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Enhancing the Temporal Resolution and Sensitivity of Beta Attenuation Monitors via Concentrated Particle Deposition and Multi-Sensor Ensemble Averaging

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Abstract. Beta attenuation monitors (BAMs) are widely used for continuous ambient particulate matter (PM) monitoring, yet their effectiveness for real-time, ultra-low-concentration detection is often limited by long response times and high detection limits. The variability of the beta source intensity is the main factor for the limitation of beta gauges. To enhance BAM performance under low-concentration conditions, two complementary approaches were investigated. A commercial BAM was modified to operate with different particle deposition areas (2.0, 1.0, 0.6, and 0.4 cm^2), thereby increasing the areal particle loading on the filter tape, while a multi-sensor array was simulated through ensemble averaging of repeated measurements to reduce beta intensity variability. Different temporal smoothing windows were also evaluated to examine the trade-off between measurement stability and response time. All experiments were conducted in a controlled aerosol chamber to ensure stable testing conditions. The research evaluated the effects of particle deposition area, array size, and smoothing window on response time, signal stability, and limits of detection (LOD). Experimental results indicate that reducing the particle deposition area to 0.4 cm^2 effectively amplifies the mass change signal per unit area, thereby increasing measurement sensitivity for active monitoring. However, this reduction also shields the detector, lowering initial beta intensity and increasing relative statistical noise. Increasing the number of measurement units to six significantly improved measurement stability, reducing the coefficient of variation (CV) of the intensity from 1.02% to 0.39%. A cost-benefit analysis further indicated that the marginal improvements became negligible beyond six units, suggesting an optimal array size of 4-6 measurement units. The study demonstrates that the most effective performance is achieved through a synergistic integration of these approaches. The enhanced signal provided by the reduced particle deposition area, together with the improved counting stability of the six-unit ensemble, enabled the use of a shorter 30-minute smoothing window without sacrificing measurement precision. This integrated configuration reduced the instrumental response time from 60 to 22 minutes while maintaining a standard deviation of 2.67 $\mu g\ m^{-3}$ and a detection limit of 7.75 $\mu g\ m^{-3}$. These findings provide a technical foundation for the development of high-resolution, real-time array-type beta gauges capable of meeting increasingly stringent global air quality monitoring requirements.

1 Introduction

Beta attenuation monitors (BAMs) are widely utilized for ambient $PM_{2.5}$ monitoring because they provide continuous, reliable, and real-time data. However, following the 2021 update to the WHO Air Quality Guidelines (AQG), which reduced the recommended $PM_{2.5}$ level to 5 $\mu g\ m^{-3}$ (WHO, 2021), ambient concentrations are now approaching the operational detection limits of many commercial BAMs. In addition, high-sensitivity monitoring with rapid response capabilities is therefore essential for effective policy development, emergency monitoring, and exposure assessment (Schweizer et al., 2016).

To enhance performance, it is necessary to reduce measurement variance while increasing the radiation attenuation per unit of time and reducing noise. Coupled with optimized smoothing algorithms, these improvements can lower detection limits. Furthermore, shortening the sampling interval minimizes errors associated with sample degradation—such as the loss of semi-volatile components or chemical reactions with the sampled gas—thereby enabling higher accuracy real-time monitoring.

The intensity of beta particles from radioactive decay is inherently unstable over short intervals. These statistical fluctuations result in significant variation in the count rate, complicating the interpretation of signal attenuation. Consequently, conventional monitors require long integration times to accumulate representative values, typically resulting in detection limits of 4 – 5 $\mu g\ m^{-3}$ for hourly averages (Shukla and Aggarwal, 2022). If higher temporal resolution is required, the detection limit increases, making many current devices inadequate for monitoring in clean or transitioning environments.

The beta attenuation method is based on the principle that beta particles lose kinetic energy through absorption and scattering as they collide with matter. The relationship between the transmitted radiation and the mass of the collected particles follows Lambert-Beer's law:

$$I = I_0 \times \mathrm{e}^{-\mu x} \tag{1}$$

Where I_0 is the incident intensity, I is the intensity after penetration, x is the particle mass per unit area (mg cm^{-2}), and μ is the mass attenuation coefficient ($cm^2\ mg^{-1}$). Generally, μ varies with the energy level of the beta source(Slezak and Buckius, 1983) and the atomic number-to-mass (Z/A) ratio of the material (Jaklevic et al., 1981).

The standard deviation (σ_r) of the beta intensity depends on the count rate through the filter, N, and the integration interval, t (Wedding and Weigand, 1993):

$$\sigma_r = \sqrt{N_0 t} \cong \sqrt{Nt} \tag{2}$$

While a higher count rate or longer acquisition time increases the absolute standard deviation, it also increases the total number of particles detected, thereby reducing the coefficient of variation. Consequently, the lower detection limit (C_{ml}) is defined as (Wedding and Weigand, 1993):

$$C_{ml} = -\ln\,(1 - \frac{1}{\sqrt{N_0 t}})K \tag{3}$$

The factor K is a dimensional factor. This relationship implies that high count rate allows for reduced acquisition times without compromising data quality. Conversely, insufficient counting requires extended sampling periods, which increases the risk of

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mass loss due to volatile particles—a known issue even with Federal Equivalent Method (FEM) equipment (Salvador and Chou, 2014).

A key approach to optimizing BAM performance is increasing the signal-to-noise ratio (SNR). A quantitative benchmark of SNR≧10 is typically required for reliable instrumentation (Vial and Jardy, 1999). Improving the SNR involves increasing the difference between I and I_0 or reducing the standard deviation of the counts. However, increasing beta source intensity to maintain precision at shorter intervals is restricted by self-absorption (Li et al., 2012).

To overcome these limitations, this study investigates the effects of minimizing the particle deposition area and employing a multi-sensor array architecture to optimize measurement performance. First, the particle deposition area is reduced to increase the sensitivity of the mass-to-attenuation ratio. Second, this study utilizes multiple repeated measurements to simulate the effect of simultaneous sampling by an array of multiple BAM units. By aggregating these independent data sets, the stochastic variation is significantly minimized through ensemble averaging. Ultimately, this integrated strategy aims to substantially lower the detection limit and shorten the response time for high-resolution, real-time particulate matter monitoring.

2. Materials and methods

To improve BAM performance, this study investigated the effects of reducing the particle deposition area and increasing the sample size (via repeated measurements). These variables were assessed in conjunction with different smoothing algorithms. The performance improvements were evaluated using response time, signal stability, and detection limits as key performance metrics. The specific research parameters and equipment operating conditions are summarized in Table 1, with detailed methodologies for each component provided below.

Table 1. Experimental parameters of the study.

Item	Parameter	Symbol	Range
Aerosol generation	Challenge Aerosol	-	NaCl
	Count Medium Diameter (μm)	*CMD*	1
	Mass Concentration (μg m^{-3})	C_M	35
Filter	Type	-	Glass Fiber
	Particle Deposition Area (cm^2)	A	0.4, 0.6, 1, and 2.0
	Particle Mass per Unit Area (mg cm^{-2})	x	< 5

Beta source	Element	*S*	C-14
	Energy (MeV)	*E*	0.156
Flow	Flow Rate (L min^{-1})	*Q*	16.67

85 To minimize measurement errors resulting from external environmental interference and to isolate the factors affecting BAM performance, the controlled aerosol concentration chamber was utilized. This setup provided a stable environment with adjustable particle sizes and concentrations. A schematic of the experimental system is shown in Fig. 1. NaCl particles with a count median diameter, CMD, of 1 µm and a mass concentration of 35 µg m^{-3} were generated using an ultrasonic atomizer (Model 8700-120MS, Sono-Tek Inc., Milton, NY, USA) coupled with a syringe pump (KDS 200/200P LEGACY, KD Scientific Inc., Holliston, MA, USA). 90

To eliminate experimental artifacts caused by particle electrostatic charges, the generated aerosol was immediately passed through an ^{241}Am neutralizer to reach a Boltzmann charge distribution. Throughout the testing process, the DustTrak II aerosol monitor (TSI 8530, TSI Inc., Shoreview, MN, USA) was employed to continuously verify the stability of the steady-state concentration.

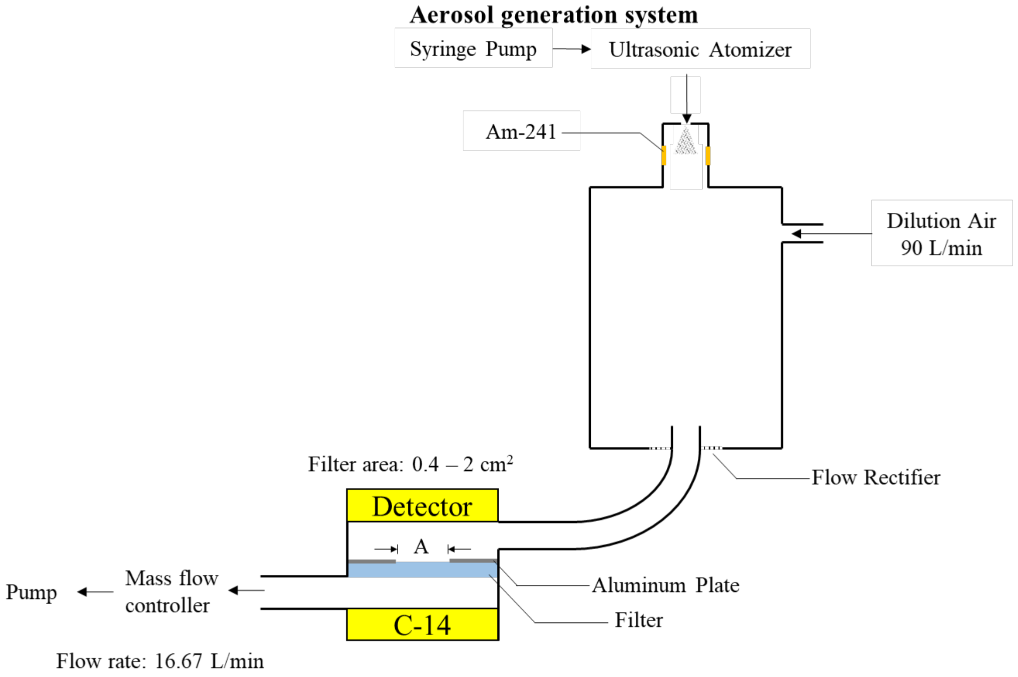

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Figure 1. The schematic diagram of the testing system.

This study utilized a commercial BAM (Model 5014i, Thermo Fisher Scientific, Franklin, MA, USA) to evaluate the influence of sample size and particle deposition area on measurement performance. The device operated with a ^{14}C source at a constant flow rate of 16.67 L min^{-1}. While the standard particle deposition area for this instrument is 2 cm^2, the experimental setup was modified to test areas of 0.4, 0.6, and 1.0 cm^2. Beta intensity counts were captured per second using an external data acquisition system (USB DAQ 4704, Advantech Co., Ltd., New Taipei City, Taiwan). The reduction in beta intensity was applied to Lambert-Beer's law to determine the accumulated particle mass over time. Finally, the slope of the mass accumulation was utilized to derive the real-time, second-by-second mass concentration according to the following formula:

$$M = xA = A \times \ln\left(\frac{I_0}{I}\right) \div \mu \tag{4}$$

$$C_M = \frac{xA}{Q\Delta t} = \frac{A}{Q\Delta t\mu} \ln\left(\frac{I_0}{I}\right) \tag{5}$$

Where C_M is the mass concentration (mg cm^{-3}), A is the sampling cross-sectional area of the filter paper (cm^2), M is the total mass of the particles loaded on the filter, x is the particle mass per unit area (mg cm^{-2}), Q is the sampling flow rate (cm^3 s^{-1}), and Δt is the time interval.

To modify the effective particle deposition area, a 0.5 mm thick aluminium plate with apertures of varying diameters was placed directly onto the filter media. By adjusting the hole sizes, the specific area through which both the sample airflow and beta particles pass was controlled. Theoretically, reducing the particle deposition area from the baseline of 2 cm^2 to 1.0, 0.6, 0.4 cm^2, while maintaining a constant concentration and sampling duration, increases the mass per unit area of the collected particles by factors of 1.0, 2.0, 3.3, and 5.0, respectively. Consequently, it can be inferred that the difference between the incident intensity I_0 and the transmitted intensity I will be significantly amplified as the area decreases, thereby enhancing the measurement sensitivity.

To avoid potential systematic errors that may arise from operating multiple physical BAMs simultaneously, this study simulated a multi-unit array using a single BAM. Under identical experimental conditions, continuous sampling was performed, and the resulting dataset was partitioned to increase the effective sample size per unit of time.

Specifically, a long-duration sampling period at a constant concentration was segmented into several intervals of equal length. For instance, eight hours of continuous data were divided into eight separate one-hour segments. These segments were then averaged to simulate the simultaneous output of eight BAM units sampling at the same location. By averaging the beta intensities across these independent intervals, we aimed to reduce the overall signal variation. This approach allows for a rigorous evaluation of the improvements in measurement stability and detection limits that would be achievable through a multi-unit configuration.

Due to the significant variability in measured beta intensity over short intervals, a smoothing method is required to obtain stable values. This study utilizes the Moving Average (MA) method, applying a temporal smoothing window of 5 to 75 minutes to the beta intensity data points. The response time is defined as the duration required for the measured mass concentration to reach 90% of its final steady-state value.

However, the average mass concentration and its associated standard deviation are not, by themselves, sufficient to fully characterize the measurement accuracy of the instrument. The relationship between the signal magnitude and the background noise must also be taken into account. To ensure representative real-time readings, an SNR of 10 was adopted as a quantitative benchmark to determine the optimal smoothing intervals required for different particle deposition areas.

3. Results and Discussions

As shown in Fig. 2, for a fixed particle loading of 105 μg, reducing the particle deposition area from 2.0 cm^2 to 1.0, 0.6, and 0.4 cm^2 resulted in an increase in the accumulated particle thickness by factors of 1.0, 2.0, 3.3, and 5.0, respectively. This demonstrates that the mass per unit area x increases as the particle deposition area is reduced. As illustrated in Fig. 2, the log-transformed attenuation of beta intensity ($\ln I_0 - \ln I$) followed the same upward trend. These results indicate that the increased particle accumulation per unit area effectively enhances the beta attenuation. For a BAM system, this enhancement is equivalent to obtaining a higher response signal, thereby significantly improving the measurement sensitivity.

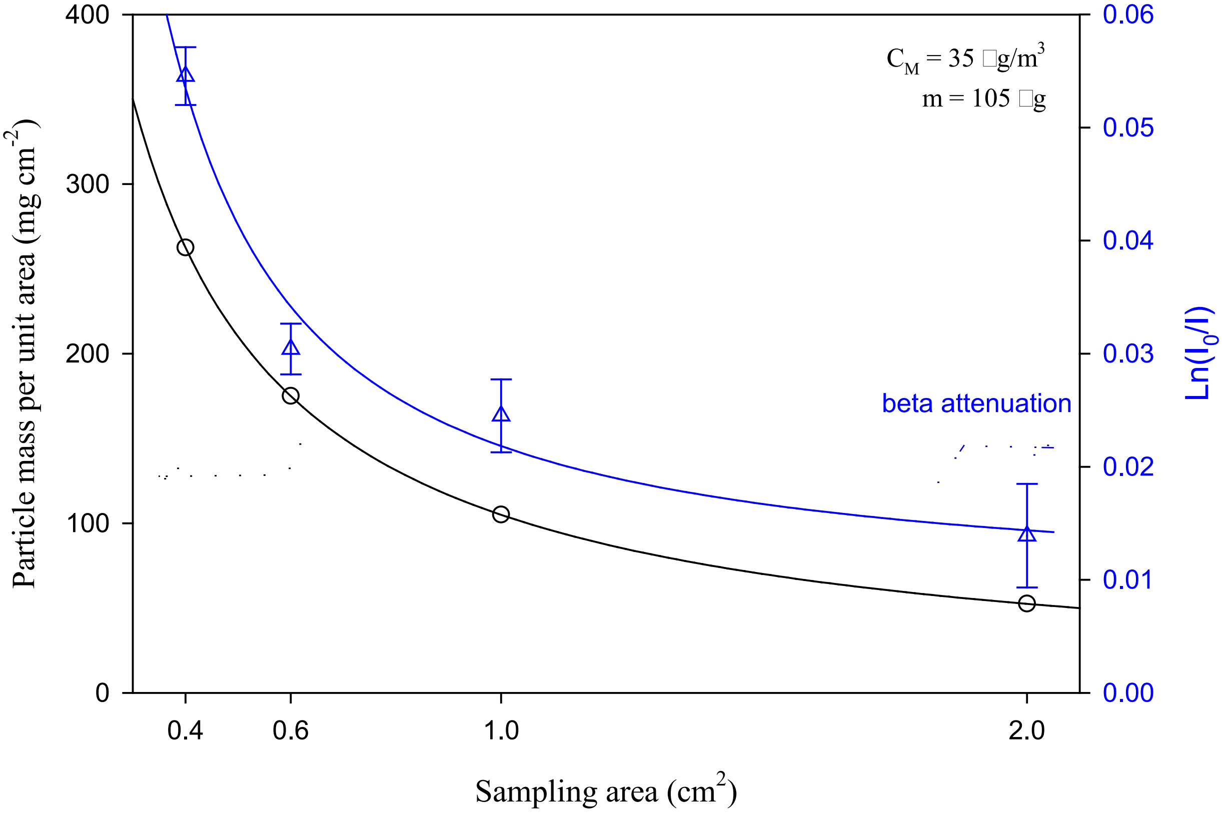
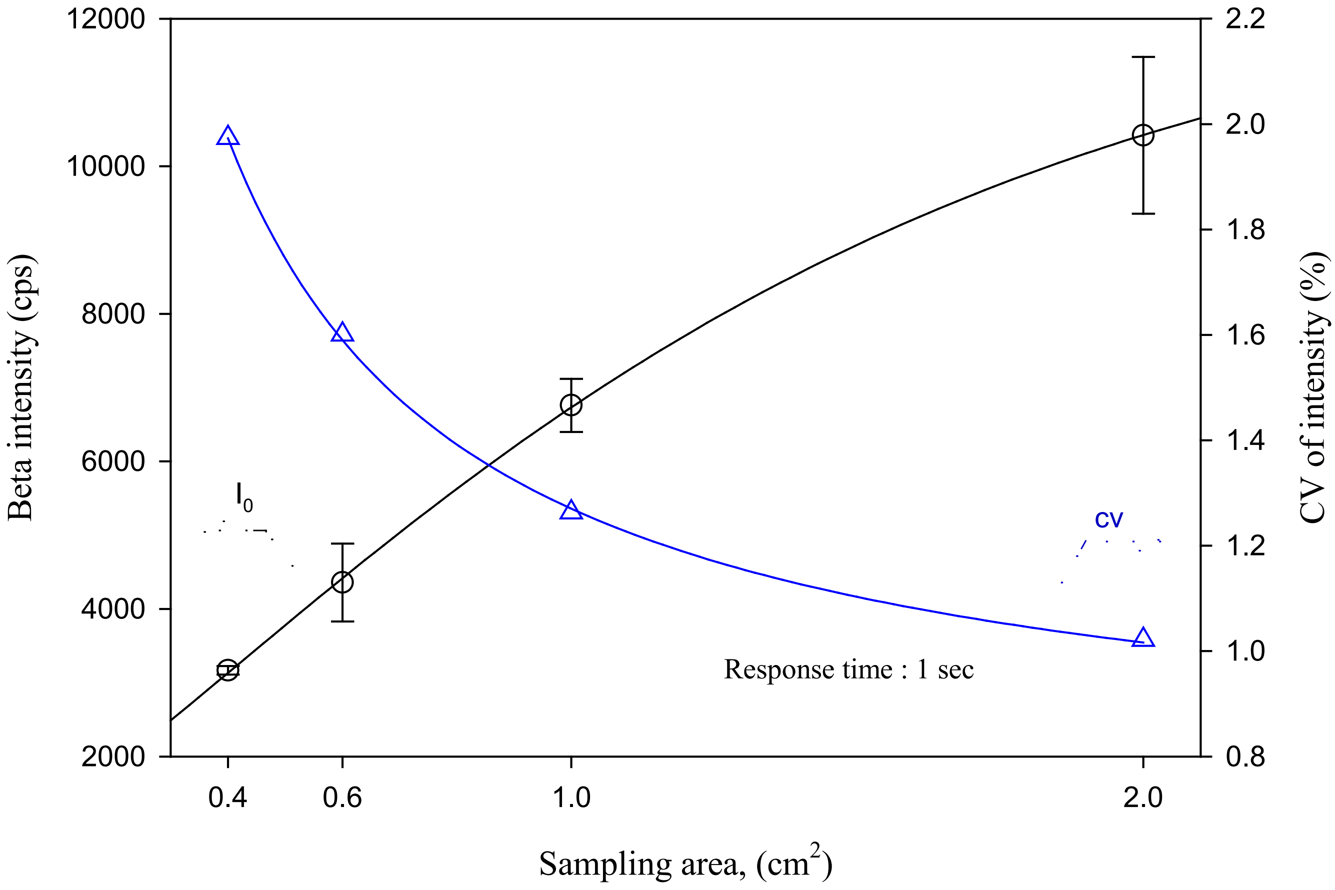


Figure 2. The effect of particle deposition area on particle mass per unit area and decay rate

However, reducing the particle deposition area also decreases the number of incident beta particles reaching the detector. This occurs because the aluminium plate shields the source and detector, narrowing the cross-sectional area available for beta particle transmission. When the particle deposition area was reduced from 2.0 cm^2 to 0.4 cm^2, the initial beta intensity dropped from 10,419 cps to 3,168 cps. Consequently, the coefficient of variation (CV) for the intensity increased from 1.02% to 1.97% due to the decrease in the average count rate (as shown in Fig. 3). This increase in statistical fluctuation directly impacts the precision and detection limit of the beta gauge.

Furthermore, reducing the particle deposition area increases the face velocity across the filter media. At a constant sampling flow rate of 16.67 L min^{-1}, the initial pressure drop rose from 58 mmHg to 118 mmHg as the area was decreased. Because of the smaller surface area, the particle loading rate (mass per unit area) accelerates, which in turn shortens the operational lifespan of the filter paper. Consequently, it is recommended to shorten the filter replacement cycle to mitigate the risk of filter tearing or structural damage due to excessive pressure.



160 **Figure 3.** The effect of particle deposition area on beta intensity and CV

However, for a fixed smoothing interval, a smaller particle deposition area also results in a lower standard deviation of the mass concentration. For example, with a 5-minute smoothing window, reducing the particle deposition area from 2 cm^2 to 0.4 cm^2 decreased the standard deviation from 175 µg m^{-3} to 101 µg m^{-3}. This demonstrates that area reduction effectively 165 improves the precision of the measurement, particularly at shorter smoothing intervals.

Longer smoothing intervals enhance measurement stability, with further improvements observed as the particle deposition area decreases. However, increasing the smoothing duration leads to a linear increase in the response time of the beta gauge, a trend that remains consistent across all tested particle deposition areas. This relationship is characterized by the equation,

170 $$y = 0.854x - 3.96 \quad (6)$$

Consequently, achieving a faster response time by using a shorter smoothing window necessitates a trade-off, as it results in lower stability for the measured mass concentration.

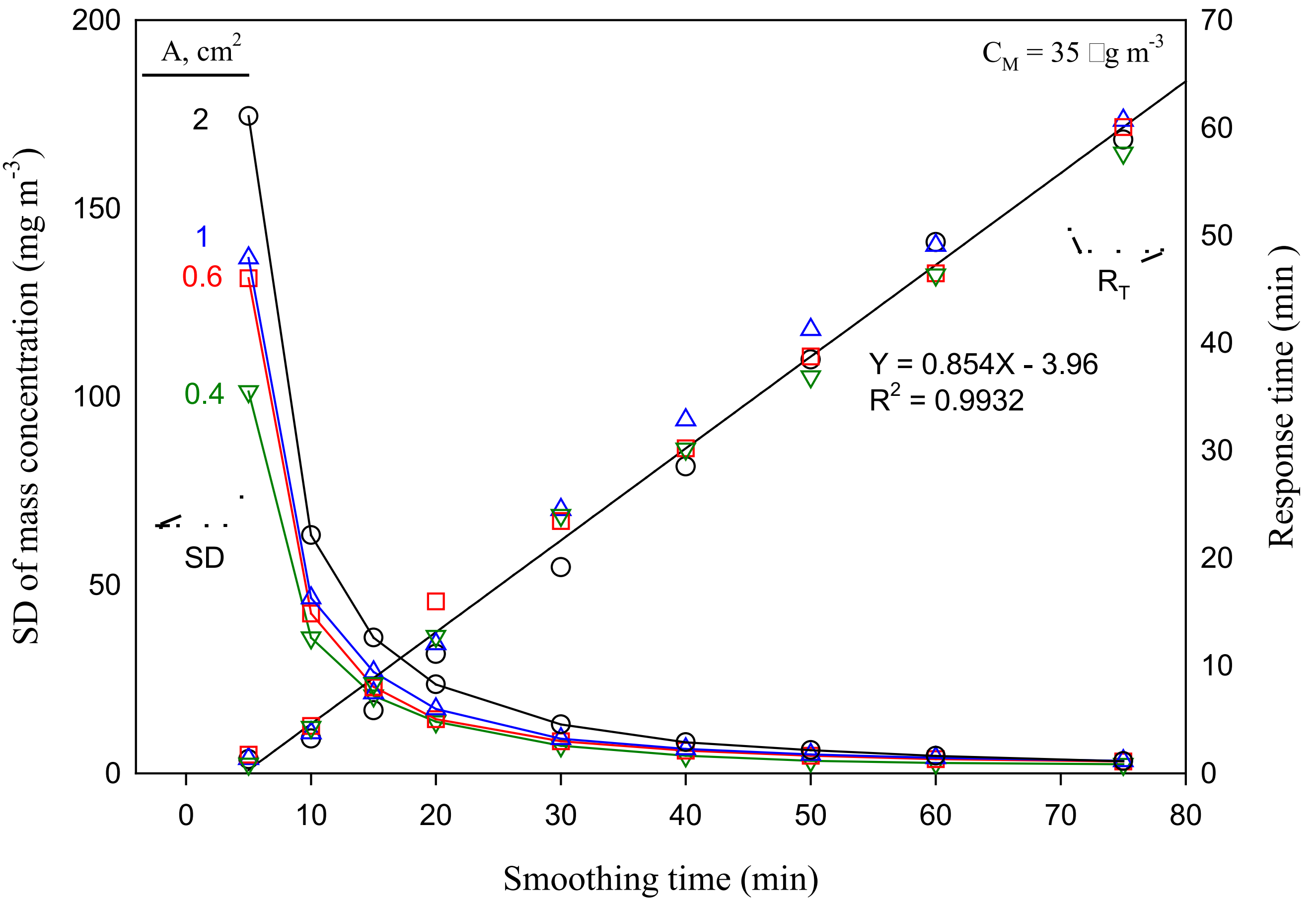


Figure 4. The standard deviation and response time at different smoothing time

As illustrated in Fig. 5, using an SNR of 10 as the benchmark, reducing the particle deposition area from 2 cm^2 to 0.4 cm^2 allows the required smoothing interval to be shortened from 75 minutes to 50 minutes. A shorter smoothing interval reflects a higher rate of particle accumulation per unit area, which subsequently amplifies the mass change signal. Consequently, reducing the particle deposition area increases the mass per unit area x, thereby enhancing the beta attenuation. Both mechanisms effectively increase the signal magnitude detected by the beta gauge, leading to a superior signal-to-noise ratio for the mass concentration measurements.

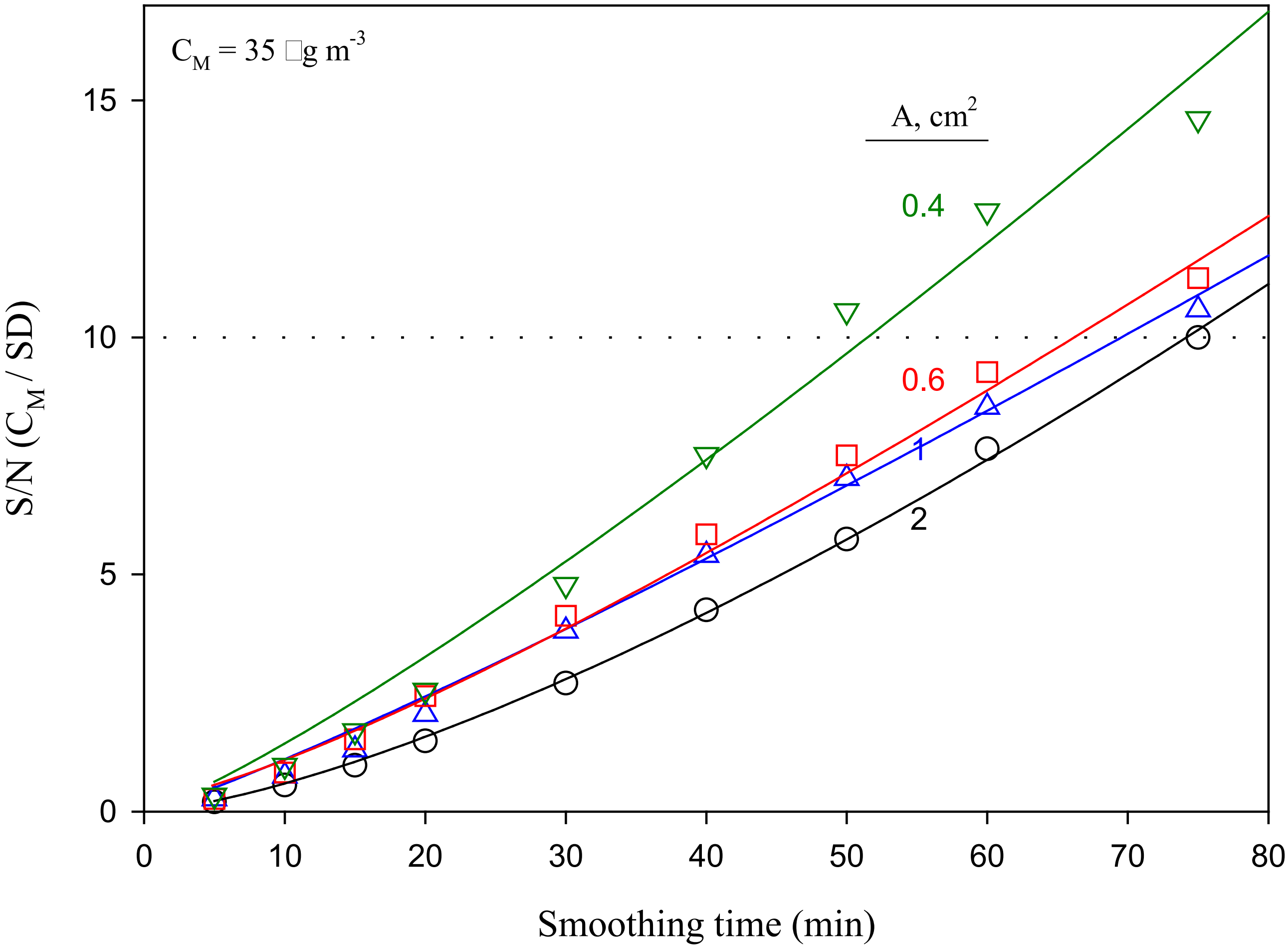


Figure 5. The effect of different particle deposition areas on the signal-to-noise ratio of mass concentration

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Figure 6 illustrates the results of six repeated BAM measurements conducted in a controlled, particle-free environment. Each measurement utilized an unused filter and was recorded for one hour with a sampling frequency of 1 Hz. This procedure was designed to simulate the baseline variation in source intensity that would be observed if six independent beta gauges were operated simultaneously under identical conditions.

190 Figure 6 compares the standard deviation (SD) of the six individual intensity readings with the SD of the ensemble average. It is evident that the SD of the individual measurements exhibits higher dispersion, reflecting the stochastic fluctuations of the source. In contrast, the SD of the averaged values is significantly lower, demonstrating a clear convergence.

This trend of reduced variance through averaging is consistent across all tested areas. However, as the area decreases, the overall measured intensity also drops. For example, at a 2.0 cm^2 particle deposition area, the SD of the six individual samples ranged from 102 to 118 cps. Upon averaging the six datasets, the intensity SD was effectively reduced to 42 cps.

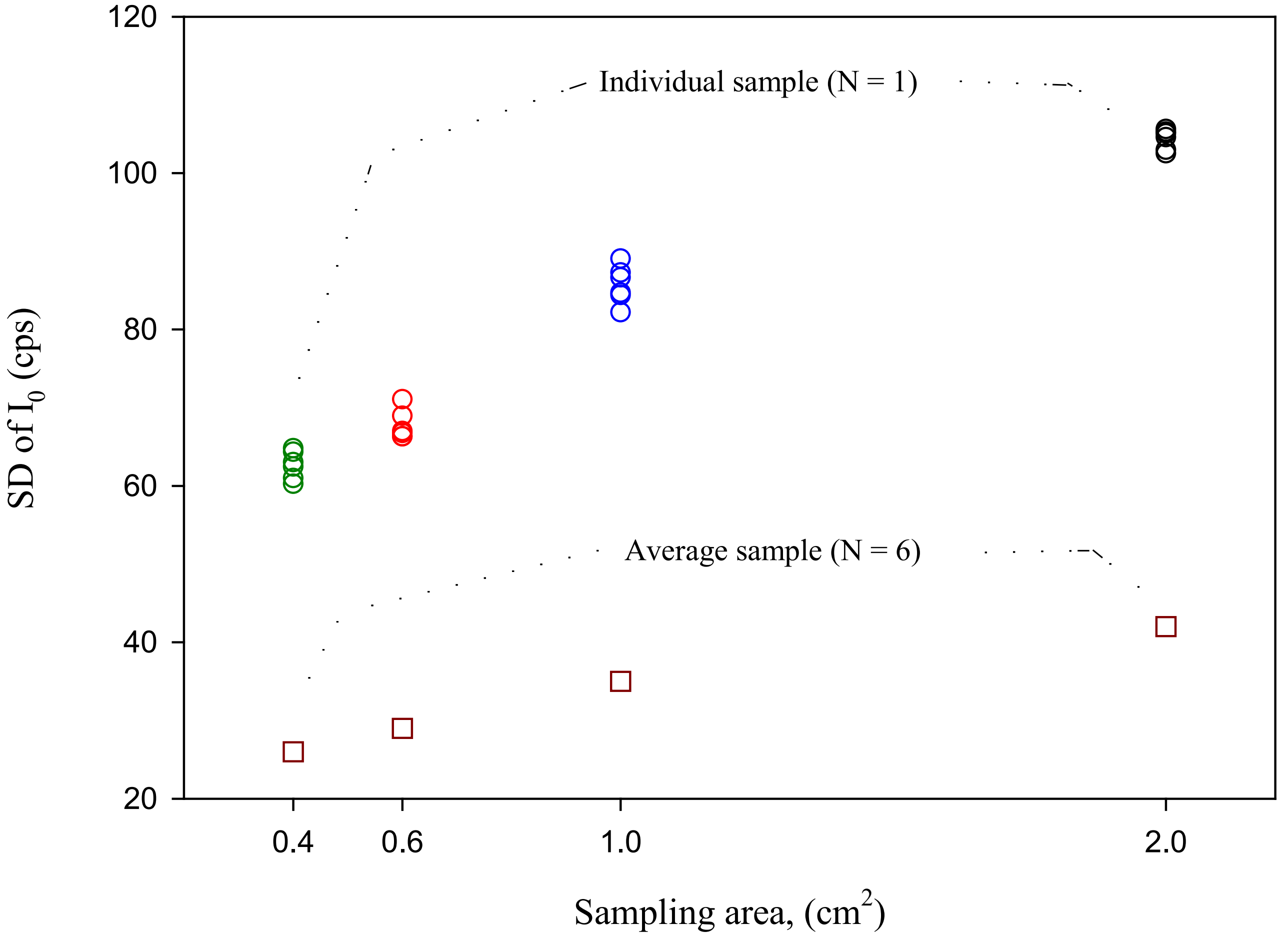

Figure 6. The SD of average sample and individual sample in different particle deposition area

Table 2 summarizes the SD and CV beta intensity for both single-sample and six-sample ensemble groups across varying particle deposition areas. For a single dataset, reducing the particle deposition area from 2.0 cm^2 to 0.4 cm^2 lowered the intensity SD from 105.6 cps to 63.0 cps. However, because the reduction in area also decreased the mean beta intensity, the CV increased from 1.02% to 2.01%.

By utilizing the average of six samples, the SD at 2.0 cm^2 was further reduced from 105.6 cps to 41.5 cps, successfully lowering the CV from 1.02% to 0.39%. Statistically, increasing the sample size effectively minimizes measurement variation.

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205 Compared to a single sampling run, the averaged beta intensity exhibits significantly lower variance, which minimizes background noise interference and results in a superior SNR for the BAM system.

Table 2. Changes in average beta intensity for different particle deposition areas and multiple groups of samples

	Sample size			
A	N = 1		N = 6	
(cm)	SD (cps)	CV (%)	SD (cps)	CV (%)
2.0	102-105	1.02-1.08	41.5	0.39
1.0	82-90	1.18-1.30	35.0	0.51
0.6	66-71	1.55-1.73	28.5	0.68
0.4	60-65	1.85-2.01	25.9	0.82

210 Figure 7 compares the effect of sample size on mass concentration, simulating the variation in monitoring results when one to six BAM units are operated simultaneously. At a test mass concentration of 35 μg m^{-3}, six individual measurement runs were performed. The resulting beta intensity data were averaged and converted into mass concentrations using a 30-minute smoothing window.

The upper panel displays the individual mass concentration readings, while the lower panel presents the results of the 215 ensemble averaging. As shown in the Fig. 7, the standard deviation of the mass concentration decreases progressively from 11.2 to 5.1 μg m^{-3}, and the CV is reduced from 31.4% to 14.3% as the number of simulated units increases. This significant convergence of the mass concentration readings demonstrates that increasing the number of BAM units, even through simulated repetitions, substantially enhances the measurement stability of the beta gauge system.

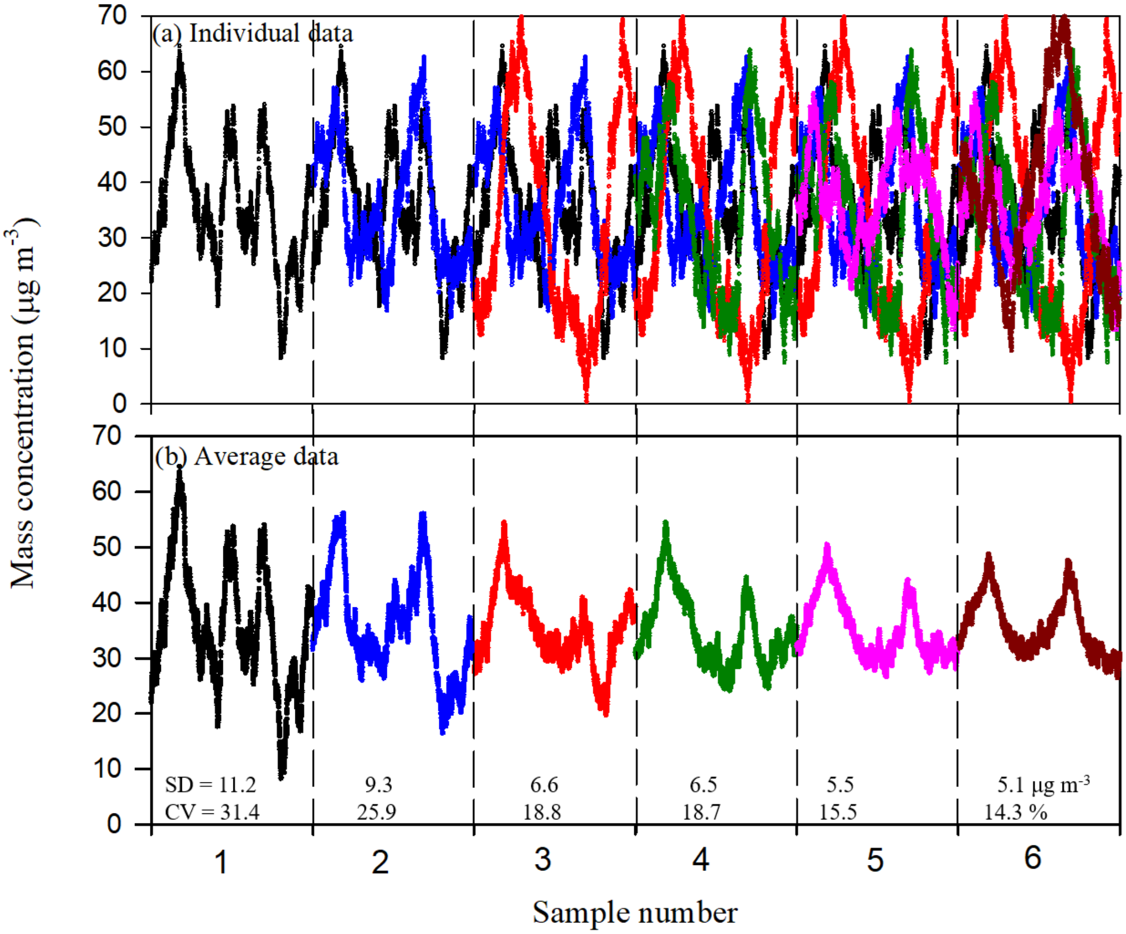
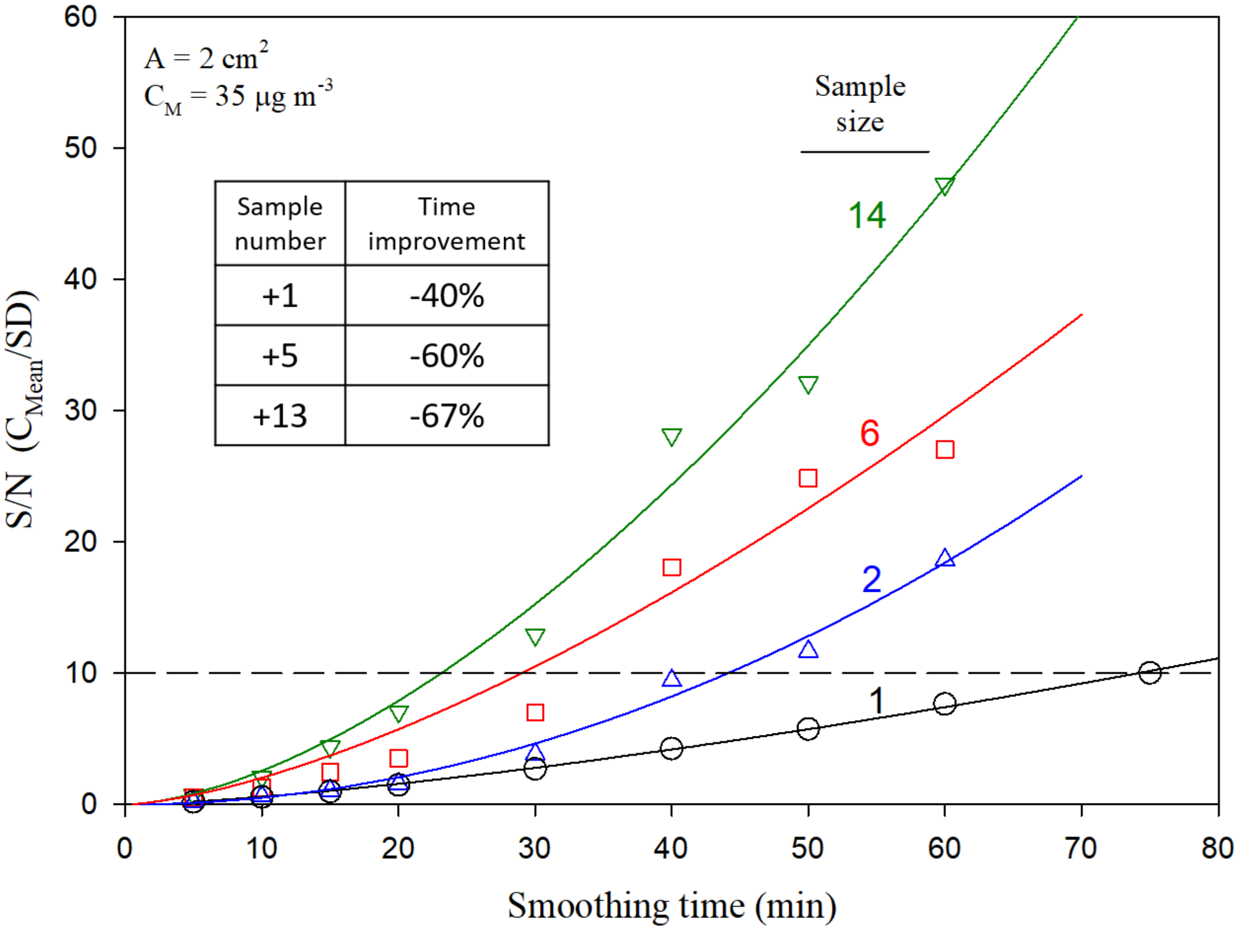


Figure 7. Comparison of mass concentration stability: (a) individual measurement runs and (b) ensemble averaged results.

To determine the optimal smoothing interval for varying sample sizes, an SNR of 10 was again utilized as the benchmark. As illustrated in Fig. 8, during ambient testing at 35 $\mu g\ m^{-3}$, increasing the number of sampling units to 2, 6, and 14 allowed the required smoothing window to be reduced from 75 minutes to 45, 30, and 24 minutes, respectively. Consequently, the corresponding response times were improved to 35, 22, and 17 minutes. These results demonstrate that increasing the number of BAM units significantly enhances the temporal resolution of the measurement without compromising signal quality.

As the number of averaged samples increases, the SNR of the mass concentration rises accordingly. This improvement enables the use of shorter smoothing intervals, thereby mitigating the issue of increased measurement variation. However, expanding the sample size involves higher capital costs. From a cost-benefit perspective, increasing the number of units by 1, 5, and 13 yielded reductions in required smoothing time of 40%, 60%, and 67%, respectively. Notably, the marginal gain in performance decreases as the sample size grows; therefore, further increases beyond a certain point would result in an inefficient allocation of resources.



Sample number	Time improvement
+1	-40%
+5	-60%
+13	-67%

Figure 8. Effect of sample group number on mass concentration signal-to-noise ratio

Figure 9 compares the relative impacts of sample size and particle deposition area on the required smoothing duration. The results indicate that the improvement gained from adding just one additional sample was significantly greater than the benefit achieved by reducing the particle deposition area to 0.4 cm^2. For the multi-unit approach, the degree of improvement exhibited diminishing returns, tending to stabilize after the addition of six or more samples; this renders continuous increases in sample size progressively less cost-effective. In contrast, the benefit of reducing the particle deposition area showed a trend of exponential improvement as the area decreased. However, a smaller particle deposition area necessitates a higher face velocity, leading to an increased pressure drop that limits both the operational duration and the total lifespan of the filter media.

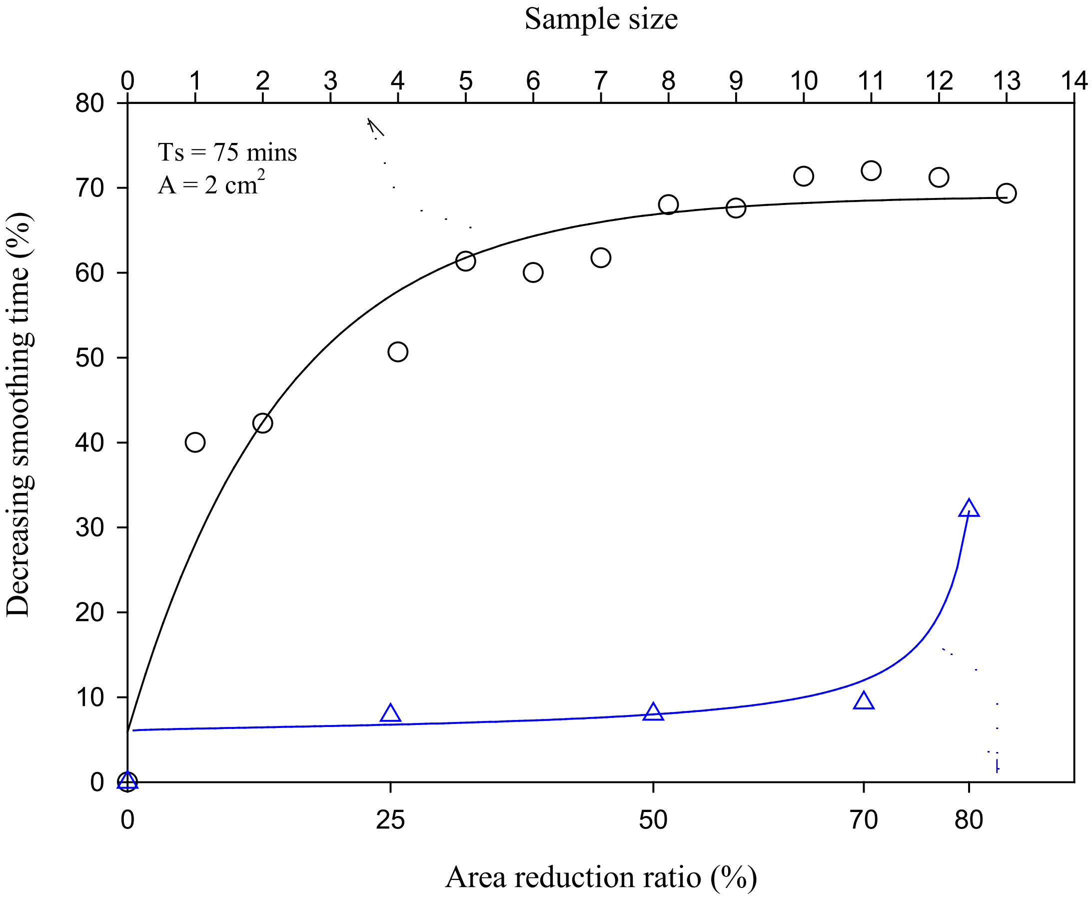


Figure 9. Comparison of increasing the number of samples and reducing the particle deposition area in shortening the smoothing time

Figure 10 illustrates how the sample size enhances the sensitivity of the beta gauge's Limit of Detection (LOD). In this study, the LOD was defined as two times the standard deviation of the blank concentration, 2σ, providing a quantitative metric to evaluate the improvements derived from both increased sample size and extended smoothing duration. As shown in Fig. 10(a), where the x-axis represents the number of simultaneous samples and the y-axis denotes the LOD, the results indicate that increasing the sample size significantly lowers the detection limit. This improvement in analytical sensitivity is most pronounced when coupled with longer smoothing intervals.

Using the detection limit of a single BAM as the baseline, the normalized detection limits for varying sample sizes and smoothing intervals are presented in Fig. 10(b). The results indicate that a 90% improvement in the detection limit was achieved by increasing the sample size to four units, reaching over 95% with six units. However, utilizing an excessive number of units reduces the overall cost-effectiveness.

Notably, the relative improvement in the detection limit driven by sample size remains largely independent of the smoothing duration. This is because the detection limit is fundamentally governed by the intrinsic standard deviation of the measurement, whereas the smoothing window is a user-defined operational parameter. Furthermore, once the sample size exceeds six units, the reduction in the detection limit reaches a plateau, with no significant further gains observed.

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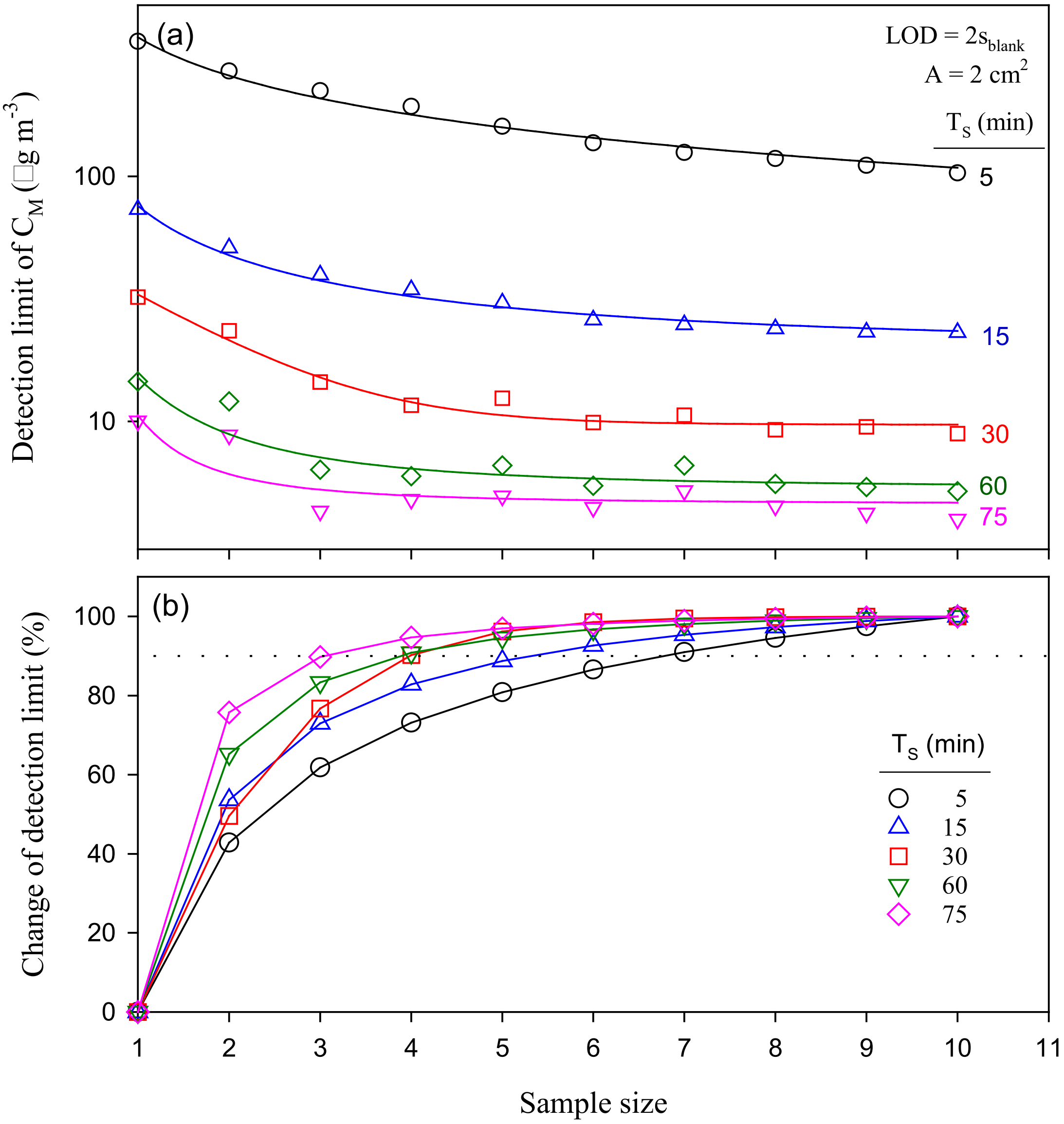

Figure 10. (a) The effects of the number of samples on detection limit; (b) The effects of the number of samples on detection

Figure 11 illustrates the combined effects of reducing the particle deposition area and increasing the sample size. As shown in the figure, for a single sampling unit with a smoothing window ranging from 5 to 75 minutes, the LOD can be reduced from 386.58 μg m^{-3} to 8.112 μg m^{-3}. However, by utilizing the ensemble average of six samples, the LOD is further suppressed, dropping from 144.21 μg m^{-3} to a significantly lower value of 0.8 μg m^{-3}. This highlights that the combination of hardware optimization and statistical averaging can improve the detection sensitivity by several orders of magnitude.

A longer smoothing interval results in a lower detection limit. However, no significant difference in the detection limit was observed across the different particle deposition areas. This is because, while a smaller area increases beta particle attenuation (the signal), it simultaneously reduces the initial incident radiation intensity I_0. This reduction in I_0 increases the relative statistical noise, effectively cancelling out the gains in sensitivity. In contrast, increasing the number of samples significantly lowers the detection limit by reducing random variation without sacrificing signal intensity. Therefore, by achieving an acceptable detection limit through multi-unit averaging, one can utilize a shorter smoothing window to obtain a faster measurement response.

The BAM utilized in this study exhibited an initial beta intensity I_0 of approximately 12,000 cps after transmission through the glass fiber filter. Based on a previous publication, the detection limit calculated using their "Eq. (3)" was 9.17 μg m^{-3}. Compared to our single-sample empirical measurement of 8.112 μg m^{-3}, this model shows a discrepancy of approximately 13%, which is likely attributable to differences in instrument geometry and source characteristics. However, when compared to our six-sample ensemble measurement of 0.8 μg m^{-3}, the formula's result represents a significant overestimation of the detection limit. This discrepancy arises because Eq. (3) fails to account for the reduction in stochastic variability achieved through averaging. Consequently, such models cannot accurately predict the improvements in standard deviation and detection limits gained by increasing the sample size to minimize intensity fluctuations.

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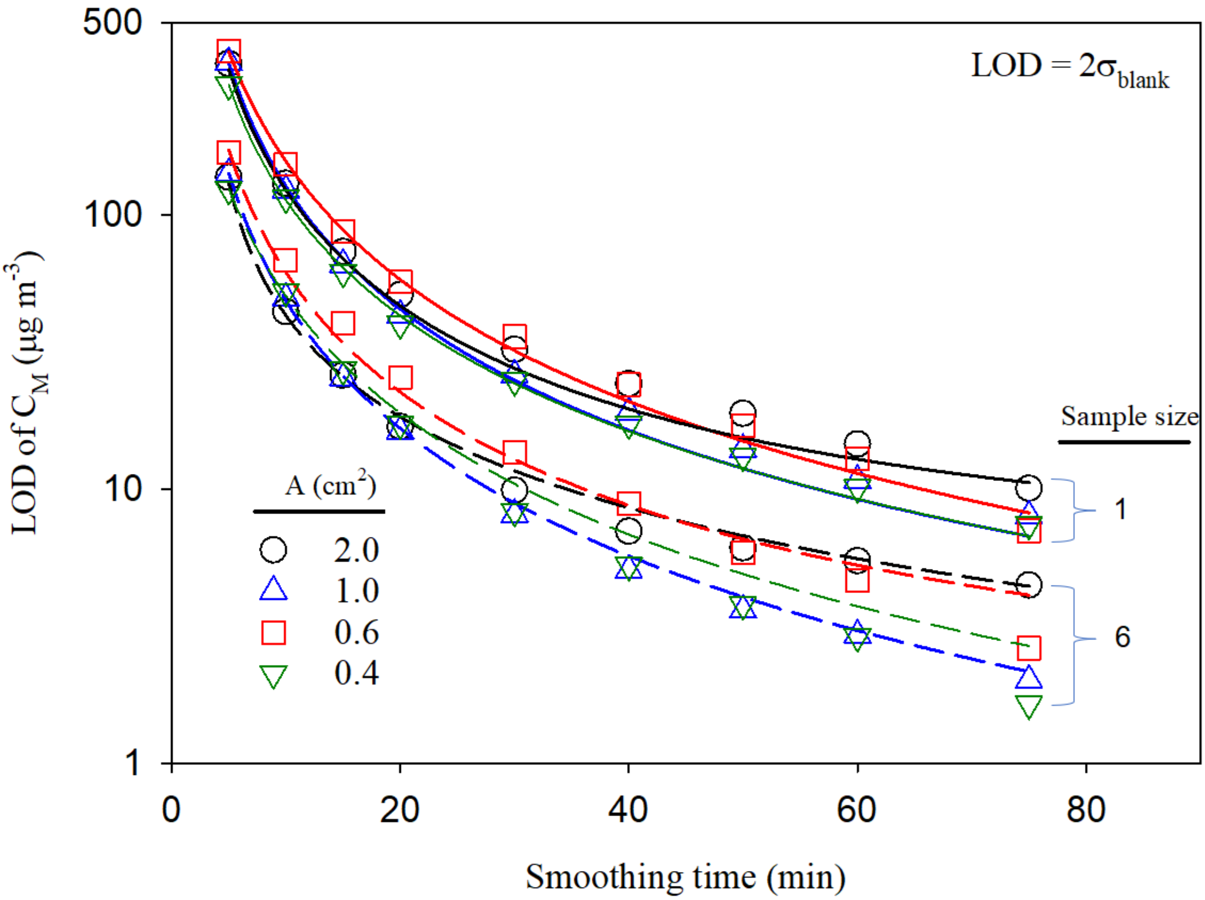

Figure 11. Effect of averaging 6 groups of samples on the mass concentration detection limit at different smoothing times

The integrated effects of particle deposition area, smoothing duration, and sample size are summarized in Table 3. By fixing the smoothing time at 30 minutes and the particle deposition area at 0.4 cm^2 for an ensemble of six samples, we evaluated the relative impacts of these optimization strategies on the beta gauge's performance metrics. Specifically, we compared three distinct methodologies based on their response time, the standard deviation measured at a mean concentration of 35 µg m^{-3}, and the LOD derived from particle-free blank tests. This comprehensive comparison highlights the advancements in analytical capabilities achieved through our proposed optimizations.

The baseline performance of the reference BAM, before any optimizations, exhibited a response time of 60 minutes, a mass concentration standard deviation of 5.54 µg m^{-3}, and a LOD of 8.10 µg m^{-3}. When evaluating individual optimization strategies, reducing the smoothing duration to 30 minutes improved the response time to 22 minutes. However, this gain in temporal resolution resulted in a reciprocal increase in both the standard deviation and the detection limit, confirming the inherent trade-off between speed and measurement stability in a single-unit configuration.

Reducing the particle deposition area to 0.4 cm^2 as a standalone optimization improved the mass concentration standard deviation to 2.4 µg m^{-3}, though it yielded no significant reduction in the detection limit. Conversely, increasing the sample size to six units alone achieved superior precision, lowering the standard deviation to 0.56 µg m^{-3} and the detection limit to 1.04 µg m^{-3}. Finally, when all three strategies were integrated—shortening the smoothing window to 30 minutes, reducing the area to 0.4 cm^2, and increasing the sample size to six—the system achieved a high-performance balance. This multi-parameter optimization reduced the response time to 22 minutes, maintained a standard deviation of 2.67 µg m^{-3}, and suppressed the detection limit to 7.75 µg m^{-3}.

This study demonstrates that to achieve high-resolution real-time monitoring with a beta gauge, a reduced smoothing window is essential for improving temporal response. However, to offset the resulting loss in stability, this must be paired with the complementary strategies of reducing the particle deposition area and increasing the sample size. Only through this synergistic approach can a beta gauge achieve the high measurement stability and analytical sensitivity required for high-resolution ambient air monitoring.

Table 3. The table of BAM performance Improvement

Index	Reference BAM	Parameters						
		Ts	A	N	Ts + N	Ts + A	A + N	Ts + A + N
A (cm^2)	2	2	**0.4**	2	2	**0.4**	**0.4**	**0.4**
Ts, (min)	75	**30**	75	75	**30**	**30**	75	**30**
N	1	1	1	**6**	**6**	1	**6**	**6**
Response time (min)	60	**22**	60	60	**22**	**22**	60	**22**
Standard deviation (µg m^{-3})	5.54	12.95	**2.40**	**0.56**	**5.41**	7.31	**0.50**	**2.67**
Detection limit (µg m^{-3})	8.10	29.02	9.29	**1.03**	7.38	26.60	**0.89**	7.75

Data: 1 s^{-1}

A: particle deposition area

Ts: smoothing time (min)

N: sample size

4. Conclusions

This study successfully demonstrated that the performance of BAMs, specifically long response times and high detection limits, can be enhanced through a combined optimization of particle deposition area, multi-sensor aggregation, and temporal smoothing. By reducing filter area and implementing multi-unit ensemble averaging, the research established a technical framework for high-resolution, real-time particulate matter monitoring.

A primary finding was that reducing the particle deposition area from 2.0 to 0.4 significantly enhances signal sensitivity by increasing the accumulated mass per unit area. While this modification induces a higher pressure drop and increases relative statistical noise due to lower incident radiation, it effectively amplifies the mass change signal for active monitoring. Complementing this, the implementation of a multi-sensor array (simulated via six-sample ensemble averaging) was found to be the most effective method for restoring measurement stability. Averaging data from six units reduced the CV of intensity from 1.02% to 0.39%, directly mitigating the stochastic fluctuations inherent in radioactive decay.

The integrated performance evaluation revealed that the optimal balance is achieved by combining a 0.4 cm^2 particle deposition area with a six-unit ensemble and a 30-minute smoothing window. This configuration reduced the instrumental response time from 60 minutes to 22 minutes. Furthermore, it maintained a stable standard deviation of 2.67 and suppressed the detection limit to 7.75, meeting the requirements for ultra-low concentration monitoring. Cost-benefit analysis indicated that the marginal gains in performance plateau beyond six units, making an array of 4 to 6 integrated detectors the most efficient deployment of instrumentation.

Finally, the study suggests that future developments should focus on array-type beta gauges featuring multiple integrated detectors and adaptive smoothing algorithms. Such architectures represent a viable pathway toward achieving the true high-resolution monitoring necessary to comply with increasingly stringent global air quality standards.

Data Availability

The data underlying the results presented in this study can be obtained from the corresponding author.

Author contributions

Chih-Wei Lin: Conceptualization, Methodology, Writing – original draft.
Chih-Chieh Chen: Conceptualization, Supervision.
Qi-Xiang Li: Investigation, Data curation, Formal analysis.
Sheng-Hsiu Huang: Conceptualization, Methodology, Writing- Review & editing.
All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

Disclaimer

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