# *Piera-1 Test Report*

***Performance Evaluation of Piera-1 Intelligent Particle Sensor (IPS) Evaluation Unit***

*Document Version 2.1*

## Introduction

Air quality is directly related to human health, and it can be assessed by measuring particulate matter (PM) concentrations. Air pollution associated with fine airborne particles of less than or equal to 2.5um in diameter (PM2.5) has been studied on its adverse effect, and researchers have shown that the smaller the particles, the more fatal to humans. These particles are known to cause numerous diseases including lung cancer, arrhythmia, asthma, pneumonitis, and cardiovascular mortality. It is crucial to continuously monitor air quality by measuring PM concentration in real-time for effective management of air quality, and get more information by categorizing particles by their sizes. Most low-cost (<$100) particulate matter sensors are primarily calibrated for PM2.5 under specific conditions, and estimate other sized particles by extrapolation. However, such extrapolated data for other sized particles especially for submicron particles leads to growing concerns on reliability and accuracy of low-cost sensors. The ideal low-cost sensor would accurately measure both mass concentration and particle count by size in real-time over the full range (PM0.1-10)

Piera has developed its first particulate sensor called **Piera-1**, which has been designed to provide submicron particle data more accurately, in a cost-effective way. Piera's highly sensitive custom ASIC is the key to achieve this, derived from a patented real-time X-ray imaging ASIC architecture and technologies. This report summarizes the results of initial evaluation and testing of Piera-1. The results show that Piera-1 is comparable to a highly expensive reference device. Additional testing is expected to be completed in the coming months by Piera and third-party labs with the goal of having independent certification under different environment conditions.

## Purpose

The initial testing and evaluation were conducted to develop and refine an algorithm that interprets the raw data from the Piera-1, and to verify consistent and reliable data readout from the algorithm applied in the sensor under specific test conditions with respect to a reference device (GRIMM 11D model year 2006).

## Working Principles and Underlying Technology

Piera-1 uses Laser Light Scattering (LLS) method to detect airborne particulates, which is ideal for real-time data gathering unlike other methods such as gravimetric, beta attenuation, etc. that could take ~15 minutes up to more than an hour to get a reading. The LLS method relies on a laser source to emit light, and a photodiode to receive reflected light from particles. It is possible to correlate the intensity of the photoelectric signal from the photodiode with particle size and concentration via characterization, which is a common practice for all of the low-cost sensors. However, it becomes extremely hard to differentiate white

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noise from the actual signal originated from particles as the particle size gets smaller, because of the performance limitations of off-the-shelf AFE's (Analog Front End) that are used by the sensor manufacturers. This limits the performance of the conventional low-cost sensors and typically the best-in-the-class sensors have a lower detection limit of 0.3um, yielding data from PM0.5 and above.

Piera-1 is built upon Piera's own ASIC that counts the number of particles and sorts them according to sizes by utilizing both light intensity and pulse width information simultaneously after digitization of the raw analog signals rather than approximating PM concentration solely based on the reflected light intensity. Also, it is generally known that longer wavelength light (red or infrared light source) is inadequate for "physical" submicron particle detection (not relying on extrapolation) so many advanced reference instruments adopt green or blue laser source. Piera-1 uses red laser to be cost-effective but, designed to detect submicron particles down to 0.1um level or below. Sensitivity of Piera-1 can be adjusted via threshold voltage control (VTH) and AFE gain control (VGC).

## Key Assumptions and Hypothesis

The following key theoretical assumptions were made for the evaluation of Piera-1.

1. **Random samples**
   The particles are saturated and evenly distributed in the identical test environment at any given time and thus, sampled air of any unit volume is considered as a correct representation of the whole environment.

2. **Statistical independence assumption & simple random sampling with replacement**
   The number of total particles is unaffected by the act of observation, and sampling of air by either a reference device and Piera-1 will not affect each other's result.

3. **Constant particle velocity**
   The air flow through Piera-1 and reference device is laminar (without any turbulence) and that the particles are moving at a constant velocity through the detection chamber.

4. **The absolute truth**
   Data from a reference device is considered as the ground truth, and will served as a basis throughout the analysis.

5. **Controlled environment**
   Other than the changes in concentration, all other factors remain the same throughout the experiment, such as temperature and relative humidity (RH).

6. **Standardization of particle shape**
   Particles in the air are spherical and smooth.

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The two assumptions 1 and 2 are the necessary statistical assumptions, stating the random samples assumption will hold, and the fact that the act of measurement does not affect the environment. The assumption 3 further enhances the assumptions 1, and the assumption 4 provides a reference point. Note that temperature and RH are not treated as evaluation parameters for this report, and held constant. With the above assumptions, it can be hypothesized that if Piera-1 and a reference device both generate data that is constant in a given test condition, there exists a relationship, or a translation function that translates Piera-1's raw data into reference device's data regardless of other factors such as sampling time or air flow rate under the Assumption 1. Such a relationship shall be defined as an algorithm. Also, the algorithm applied on Piera-1 should yield results that match data obtained by any reference device. It is reasonable to believe that the data collected by Piera-1 over longer sampling time will result in less variance due to the larger sample size, and will converge on to the ground truth with less error. It was predicted that since there will be significantly more smaller particles compared to larger particles, Piera-1 will yield results with higher deviation for larger sized particles especially in low concentration conditions.

Note that Piera-1 sensors tested in this report have been updated with new firmware (version 1.5) to reduce the effect of Brownian motion of the particles. Brownian motion is caused by particles colliding with one another and changing direction. This can result in fluctuating results. The new firmware enables Piera-1 to output data with less fluctuations without compromising the accuracy and reliability. Piera-1 is calibrated with GRIMM 11D (model year 2006) particle counter.

## Testing Methodology

Test data was collected from a Piera-1, and a reference device from GRIMM (11D model year 2006), placed within a controlled air chamber (50x50x50 $cm^3$ or ~4.414 $ft^3$). The evaluation was conducted by applying a smoke detector test spray while keeping the temperature (25℃) and RH (35%) constant. The test chamber was properly ventilated to remove any residual particles after each testing. The data from Piera-1 was plotted against 11D reference device data for comparison. Note that 11D model year 2006 outputs differential particle count data for specific sizes (31 channels from 0.25um to 35um but discrete particle bin data for 0.3um, 0.5um, 1.0um, 2.5um, 5.0um and 10um are not available), and some interpolation has to be done to best approximate data that matches Piera-1's output bin sizes.

The air chamber filled with typical indoor air without introducing additional particulates. Then extra particles were introduced within the test chamber by spraying a smoke detector tester spray, which generates aerosol particles in range from 0.01um to 10um in size with unknown distribution. A natural exponentially decaying particle concentration procedure was adopted to obtain results over the entire range of concentration in a relatively short amount of time. The particle concentration in the air chamber was controlled below the detection limit of 11D which is 3 million particles per liter.

Exact one-to-one data matching was not feasible because 11D outputs data in every 6 second, while Piera-1's sampling interval is set to 0.2 second, and thus overall average was used to compare the two datasets from Piera-1 and 11D.

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Figure 1. Evaluation environment setup. Piera-1 was placed in close proximity to the 11D's air intake hose. The test spray used in the testing is shown on the right.

| Equipment Used | Make and Model | Purpose |
|---|---|---|
| Particle counter | Grimm 11D (model year 2006) | Gathering reference data |
| Smoke detector test spray | Smoke Centurion M8 | Particle generation |
| Temp. and RH sensor | HuBDIC HT-3 | To monitor temp. and RH |

Table 1. List of test equipment used.

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## Results and Discussion

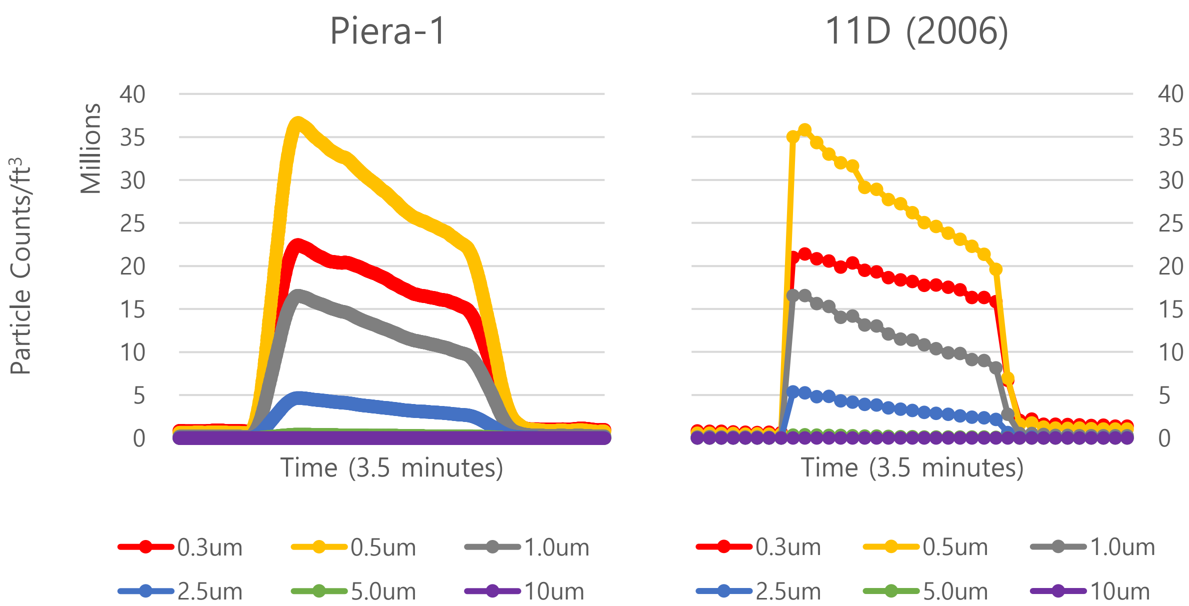


Figure 2. Differential particle count plots for 0.3um, 0.5um, 1.0um, 2.5um, 5.0um and 10um from Piera-1, and 11D.

| | | 3.5 Minute Average (Particle Counts) | Absolute Error (%) | Coefficient of Determination ($R^2$) |
|---|---|---|---|---|
| **PM0.3** | 11D | 10,653,994 | 0.035 | 0.997 |
| | Piera-1 | 10,650,218 | | |
| **PM0.5** | 11D | 15,337,189 | 0.115 | 0.997 |
| | Piera-1 | 15,319,488 | | |
| **PM1.0** | 11D | 6,686,323 | 1.258 | 0.993 |
| | Piera-1 | 6,770,455 | | |
| **PM2.5** | 11D | 1,942,618 | 0.277 | 0.975 |
| | Piera-1 | 1,948,006 | | |
| **PM5.0** | 11D | 113,632 | 3.365 | 0.995 |
| | Piera-1 | 117,456 | | |
| **PM10** | 11D | 493 | 7.884 | 0.840 |
| | Piera-1 | 532 | | |

Table 2. The summary of results. The error of Piera-1 with respect to 11D is less than 4% under 5.0um particle sizes. The error was calculated based on 3.5-minute average particle count data.

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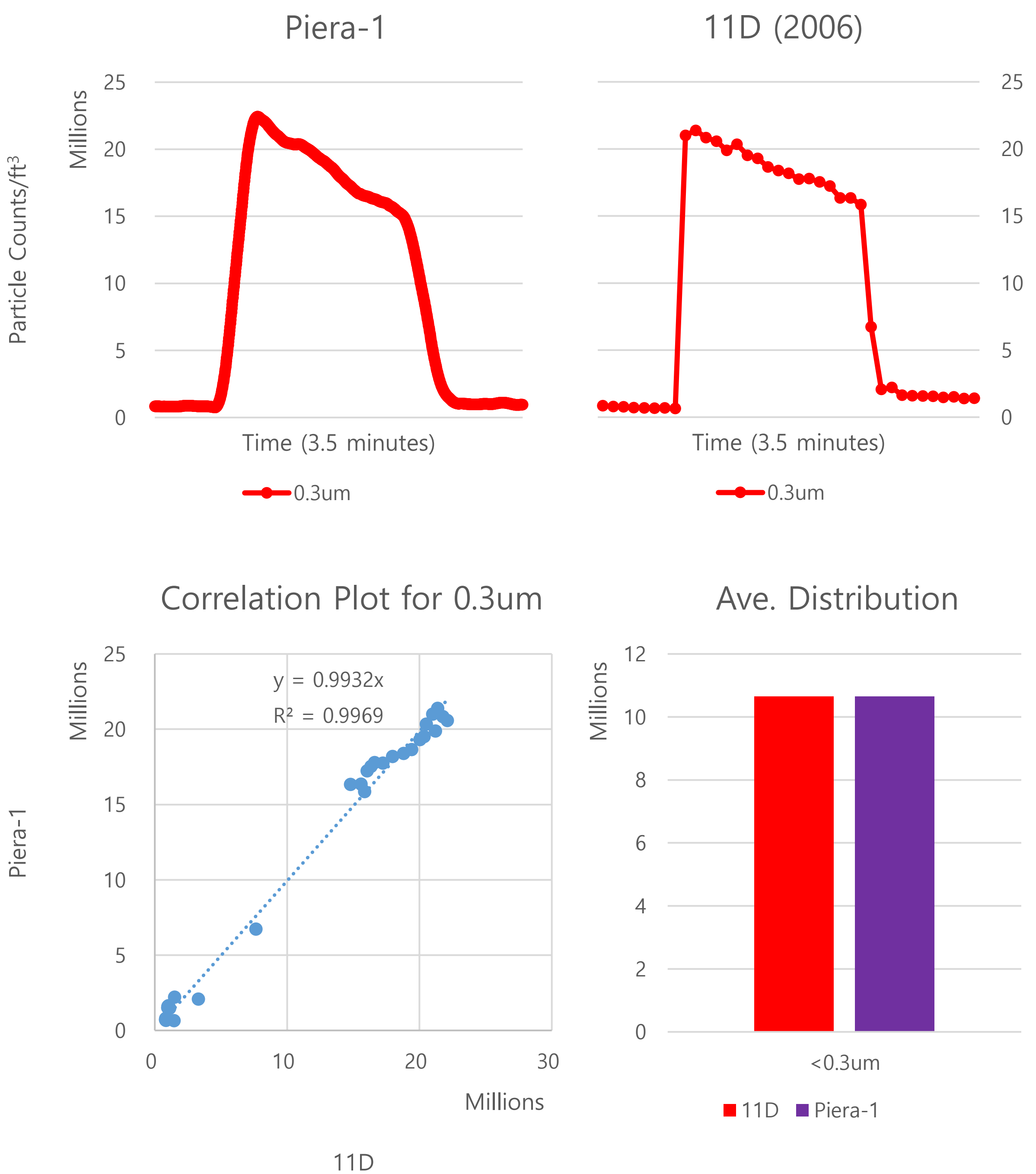


Figure 3. Differential particle count plots for 0.3um, from Piera-1, and 11D with correlation curve and average distribution.

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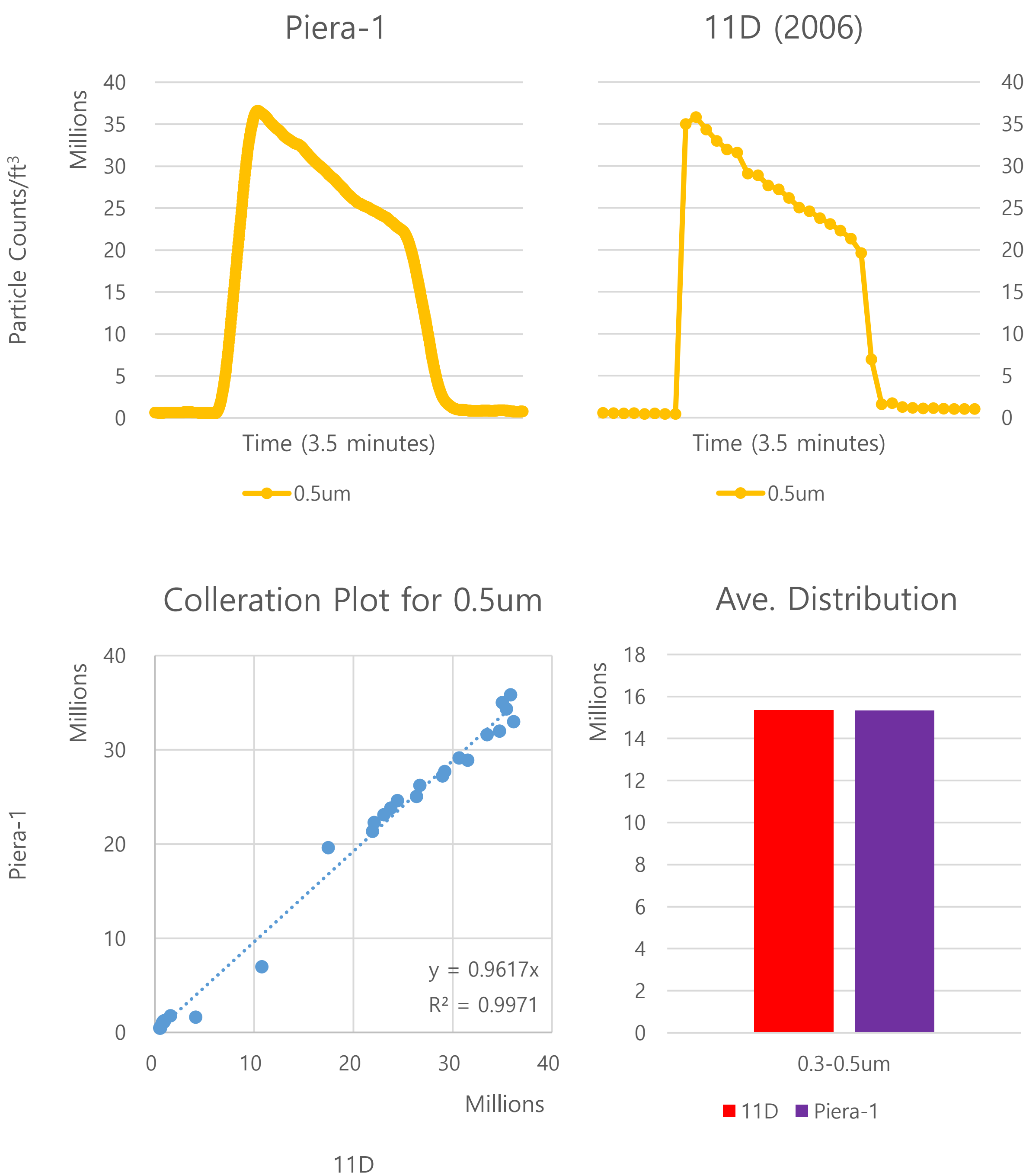


Figure 4. Differential particle count plots for 0.5um, from Piera-1, and 11D with correlation curve and average distribution.

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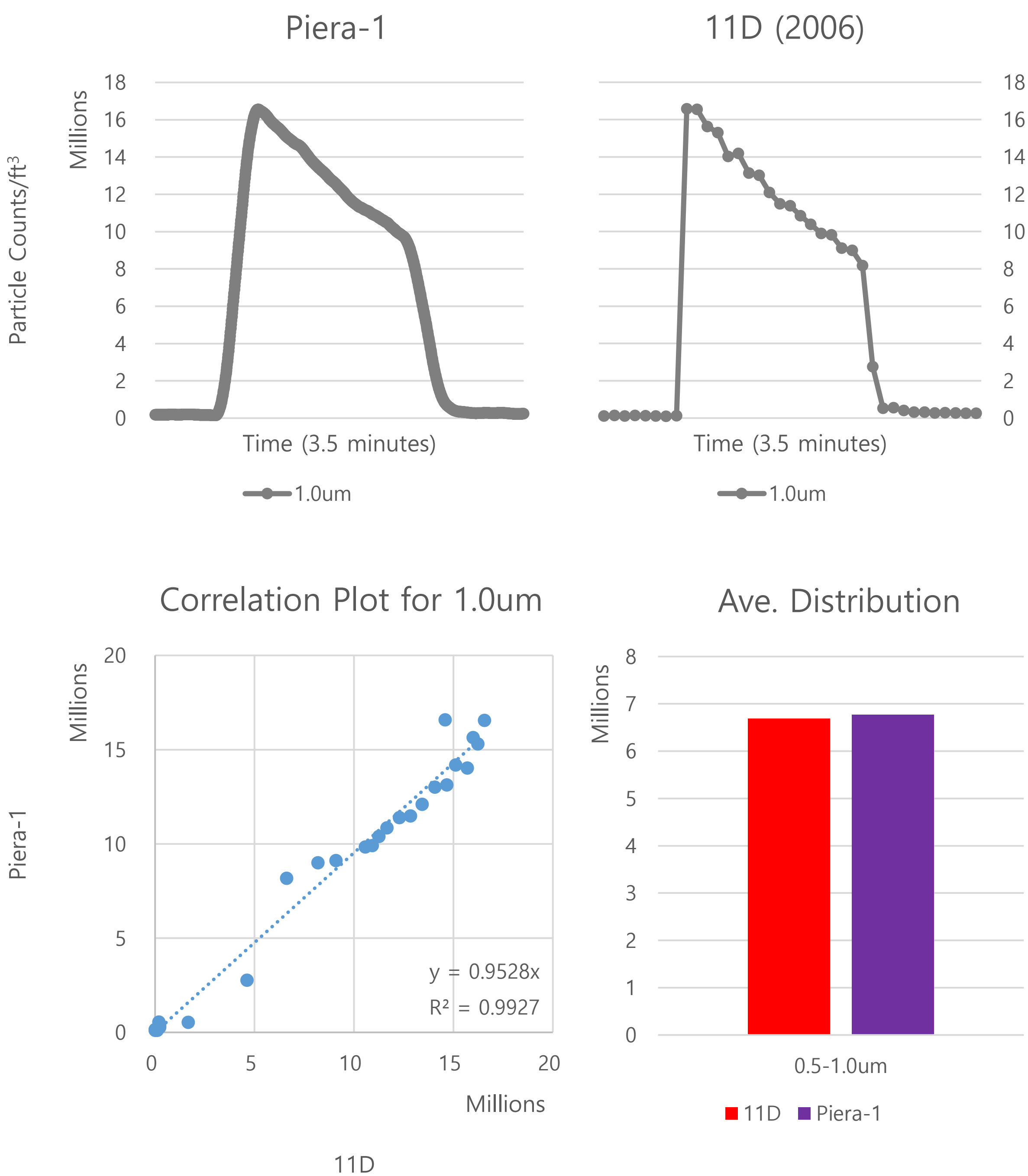


Figure 5. Differential particle count plots for 1.0um, from Piera-1, and 11D with correlation curve and average distribution.

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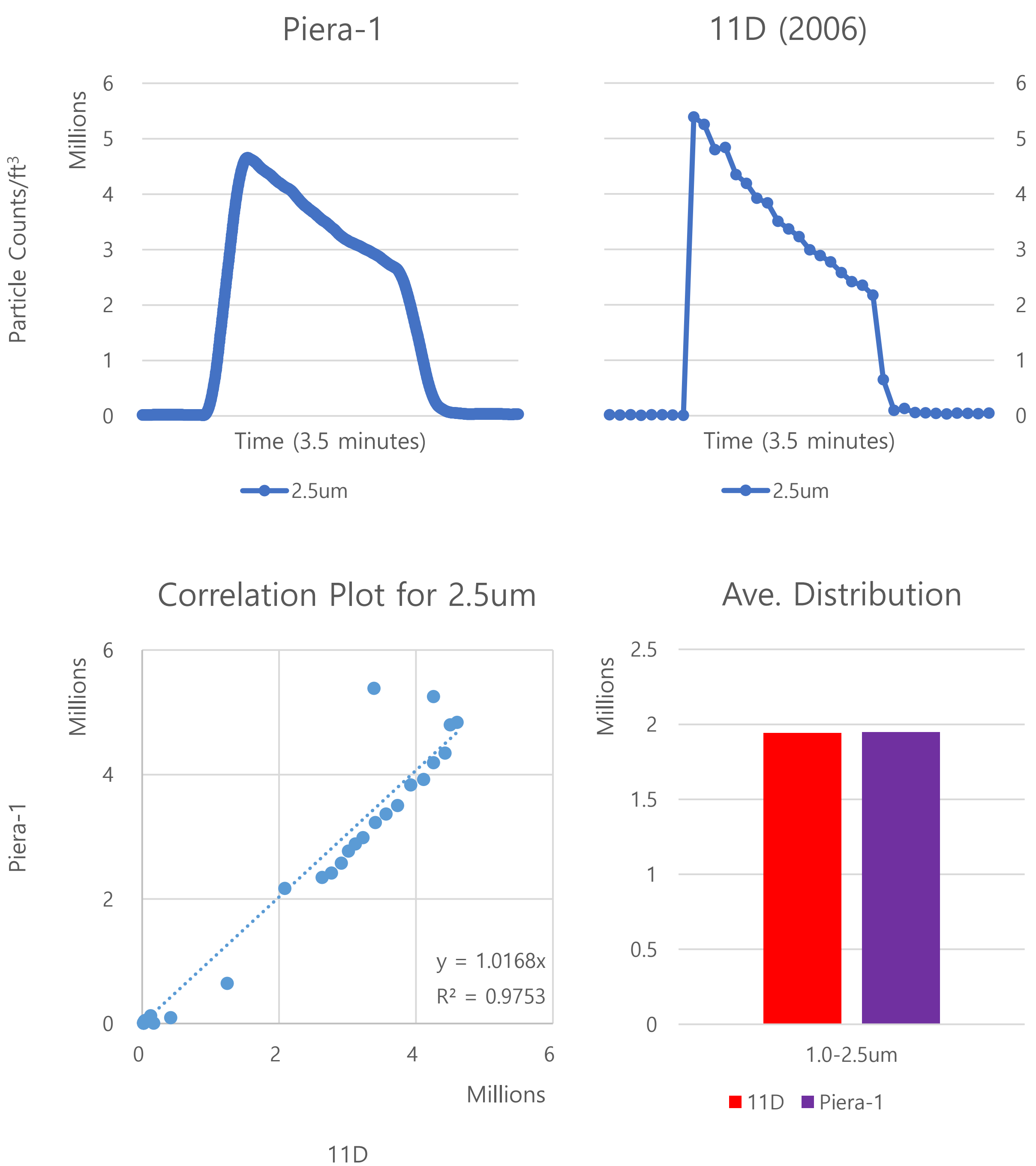


Figure 6. Differential particle count plots for 2.5um, from Piera-1, and 11D with correlation curve and average distribution.

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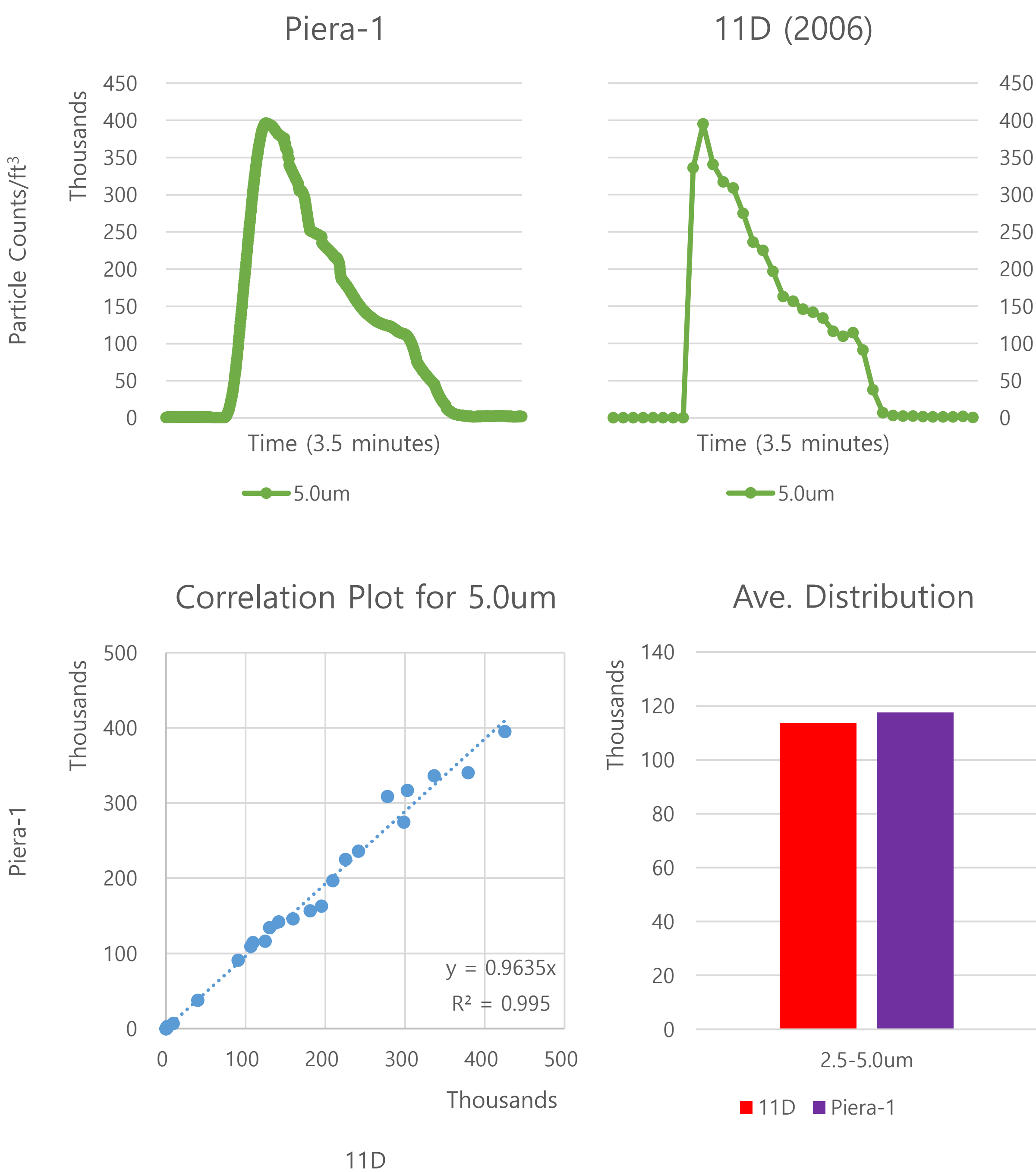


Figure 7. Differential particle count plots for 5.0um, from Piera-1, and 11D with correlation curve and average distribution.

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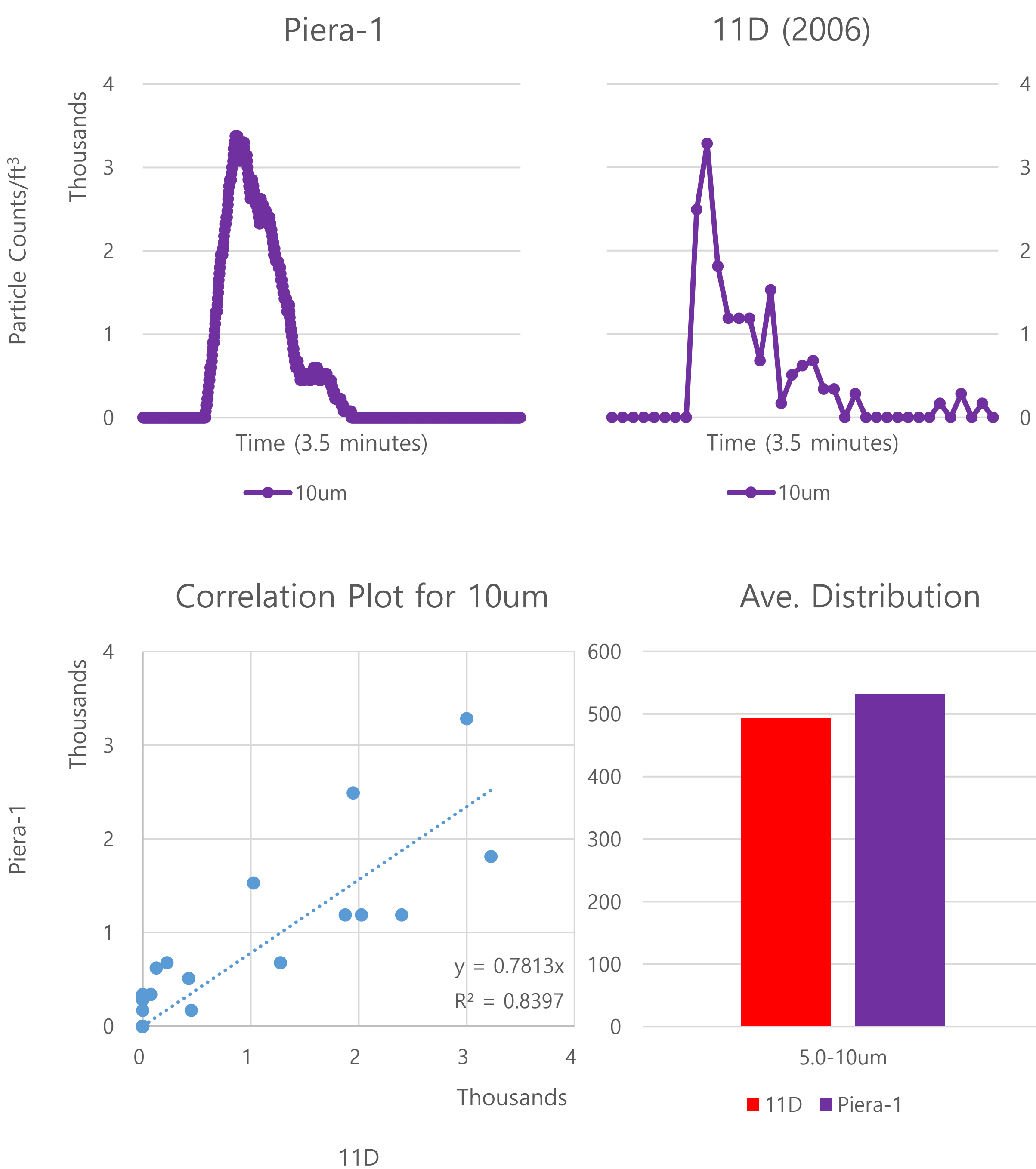


Figure 8. Differential particle count plots for 10um, from Piera-1, and 11D with correlation curve and average distribution.

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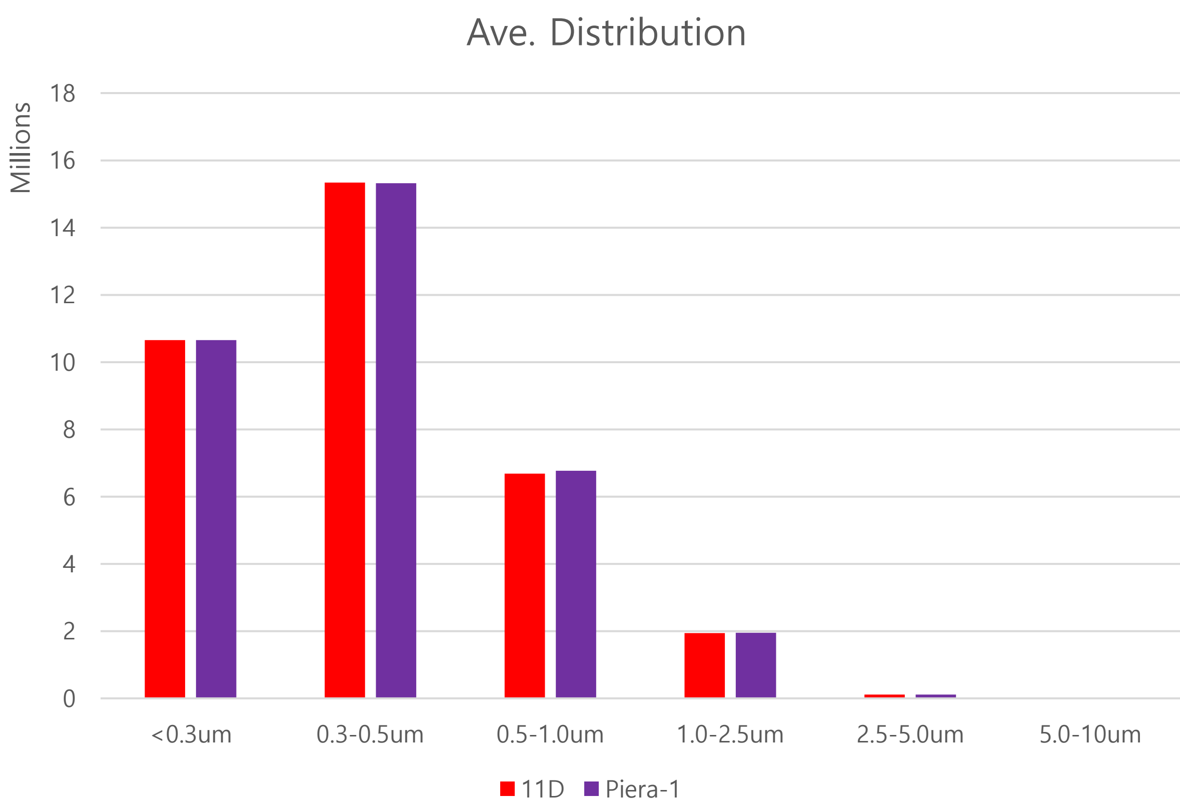


Figure 9. Average differential particle count histograms for all available bins from Piera-1, and 11D.

The result shows there exist very strong correlations ($R^2$ > 0.97 for particle sizes 0.3um – 5.0um, and $R^2$ > 0.83 for 10um) between Piera-1 and 11D data, indicating clear 1:1 correspondence. The absolute error is less than 4% for Piera-1 for all particle size bins except for 10um, which is ~8%. This is an expected result as the particle concentration was low at 10um region. Overall Piera-1's data trend pattern for each bin converges well onto 11D's corresponding bin as shown in the Figures 3 to 8.

Note that the above test result could vary depending on the type of test particles and test conditions.

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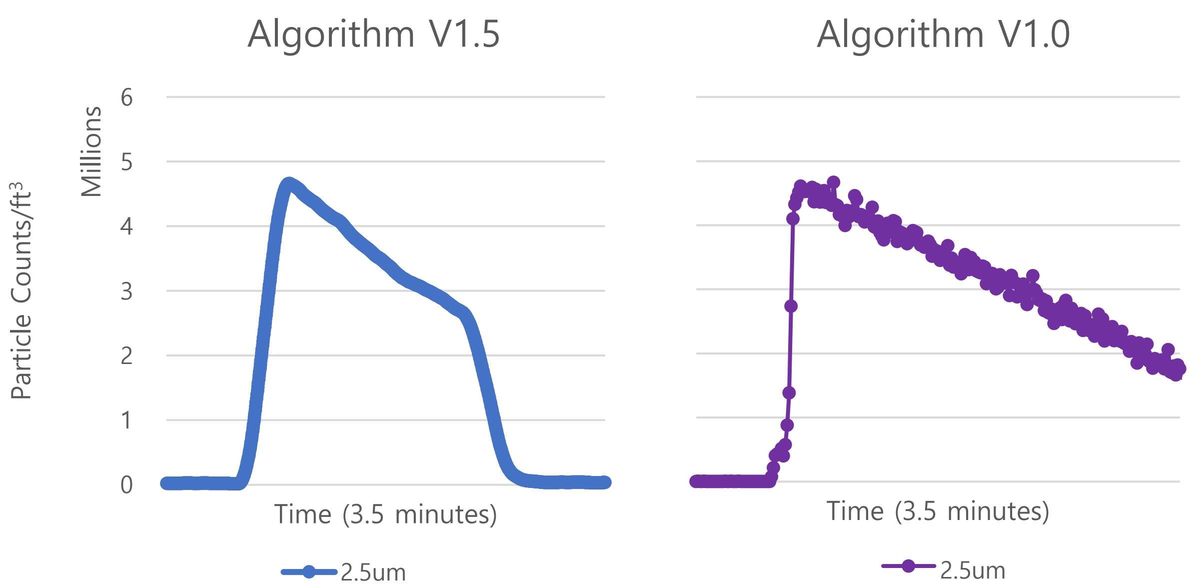


Figure 10. Updated algorithm to reduce the effect of Brownian motion.

The plots in Figure 10 show the difference between two Piera-1 units with different algorithm applied. The algorithm was updated to reduce the effect of Brownian motion, and resulting data is more stable without much fluctuations. Note that the data for Piera-1 with algorithm V1.5 and V1.0 was **not** obtained in the identical test settings. Intended only to illustrate the difference in data patterns over a similar particle count range for 2.5um particles.

The algorithm V1.5 adopted Piera-1 unit exhibits stronger correlation to the reference device ($R^2 > 0.97$ as opposed to $R^2 > 0.87$ for 2.5um particle size bin). The sensor's sensitivity to instantaneous changes in particle concentration is decreased compared to the previous version however, it can be compensated by adjusting the sampling time.

Obtaining mass concentration value from particle count number can be done and yet, requires several assumptions: the assumption 6 stated at the beginning of this paper, assuming that the fine particles take spherical shape, and that their chemical compositions have no significant contribution to their weights. Assuming each particle has the same density, the mass concentration can be calculated and estimated based on particle count data. Table 5 illustrates the difference between the optical and gravimetric method.

Any mass concentration data from any optical sensor should only be treated as an indicator, and it may not be accurate depending on the environment where the data was taken from.

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| | Optical Method | Gravimetric Method |
|---|---|---|
| **Particle Count** | Direct Measurement | Interpolated Estimation<br><br>Usually distinguishes only PM10 from PM2.5 based on pre-filtering before particle accumulation |
| **Mass Concentration** | Interpolated Estimation<br><br>Calculated from particle count number and assumed density of different sized particles | Direct Measurement |

Table 3. Comparison between optical and gravimetric method.

## Summary

Piera-1's particle analytic algorithm was updated to reduce the effect of random motion of particles, or Brownian motion to yield more stable data. This version of Piera-1 was calibrated with GRIMM 11D (model year 2006) particle counter in a controlled test condition using a dust spray that generates 0.1um to 10um sized aerosol particles. The evaluation revealed that Piera-1 is capable of detecting wide range of different sized particles (validated for 0.3um – 10um) with high accuracy with respect to 11D. Data plots also showed very strong correlation to 11D with high linearity in all tested conditions.

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