A NEW HIGH-SENSITIVITY BETA GAUGE FOR $PM_{2.5}$ MONITORING

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Abstract

In this paper we will introduce a new, high-sensitivity beta gauge for $PM_{2.5}$ monitoring based on the Met One Instruments BAM-1022, a US-EPA $PM_{2.5}$ designated device widely used and often singled out for its ability to accurately measure $PM_{2.5}$ concentrations. The new device, known as the BAM-1022-PLUS, employs modifications designed to improve sensitivity and reliability. We will present further details on these modifications as well as details of laboratory tests, andfield trials. These demonstrate the improved sensitivity as well as continued, strict adherence to US-EPA requirements for class 3 equivalency standards for multiplicative and additive bias against the filter-based reference standard.

Keywords: US-EPA Designated Automatic $PM_{2.5}$ Monitors, Beta Attenuation, Beta Gauge.

1. Introduction

Particulate Matter (PM) whose aerodynamic diameter is 2.5 microns or less, known colloquially as $PM_{2.5}$, is a pollutant mainly generated from combustion processes, both anthropogenic and natural. It is a *criteria pollutant*, which in regulatory parlance are substances which are deemed to harm health, damage the environment and cause property damage.[1] In addition to $PM_{2.5}$, criteria pollutants include ozone, sulphur dioxide, lead, and PM_{10}.

With respect to $PM_{2.5}$, both daily and yearly national air quality standards exist in Australia and worldwide. The National Environment Protection Measure (NEPM) goal is proposed to be reduced to 20 μg/m^3 daily, and 7 μg/m^3 annually from 2025, a reduction of 20% for the daily limit. In the United States the annual standard is 9 μg/m^3 as of April 2024. The annual standard for $PM_{2.5}$ was previously 12 μg/m^3, and 15 μg/m^3 before that; a 40% reduction since inception during the 1990s.[2]

The substantial reduction in annual $PM_{2.5}$ standards in recent years occurred while ambient PM levels have dropped. This has driven the operators of air quality monitoring networks to seek continuous $PM_{2.5}$ monitors with higher sensitivity i.e. decreasing Lower Limits of Detection (LLD).

In this paper we present laboratory and field test results for a new US-EPA designated beta attenuation mass monitor “BAM”, known as the Met One Instruments BAM-1022-PLUS. This instrument has a substantially improved LLD compared to current BAM market entries, but maintains other regulatory and customer-driven performance metrics such as accuracy, precision and reliability.

US-EPA and other regulatory authorities require, in addition to sensitivity, that continuous $PM_{2.5}$ monitors meet minimum accuracy and inter-unit precision standards.[3] Accuracy is calculated by measuring the difference between the *daily* average of continuous $PM_{2.5}$ monitors and collocated reference standards at multiple monitoring sites. Precision is determined by measuring the daily root-mean squared relative standard deviation of triplicate, collocated monitors. As the reference standard for $PM_{2.5}$ is a daily measurement, all official performance determinations for continuous monitors such as the BAM-1022-PLUS, must also be on the daily timescale.

2. Beta Attenuation Monitors

Beta attenuation mass monitors are commonly used in air quality monitoring networks to measure the concentration of airborne particulate matter such as PM_{10} and $PM_{2.5}$. Beta rays are generated inside the BAM continuously, typically from a ^{14}C source. Those beta rays are detected with a photomultiplier tube equipped with a scintillator. Filter media is placed between the ^{14}C source and the detector upon which sampled $PM_{2.5}$ is collected continuously. The mass change between the source and detector caused by the accumulation of PM onto the filter media is registered as a reduction in the measured

[1] https://www.epa.gov/criteria-air-pollutants/naaqs-table

[2] https://www.epa.gov/pm-pollution/national-ambient-air-quality-standards-naaqs-pm

[3] Table C-4 to Subpart C of Part 53, Title 40

beta ray signal from the photomultiplier tube thereby permitting the computation of the differential PM concentration.[4]

The BAM-1022 is regarded as generating highly accurate mass measurements with very good precision compared to instrumentation employing other principles of operation, such as the Teledyne T640, an optical PM monitor.[5] One reason for this is that BAMs are generally indifferent to the optical and chemical properties of the aerosol while making their mass determinations, instead being primarily sensitive to atomic mass only.[4] BAMs typically lack the sensitivity of optical PM methods, such as the Teledyne T640 or the Thermo-Fisher TEOM series. This methodological difference in sensitivities as well as the reductions in worldwide $PM_{2.5}$ concentration levels and standards provide ample impetus to develop a beta gauge with improved LLD.

2.1. Comparison of BAM-1022 to BAM-1022-PLUS

The BAM-1022-PLUS is a derivative of the BAM-1022, a well-established continuous $PM_{2.5}$ monitor used in some of the largest air quality monitoring networks in the United States. For the BAM-1022-PLUS the 2.22 MBq ^{14}C source used in the BAM-1022 was substituted with a stronger 3.70 MBq ^{14}C source. The analyser was also modified to accommodate ultra-thin PTFE filter media.[6] Additional, less significant changes were made as well to improve reliability in the field.

BAM measurement sensitivity is largely determined from the beta ray integrated signal (counts) reaching the detector as well as their reproducibility under constant environmental conditions. Higher integrated counts can be achieved through longer count times (i.e., 2-minute integrated counts vs 1-minute integrated counts), but this comes at the expense of reduced time resolution. By increasing the source radiation rate, the integrated counts are increased without increasing the count time.

Higher integrated counts can also be achieved by having less non-PM mass between the ^{14}C source and the detector. We have effectively reduced this by substituting ultra-thin PTFE filter media[6] for the ubiquitous glass-fiber filter media used by most beta attenuation mass monitors. Ultimately, sensitivity is a function of the fraction of total mass between source and detector "background mass" compared to accumulated PM mass.

We have observed that by substituting PTFE filter media for the glass-fiber filter media previously used, we can effectively remove approximately 80% of the background mass. This makes it much easier to resolve the sub-2.5 $\mu g/m^3$ aerosol mass that commonly comprises $PM_{2.5}$ ambient particulate matter.

3. Laboratory and Field Testing Results

In this section we will cover the internal laboratory tests and external field tests that we conducted to qualify the performance of the BAM-1022-PLUS.

3.1. Laboratory Testing

Laboratory testing included span calibration against a known PM standard, background determination, and lower limit of detection (LLD) determination.

Span calibration is performed by exposing the BAM-1022-PLUS unit under test (UUT) to a $PM_{2.5}$ aerosol whose *hourly* concentration varies from approximately 20 $\mu g/m^3$ to concentrations exceeding 250 $\mu g/m^3$ for 48-hours. This is done using a smoke chamber into which the smoke from the burning specialised incense sticks is homogeneously distributed. This creates an environment where uniformly distributed PM concentrations may be reliably sampled simultaneously by the UUT and reference.

A second beta gauge, previously calibrated against a series of NIST-traceable (National Institute of Standards and Technology) reference standard measurements, serves as the reference. After a (typical) minimum of 48 hourly concentration values are logged on both the UUT and reference standard, a linear regression is used to determine the multiplicative adjustment ("K-factor") needed to bring the UUT into agreement with the reference.

In addition to the span/smoke-chamber calibration, a background test is run to determine the offset, if any,

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[4] A β-gauge method applied to aerosol samples, Joseph M. Jaklevic, Ray C. Gatti, Fred S. Goulding, and Billy W. Loo Environmental Science & Technology **1981** *15* (6), 680-686 DOI: 10.1021/es00088a006

[5] Long, R. W., Urbanski, S. P., Lincoln, E., Colón, M., Kaushik, S., Krug, J. D., … Landis, M. S. (2023). Summary of PM2.5 measurement artifacts associated with the Teledyne T640 PM Mass Monitor under controlled chamber experimental conditions using polydisperse ammonium sulfate aerosols and biomass smoke. Journal of the Air & Waste Management Association, 73(4), 295–312. https://doi.org/10.1080/10962247.2023.2171156

[6] Shinohara, M., Mizuno, Y., Murao, N., and Ohta, S. (2007). Application of PTFE/Non-woven Fabric Membrane filter on the Measurement Method of PM 2.5 by the Beta-ray Absorption Technique. *Journal of Japan Society for Atmospheric Environment/Taiki Kankyo Gakkaishi*, *42*(5), 292-300

as well as the instrument noise "σ", which is used to determine the lower limit of detection "LLD" of the device. Significant offsets can be problematic to accuracy as they contribute to additive bias. Offset is frequently not fixed and can be due to uncontrolled environmental factors as well as calibration issues. Excessive reference field-blanks[7] and trip-blanks can lead to uncorrectable bias.

Background determination is performed by repeatedly sampling an aerosol of constant, known $PM_{2.5}$ concentrations over typically 48-hours. The sample (not population) standard deviation of these repeated measurements is the instrument noise σ. The only way to generate a repeatable, known $PM_{2.5}$ aerosol is to create air devoid of any aerosol at a concentration of 0 μg/m³. The offset (background) is an average of those repeated zero-air measurements. The BAM-1022-PLUS and BAM-1022 "BKGD" value would be minus one multiplied by the measured offset. The measured background on the BAM-1022 and the BAM-1022-PLUS was always within the range ± 1 μg/m³ meaning that excessive offsets should never be an issue with either of these devices.

Table 1 shows the results from the instrument sensitivity determination discussed above for 4 prototype BAM-1022-PLUS monitors equipped with 3.70 MBq sources and modified to accommodate the ultra-thin PTFE filter media. To perform the comparison, we selected at random 9 production BAM-1022 monitors. In a constant temperature setting (within a ± 1°C range) all analysers sampled "zero-air" for a minimum of 24 hours. The results are summarised below in Table 1.

Table 1: Instrument Noise and Background

Analyser	**Background (μg/m³)**	**σ (μg/m³)**	**Sample Size**
BAM-1022	+0.23	1.70	9
BAM-1022-PLUS	-0.55	0.75	4

Lower limits of detection (LLD) for a particular measurement are typically (but not always) expressed as twice the instrument noise (2σ). We would typically report slightly larger values for the LLD for instrument specification purposes to provide end users with a reasonable margin of error should they decide to perform an acceptance test or periodic QA/QC tests on the device. For example, the published LLD for the BAM-1022 is 4.8 μg/m³ instead of the 3.4 μg/m³ that we derived from the small (n = 9) data set presented above. And, in the case of the BAM-1022-PLUS it is likely that the LLD will be *conservatively* specified at 2.4 μg/m³ based on these results.

3.2. Field Testing Results

The BAM-1022-PLUS was subjected to a modified US-EPA class 3 (the class BAM measurement technology falls into) $PM_{2.5}$ equivalent method determination (modified such that testing was performed at a reduced number of sites compared to a complete class 3 test). Testing occurred at two test sites: Mira Loma CA and Elizabeth NJ. At each site triplicate sequential $PM_{2.5}$ reference samplers were collocated with triplicate BAM-1022-PLUS candidate monitors. Strict collocation requires that all candidate monitors (BAM-1022-PLUS) be between 1 and 4-meters of each reference sampler. Inlet tubes must be from the same height and free from any local obstruction such as nearby building walls, tree branches, HVAC intakes, or other overhead obstructions.

Mira Loma CA is located on the West Coast of the US, approximately 75 km ESE of Los Angeles California. Our test site is adjacent to one operated by the South Coast Air Quality Monitoring District (SCAQMD), the regional authority for the Los Angeles Basin.

The monitoring site is in a region of past intensive dairy farming and other agricultural activities for many decades. Now, however, the region is mainly suburban. As a result of the dairy/agricultural legacy, the area is notorious for producing high levels of nitrates as part of the aerosol, sometimes creating a challenge for automatic PM monitors. During the summer months photochemical processes can contribute to the diversity of the measured PM, as can PM arising from forest and brush fires, which often occur in the nearby mountains and foothills during the dry summer (June-October) season. Testing took place at this site during August and September of 2023. At this testing site we ran triplicate, collocated US-EPA-designated $PM_{2.5}$ sequential samplers (Met One Instruments E-SEQ-FRM) configured to sample from midnight-to-midnight against triplicate BAM-1022-PLUS candidate monitors configured to sample $PM_{2.5}$ and logging data at the top of each hour. The results are summarised in Figure 1, Figure 2, Figure 3, and Figure 4.

[7] https://www.epa.gov/system/files/documents/2023-08/PM25_PEP_Field_SOP_2023_05%20finalsigned_508_0.pdf

Regression statistics		Slope[1]	Intercept[2]	Correlation (r)
Statistics for this test site:		1.080	-0.230	0.98984
Limits for	Upper:	1.100	0.789	
PM2.5 Class III	Lower:	0.900	-2.000	0.93000
Test Results (Pass/Fail):		PASS	PASS	PASS

Figure 1: Regression Statistics for Mira Loma California

Precision	Data set mean, µg/m³ FRM	Data set mean, µg/m³ Candidate	Data set precision, µg/m³ FRM	Data set precision, µg/m³ Candidate	Relative precision (CV) FRM	Relative precision (CV) Candidate
Mean:	11.0	11.6	0.1	0.3	1.2%	2.4%
Maximum:	17.3	18.5	0.4	0.9	4.1%	6.1%
Minimum:	4.0	4.0	0.0	0.0	0.1%	0.2%
Candidate / FRM Ratio:		105.9%		217.2%		195.9%
RMS Relative Precision for this site:					1.5%	2.8%
Test requirements - PM2.5 Class III:					10.0%	15.0%
Precision Test Results for site:					OK	PASS

Figure 2: Precision Statistics for Mira Loma California

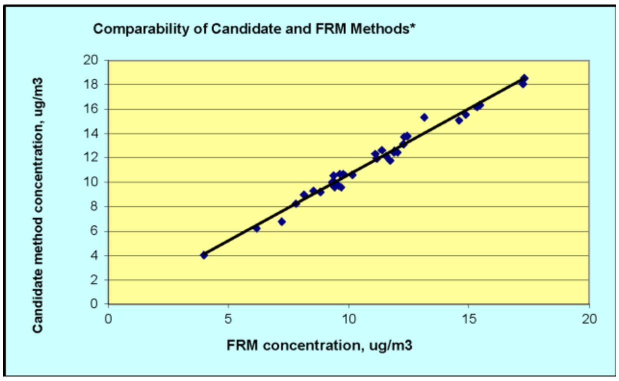

Figure 3: Mean (Triplicate) Candidate vs. Mean (Triplicate) Reference Scatter Plot

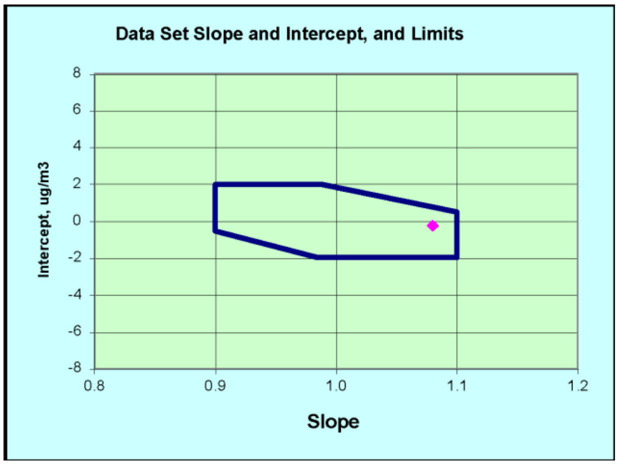

Figure 4: Additive (Intercept) vs Multiplicative Biases Within US-EPA Limits

The Elizabeth NJ test site is located adjacent to a turnpike toll plaza approximately 20 km ESE of midtown Manhattan (New York City). Our test site is adjacent to a test site run by the State of New Jersey Department of Environmental Protection "NJDEP". The NJDEP site runs a daily $PM_{2.5}$ FRM sampler and makes the daily results available on its website. The region is heavily industrialised with petroleum and petrochemical facilities. Field testing occurred during the winter months from December 2023 until January 2024. As with the Mira Loma test site triplicate, collocated US-EPA-designated $PM_{2.5}$ sequential samplers (Met One Instruments E-SEQ-FRM) configured to sample from midnight-to-midnight against triplicated BAM-1022-PLUS candidate monitors configured to sample $PM_{2.5}$ and log data at the top of each hour. Those results are summarised in Figure 5, Figure 6, Figure 7, and Figure 8.

Regression statistics		Slope[1]	Intercept[2]	Correlation (r)
Statistics for this test site:		0.929	0.665	0.98807
Limits for	Upper:	1.100	2.000	
PM2.5 Class III	Lower:	0.900	-1.038	0.95000
Test Results (Pass/Fail):		PASS	PASS	PASS

Figure 5: Regression Statistics for Elizabeth New Jersey

Precision	Data set mean, µg/m³ FRM	Data set mean, µg/m³ Candidate	Data set precision, µg/m³ FRM	Data set precision, µg/m³ Candidate	Relative precision (CV) FRM	Relative precision (CV) Candidate
Mean:	10.1	10.1	0.2	0.5	1.8%	5.5%
Maximum:	23.1	21.6	0.6	0.9	8.4%	13.8%
Minimum:	3.6	3.5	0.0	0.1	0.2%	2.0%
Candidate / FRM Ratio:		99.5%		321.3%		298.4%
RMS Relative Precision for this site:					2.3%	6.2%
Test requirements - PM2.5 Class III:					10.0%	15.0%
Precision Test Results for site:					OK	PASS

Figure 6: Precision Statistics for Elizabeth New Jersey

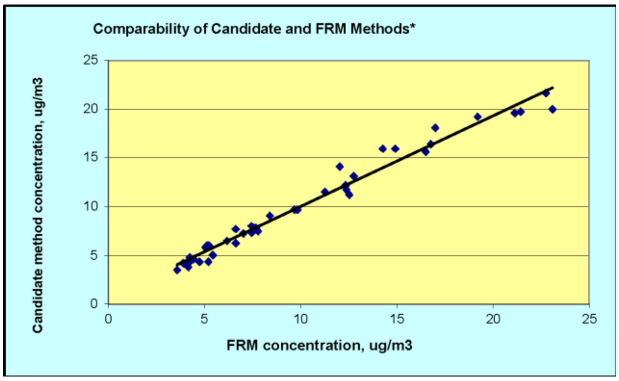

Figure 7: Mean (Triplicate) Candidate vs. Mean (Triplicate) Reference Scatter Plot

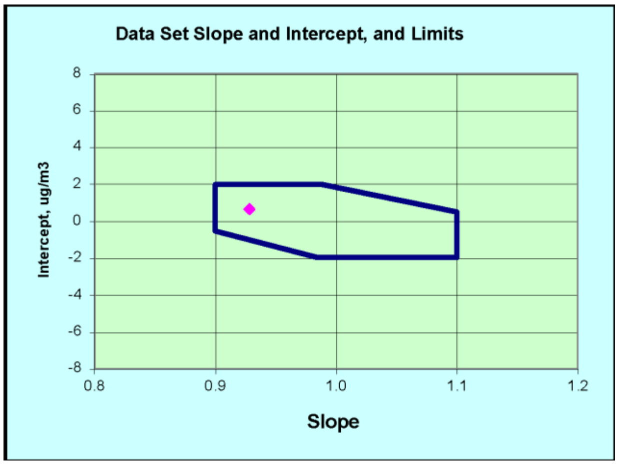

Figure 8: Additive (Intercept) vs Multiplicative Biases Within US-EPA Limits

The BAM-1022-PLUS candidate met the EPA requirements for additive and multiplicative bias at both test sites. Correlation between the candidate and reference was very strong (r > 0.988 in both instances) though PM concentrations averaged only around 10-11 μg/m^3 at both test sites. RMS precision requirements were also easily met at both test sites. In fact, although computations aren't shown here, had the hourly (instead of daily) values been used to compute the RMS relative precision for the BAM-1022-PLUS, the results would have still met EPA requirements for the daily RMS relative precision.

4. Discussion and Conclusion

Both monitoring sites have in the past produced reliably high $PM_{2.5}$ concentrations. Historically, in August and September the combination of thin marine layer confining pollutants near the ground, local forest and brush fires as well as photochemical processes in Southern California have produced reliably high PM concentrations.

Yet $PM_{2.5}$ concentrations have dropped dramatically in the Los Angeles basin over the past 25 years. In Mira Loma, the site in the Los Angeles basin with the highest $PM_{2.5}$ concentrations, 24-hour design values[8] have dropped since 2000 by approximately 50% to around 35 μg/m^3 [9]. At the same time annual design values have dropped since 2000 also by around 50% to around 15 μg/m^3 and touching 12 μg/m^3 in 2022 – a remarkable feat: the most heavily polluted site in what has traditionally been one of the most heavily polluted regions in the United States meeting (at the time) the US annual standard for $PM_{2.5}$. Of course, since then the standard has been reduced from 12 μg/m^3 to 9 μg/m^3.

During our test campaign at Mira Loma the average daily concentration as measured by the BAM-1022-PLUS monitors was 11.6 μg/m^3, compared to the average daily concentration of 11.0 μg/m^3 as measured by the reference samplers. Daily averages at these concentration levels necessarily point to hourly averages frequently of between 5 μg/m^3 and 10 μg/m^3. Given that the published hourly LLD for the BAM-1022 is 4.8 μg/m^3, this means that concentrations will be logged where signal-to-noise ratios "SNR" of only 1-2 can be expected. Such values are problematic for statisticians trying to perform analyses and draw conclusions from hourly information. It strongly indicates the need for continuous $PM_{2.5}$ monitors that can provide meaningful data at the sub-5 μg/m^3 level.

Based on the information collected on the BAM-1022-PLUS we can see the LLDs drop to values closer to 2 μg/m^3 meaning that even for concentrations of around 5 μg/m^3 we are able to see reasonable SNR values (> 2) at the hourly level.

The BAM-1022-PLUS meets this requirement while avoiding any of the aerosol-specific accuracy issues attendant with optical mass monitors.[5]

5. References

[8] 40 CFR Appendix-N-to-Part-50 4.04.2(a)

[9] https://www.aqmd.gov/docs/default-source/clean-air-plans/air-quality-management-plans/2022-air-quality-management-plan/aqmp-ag-presentations-5-25-23.pdf?sfvrsn=14