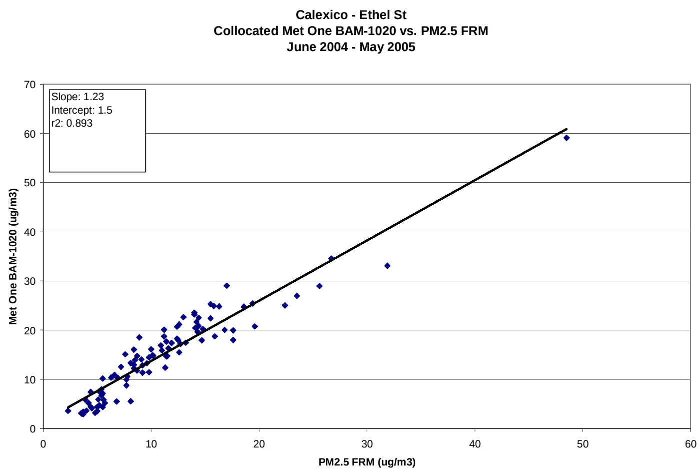

Figure 8. Calexico Collocated BAM-1020 vs. FRM.

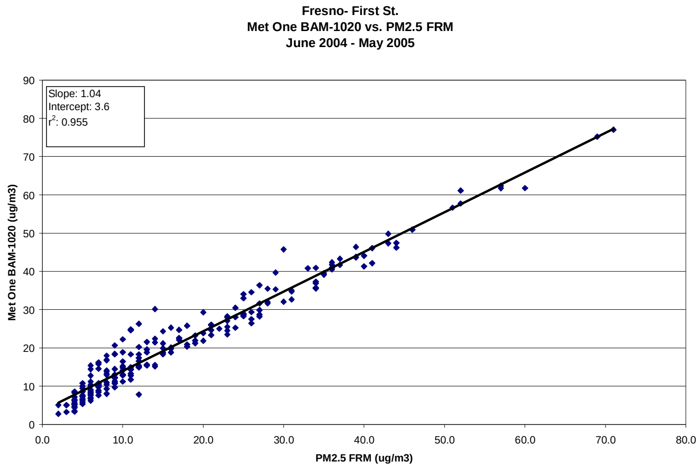

Figure 9. Fresno BAM-1020 vs. FRM.

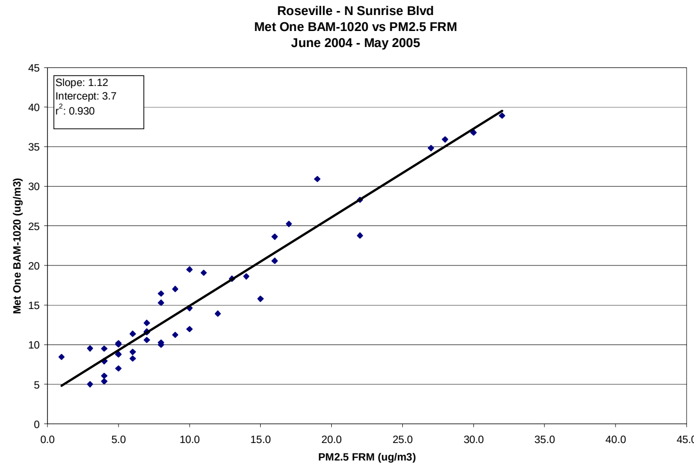

Figure 10. Roseville BAM-1020 vs. FRM.

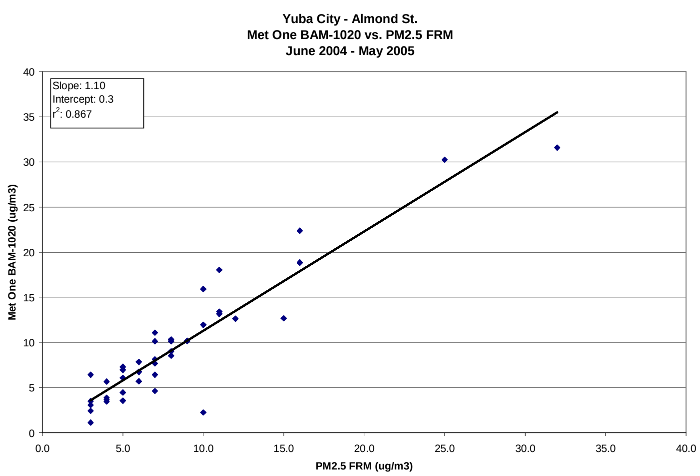

Figure 11. Yuba City BAM-1020 vs. FRM.

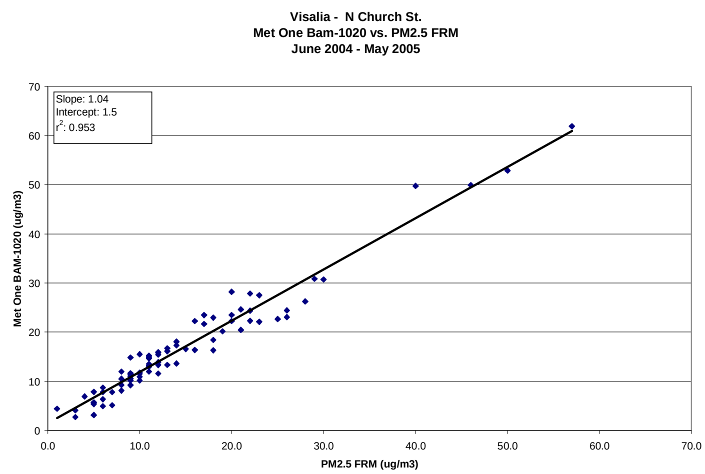

Figure 12. Visalia BAM-1020 vs. FRM.

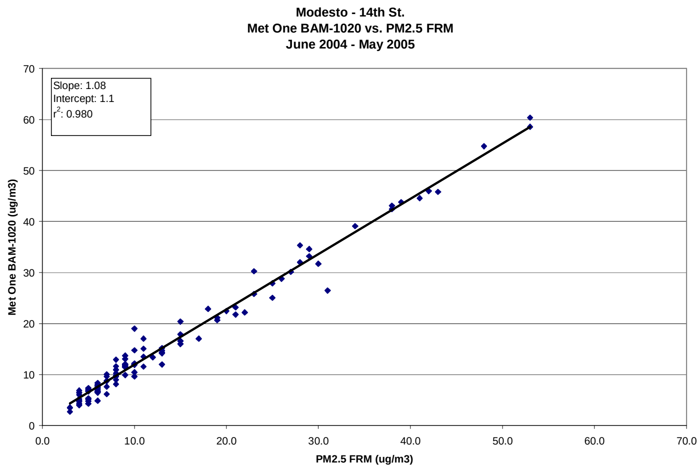

Figure 13. Modesto BAM-1020 vs. FRM.

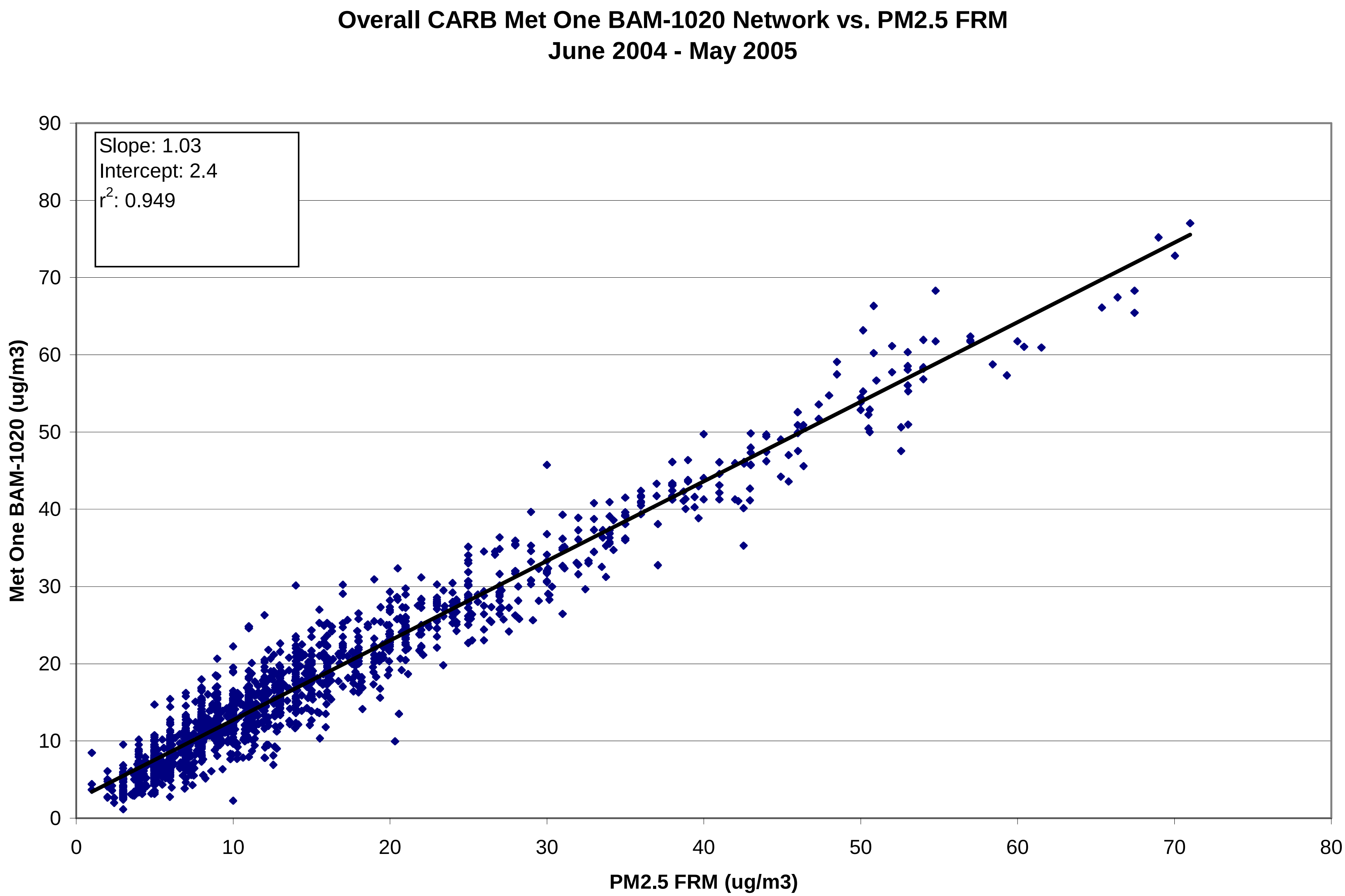

Figure 14. Overall BAM-1020 vs. FRM.

The second method used to assess comparability was to calculate relative percent difference (RPD = difference / mean) between annual averages achieved with each method. Table 2 displays the annual average concentrations derived from both the BAM-1020 and PM2.5 FRM. **These averages are based only on matched data sets.** In other words, only BAM-1020 data coincident to the FRM samples were used for calculating the annual average. The last column in Table 2 contains the RPD between the two average concentrations. As shown, annual average concentrations derived from the BAM-1020 are 10.0 to 37.0 percent greater than the corresponding PM2.5 FRM averages and conform to the linear relationships described in Table 1: ($BAM_{annual\ avg}$ = slope x $FRM_{annual\ avg}$ + intercept). In most cases, the differences seen between BAM and FRM annual averages are primarily attributable to the positive y-intercept of the relationships.

	Annual Average Concentration June 2004 – May 2005		
Site	**BAM $\mu g/m^3$**	**FRM $\mu g/m^3$**	**% RPD**
Bakersfield	21	19	10
Chico	18	14	25
Sacramento	15	12	22
Calexico	15	11	31
Fresno	21	17	21
Modesto	16	14	13
Roseville	16	11	37
Yuba City	10	9	11
Visalia	17	15	13

Table 2. BAM-1020 and FRM Annual Averages (June – May).

Precision Analysis

During this study period, four sites operated collocated, or paired, BAM-1020 monitors. Coincident data from the primary and secondary (collocated) monitors were compared through linear regression, duplicate analyses and time series plots to assess inter-unit precision.

As shown in Table 3, collocated BAM-1020 regression results (primary BAM-1020 vs. collocated BAM-1020) of 24-hour average concentrations achieve near unity slopes and high correlation indicating good precision.

	24-Hour Average Precision June 2004 – May 2005		
Site	**Slope**	**Intercept $\mu g/m^3$**	**r^2**
Bakersfield	0.97	-1.8	0.974
Chico	0.96	0.6	0.987
Sacramento	0.98	0.8	0.957
Calexico	1.02	-0.3	0.923

Table 3. BAM-1020 Precision 24-Hour Average Concentrations.

The primary versus collocated BAM-1020 24-hour averaged data plots are illustrated in Figures 15-18.

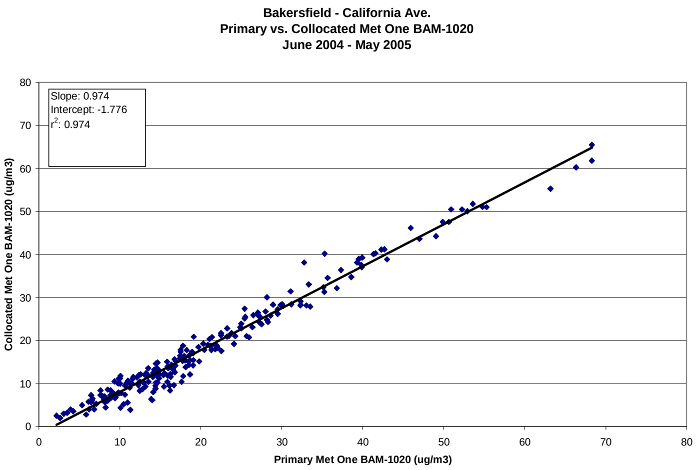

Figure 15. Bakersfield Primary vs. Collocated BAM-1020.

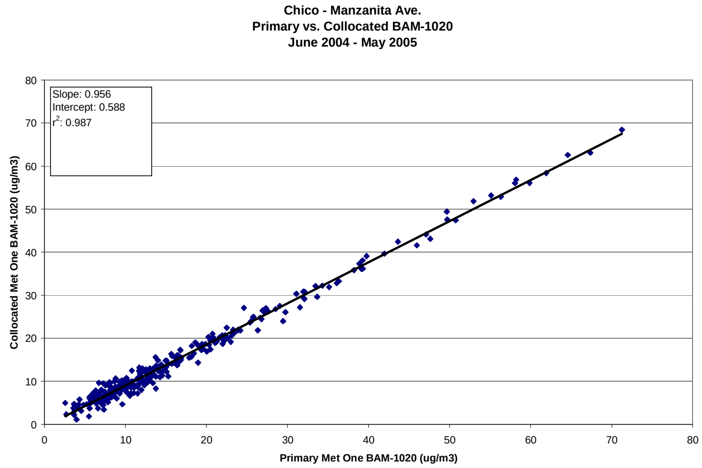

Figure 16. Chico Primary vs. Collocated BAM-1020.

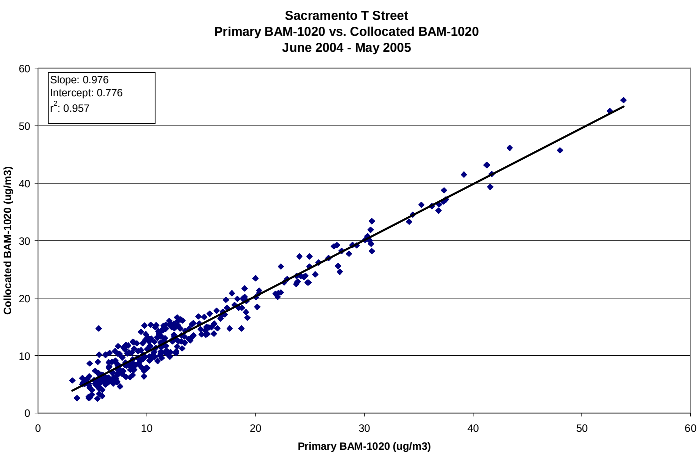

Figure 17. Sacramento Primary vs. Collocated BAM-1020.

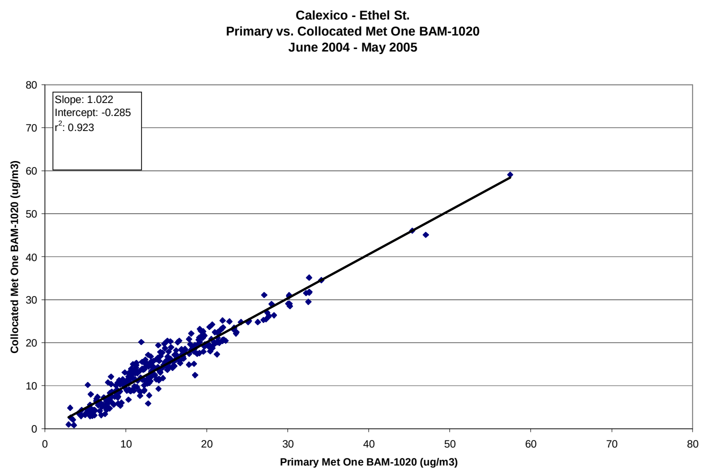

Figure 18. Calexico Primary vs. Collocated BAM-1020.

For comparison, Table 4 displays the collocated FRM regression results for four sites. Note that slopes and correlation coefficients are similar to those derived from BAM to BAM regressions indicating similar precision for 24-hour averaged data.

	June 2004 – May 2005		
Site	**Slope**	**Intercept**	**r^2**
Bakersfield	1.00	0.8	0.977
Fresno	0.98	0.1	0.998
Yuba City	0.98	0.1	0.998
Calexico	0.98	0.0	0.988

Table 4. FRM Precision, 24-hour integrated samples.

The 2004 primary versus collocated FRM data plots are illustrated in Figures 19-22.

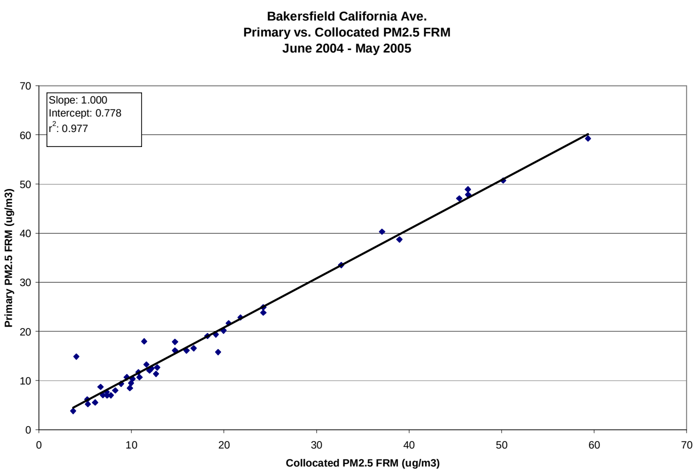

Figure 19. Bakersfield Primary vs. Collocated PM2.5 FRM.

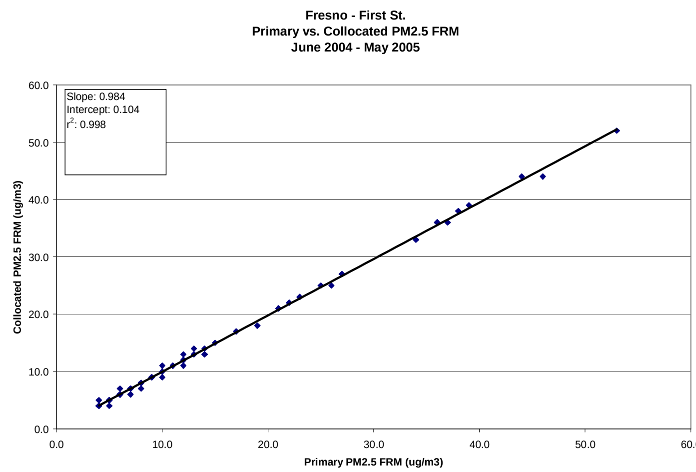

Figure 20. Fresno Primary vs. Collocated PM2.5 FRM.

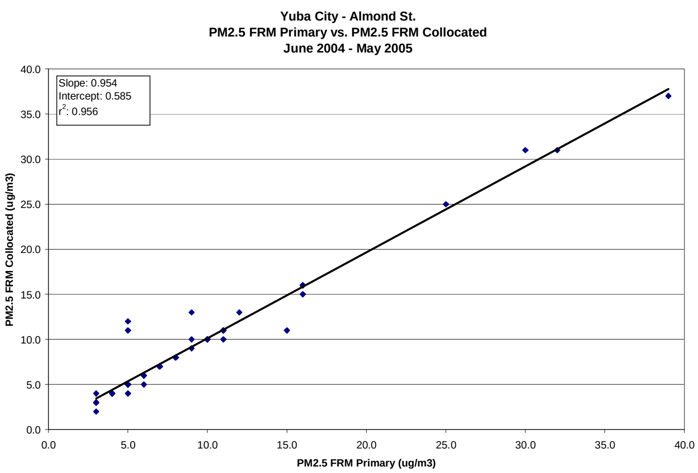

Figure 21. Yuba City Primary vs. Collocated PM2.5 FRM.

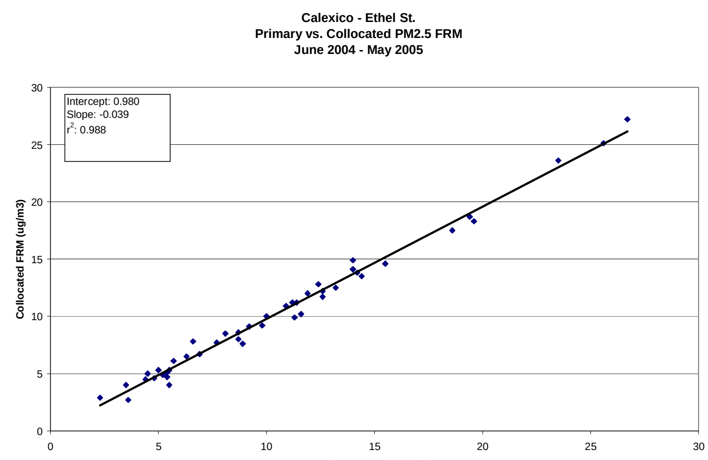

Figure 22. Calexico Primary vs. Collocated PM2.5 FRM

When hourly data values are similarly plotted, we see similar slopes and intercepts but moderately lower correlation. The difference is due to greater inherent noise with each single hourly measurement. This noise smoothes over longer averaging periods.

Figures 23 – 26 displays the hourly BAM-1020 precision values. The x and y axes are scaled to 250 $\mu g/m^3$ for comparison purposes.

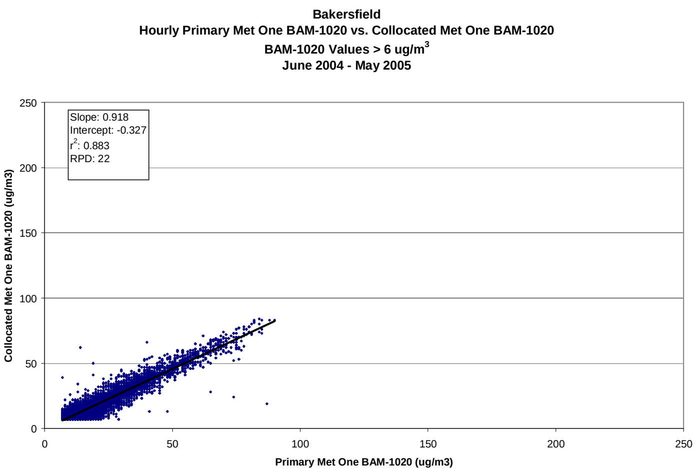

Figure 23. Bakersfield Primary vs. Collocated Hourly BAM-1020.

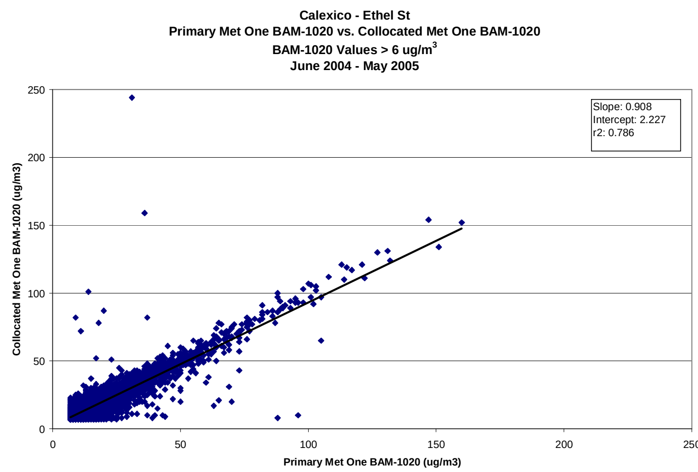

Figure 24. Calexico Primary vs. Collocated Hourly BAM-1020.

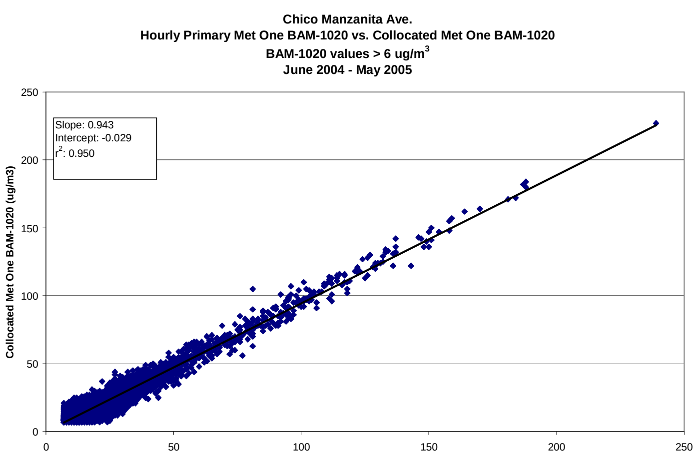

Figure 25. Chico Primary vs. Collocated Hourly BAM-1020.

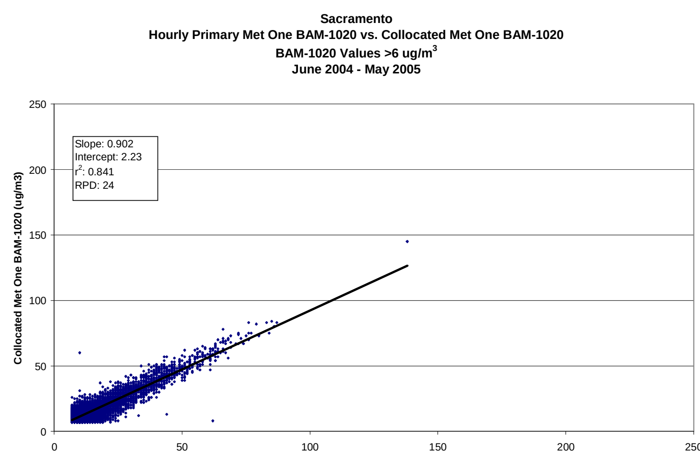

Figure 26. Sacramento Primary vs. Collocated Hourly BAM-1020.

Precision was also evaluated using Relative Percent Difference (RPD) and Coefficient of Variation (CV) as defined in 40CFR58 Appendix A, Section 5.5.2, *Collocated Sampler Precision where Sampler is not an FRM Device*. Per this 40CFR58 criteria, hourly collocated concentrations were evaluated as duplicate samples only when both values were greater than 6 ug/m^3. Table 5 lists the average RPD and CV achieved for the 12 month period. RPD is defined as the difference of duplicate measurements divided by the mean. CV is defined as the RPD divided by the square root of 2 and expresses the variability in the difference as a percentage of the mean. As shown, the average RPD for the four collocated sites was consistently 22 to 24 percent, and CV was 16 to 17 percent.

Site	Relative Percent Difference (RPD)	Coefficient of Variation (CV)
Bakersfield	22%	16%
Calexico	23%	16%
Chico	23%	16%
Sacramento	24%	17%

Table 5. BAM-1020 Average Duplicate RPD and CV (Hourly Data).

Lastly, a strictly qualitative method was used to give a visual sense of precision through time series plots. An eleven day period in October was chosen as a typical fall pattern where each site shows both low and high mass concentrations. The greater the BAM-1020/FRM overlay, the greater the precision.

Figures 27 - 30 are time series plots that display eleven days (10/08/04 to 10/18/04) of hourly collocated BAM-1020 data for each of the four collocated sites.

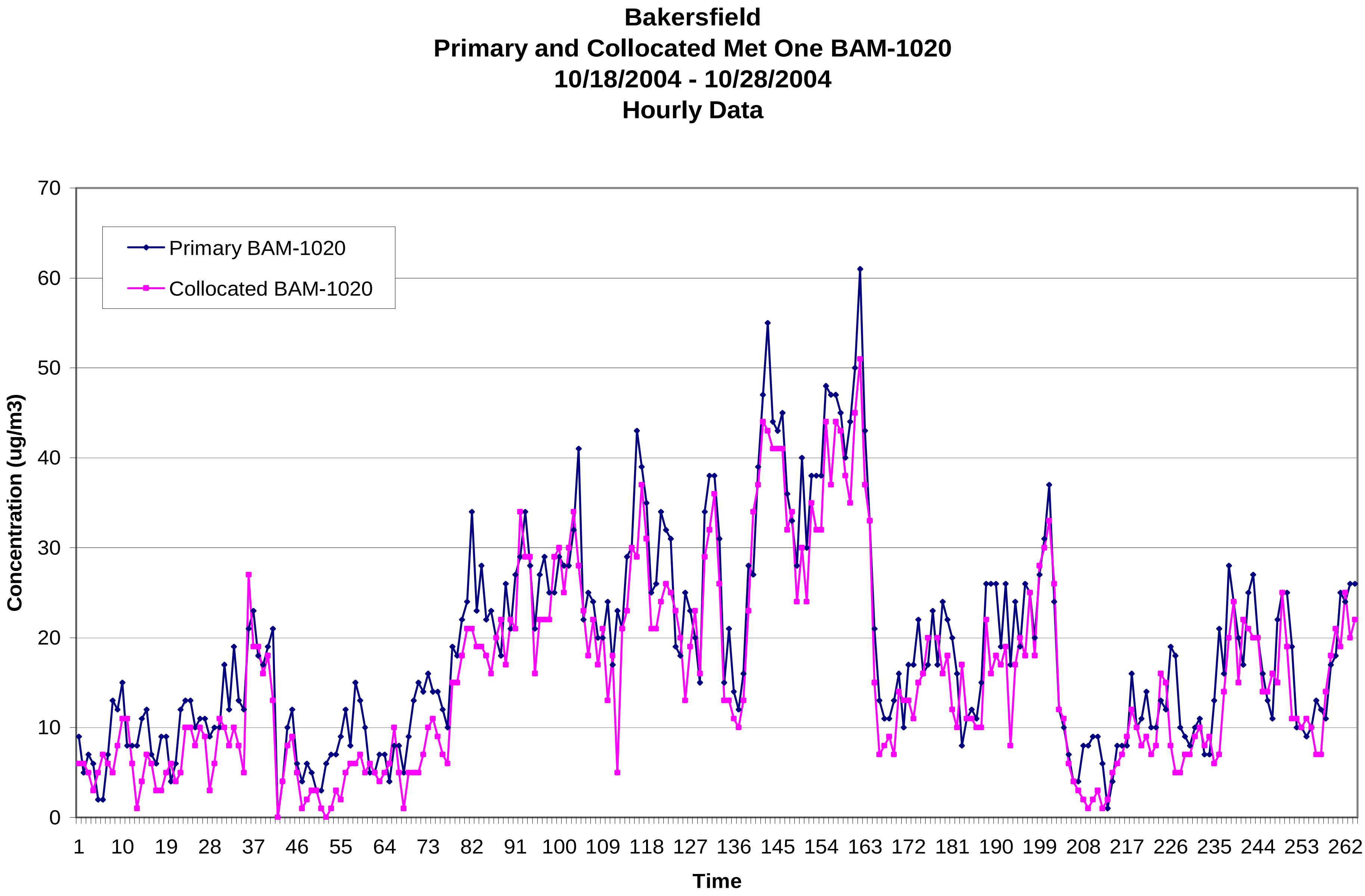

Figure 27. Bakersfield BAM-1020 Hourly Time Series.

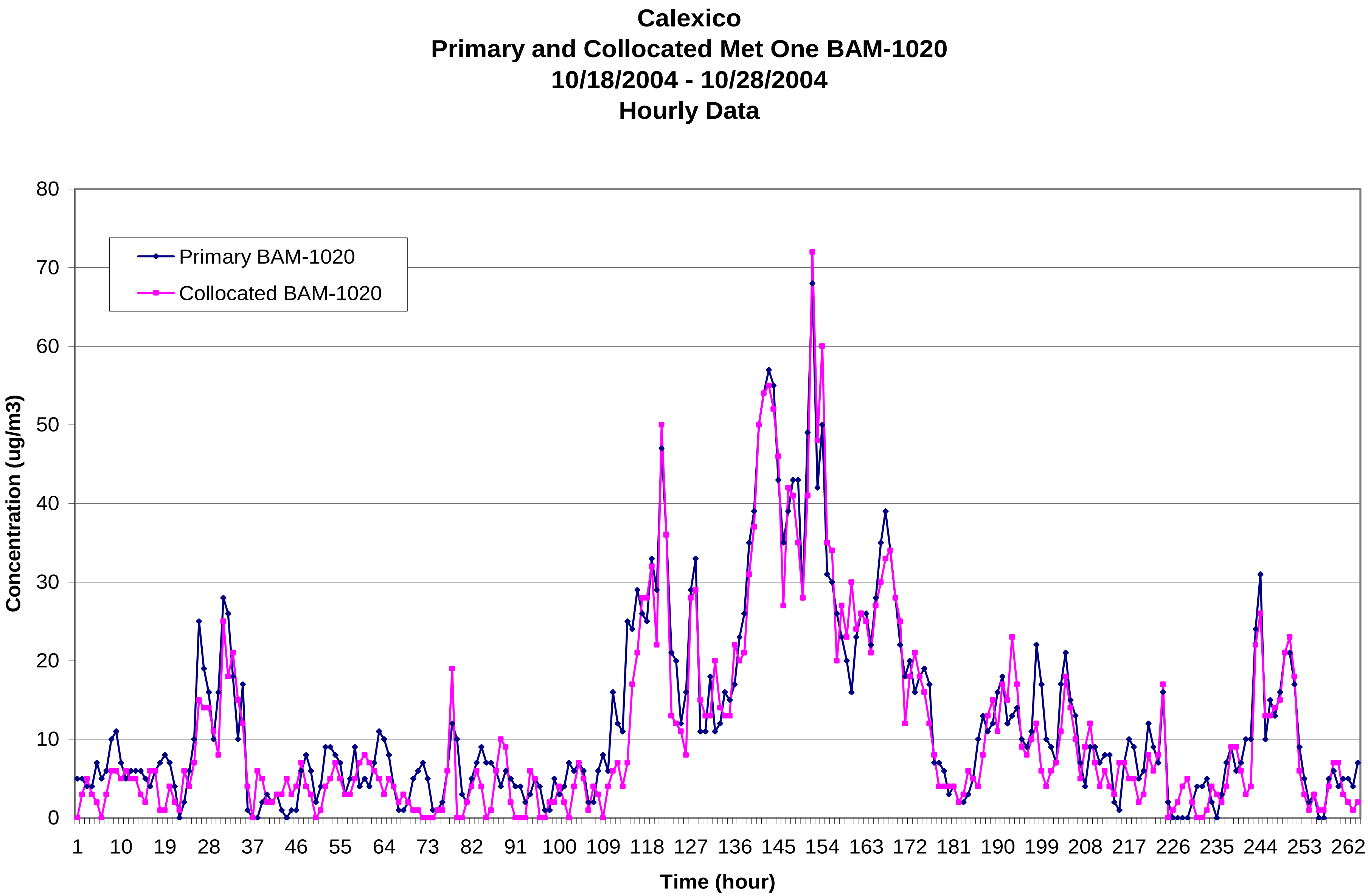

Figure 28. Calexico BAM-1020 Hourly Time Series.

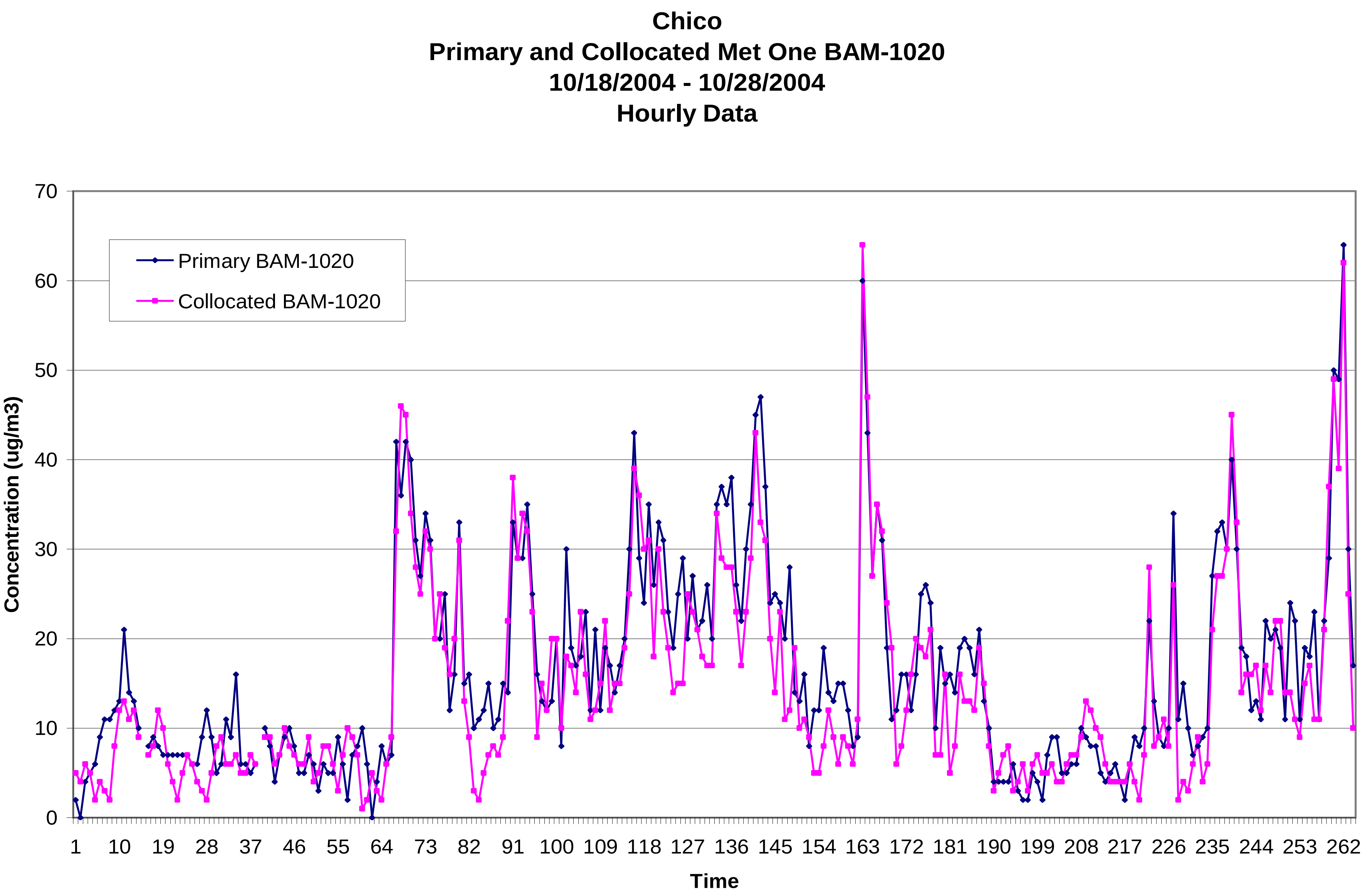

Figure 29. Chico BAM-1020 Hourly Time Series.

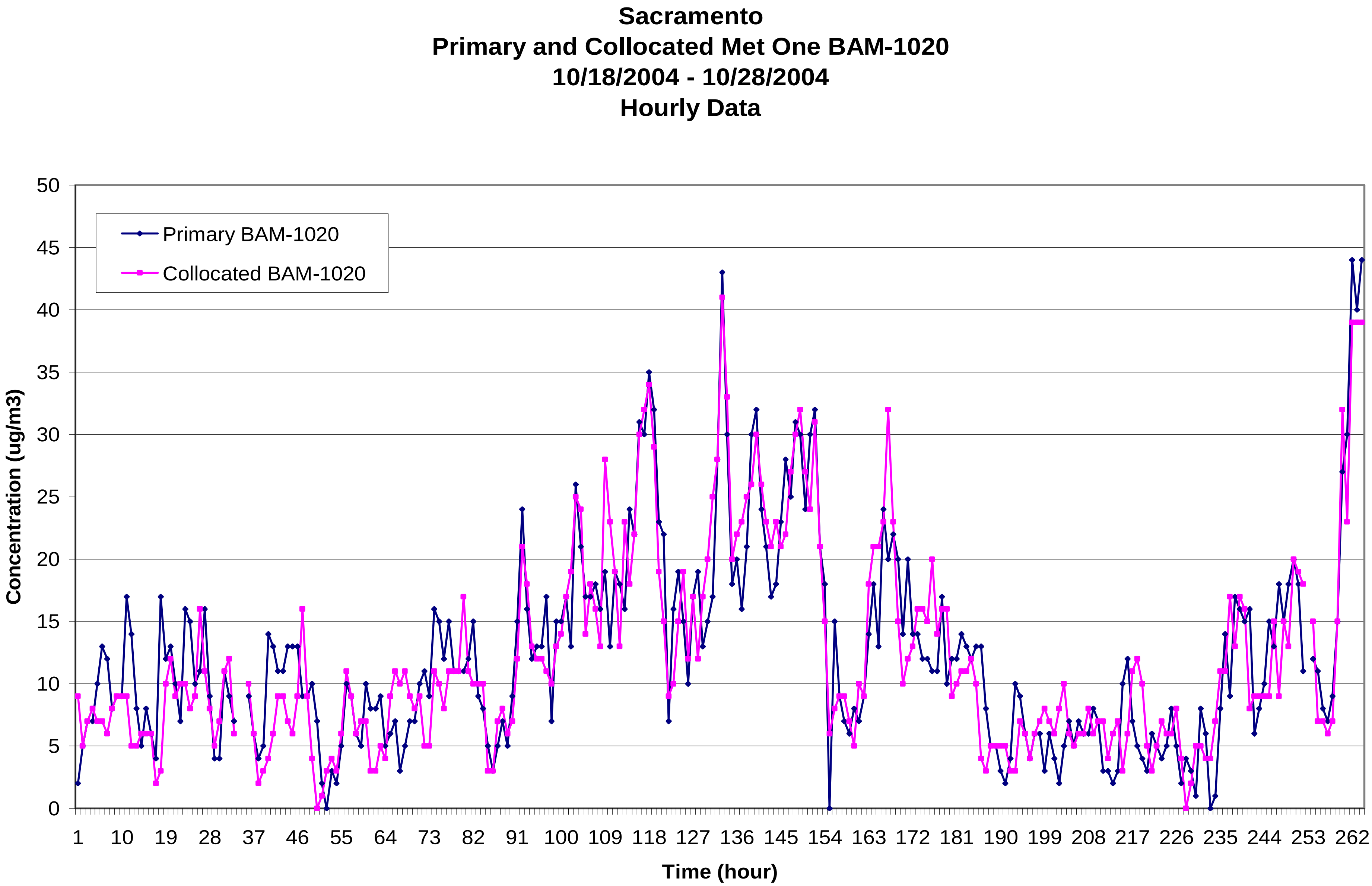

Figure 30. Sacramento BAM-1020 Hourly Time Series.

DISCUSSION

Based on the data examined in this report, the BAM-1020 monitor provides data comparable to the FRM and can augment the PM2.5 FRM sampler for many PM2.5 monitoring needs. For all the sites examined, BAM to FRM mass correlation coefficients (r^2) range from 0.867 to 0.989, with slopes ranging from 1.00 to 1.23 and intercepts ranging from 0.0 to 3.7.

Examination of the y-intercepts and slopes show that the y-intercepts are equal to or greater than zero and slopes equal to or greater than 1, generally reflecting a positive bias compared to the FRM. It is this positive bias which, if minimized, could further improve the comparability of the BAM-1020 to the FRM.

At the Calexico site, the primary and collocated BAM-1020 to FRM slopes are 1.21 and 1.23 respectively. One possible cause for these observed differences at the Calexico site is that the FRM and BAM-1020 inlets are vertically offset from each other by approximately three meters with the BAMs at the higher elevation. Other causes, such as the nature of the particulate matter or meteorology in this area of the state, can not be ruled out.

Because of similarly observed differences between BAM monitors and FRMs seen by other state and local air quality agencies, some users have taken to correcting the BAM data based on empirical comparisons to the FRM. However, as shown in Table 1, the empirical relationships changes from site to site and even unit to unit for collocated monitors. Because of this, there is no universal correction that can be applied to adjust data from all monitors to attain similar comparison to the FRM.

When annual averages are compared, the BAM-1020 averages 3 $\mu g/m^3$ greater than the FRM. While a difference of 3 $\mu g/m^3$ is insignificant when evaluating peak hourly (or daily) PM2.5 levels, it becomes much more significant at levels near the annual state standard of 12 $\mu g/m^3$. While the differences shown in Table 2 may seem severe, it is important to keep in mind that the BAM-1020 and FRM operate on different measurement principles and the observed differences in the data may be due to known negative sampling artifacts of the FRM or, possibly, due to unknown sampling artifacts of the BAM-1020.

The FRM method calls for sampling to begin at midnight, typically the colder part of the day. At colder temperatures semi-volatile species like Ammonium Nitrate condense and are collected on the FRM filter. Later in the sampling cycle when the day is warmer, some, or all, of the semi-volatile species are vaporized and lost from the filter. These species are never measured during post-exposure filter weighing. A similar scenario with the BAM-1020 would mean that semi-volatile species (together with non-volatile species) are collected, measured <u>and recorded</u> within 50 minutes of sampling and never exposed to the higher temperatures later in the day. This is one *plausible* explanation for the observed differences though it is beyond the scope of this paper to definitively *explain* the differences.

RECOMMENDATIONS

Based on the results of this evaluation, staff has recommends the following:

1. **Continue to use the BAM-1020 for time sensitive applications such as air quality forecasting, informing agricultural and prescribed burn decisions, and public health reporting. Continue to use the BAM-1020 to provide highly time-resolved PM2.5 data for modeling, assessing transport, and assessing exposure**. The ARB BAM-1020 monitoring network provides reliable data while demonstrating an overall acceptable performance when compared to the PM2.5 FRM sampler network.

2. **ARB staff should continue to work with the instrument manufacturer to improve the current version of BAM-1020 monitor and supply input for the potential development of a "next generation" continuous PM monitor**.

3. **Data users should become knowledgeable of the operating capabilities and limitations of the methods used to collect PM data.** It is the intent of this paper to provide information on the performance of the BAM-1020 in terms of data capture, precision and comparison to the FRM. The PM2.5 FRM and BAM-1020 monitors are both currently CAS methods and therefore can both be used for State regulatory purposes.

4. **Data users should recognize that different measurement methods produce different results and that continuous PM2.5 data should not be unintentionally mixed with FRM PM2.5 data when preparing analyses.** A review of Table 2 (page 11) indicates that annual average concentrations as measured by the BAM-1020 are, on average, 3 μg/m3, (or 20% RPD) greater than the annual average measured by the FRM. (Annual averages were calculated using only coincident data. Meaning the exact same days and hours were used to calculate an annual average for each method.)