TSI AEROTRAK® PORTABLE PARTICLE COUNTER MODEL 9110

APPLICATION NOTE CC-107

Introduction

This purpose of this document is to detail the advanced, state of the art features TSI has incorporated in the design of the AeroTrak 9110 0.100 µm 1 CFM particle counter.

Measuring 0.100 µm airborne particles in clean spaces using optical scattering techniques is challenging. The amount of light scattered by 0.100 µm particles is very small. Ensuring that this signal is clear of any electronic noise is a key design requirement. 0.100 µm particles must be detected and counted efficiently; they must not be lost in electronic noise.

End users need an optical particle counter to have excellent size resolution in order that the sizing and counting of particles is consistent year after year. Calibration sizing errors due to poor size resolution are unacceptable.

Semiconductor cleanroom air is very clean and commonly very low levels of airborne particles are counted. When measuring the particulate cleanliness of the air it is unacceptable to end users that the measurement be confounded by false particle counts. The difference between good and poor performing instruments is their ability to differentiate between false counts and true particle count events.

Understanding the root cause of airborne particle contamination in a manufacturing environment is important to end users. Optical particle counters with a wide dynamic size range can help to provide important information to support this work.

With all good designs it is not one single feature, it is the combination of many advanced features that delivers excellence. The result is a reliable, easy to use instrument that is lightweight and delivers an excellent measurement in semiconductor applications.

What follows are details of innovative, state of the art techniques developed by TSI that build on 25 years of 0.100 µm particle detection technology in cleanroom applications.

State of the Art- Active Cavity Laser

Basic Optical Particle Counter technology has been around since the 1960s, and continues to evolve.

The AeroTrak 9110 portable particle counter deploys 633nm Helium-Neon or HeNe laser active cavity laser sensing technology. HeNe lasers from the 1990s are still in operation today, so they have a proven long life.

Just because laser diode technology is newer it does not mean that it is better. Laser diode based "0.100 µm" products are difficult and expensive to maintain, real laser diode lifetimes are unknown and unproven.

Typically only 1% of the laser power available in a HeNe laser ever makes it to the outside world. Active cavity simply means we are releasing the laser power that is locked up between the mirrors of a HeNe laser into the sensing area of the particle counter optics.

Active cavity HeNe laser based optics technology is over 25 years old. The optics technology deployed by TSI in the Model 9110 is based on this foundation. However, TSI has taken all the lessons learned over these years and completely redesigned the AeroTrak 9110 particle counter's optics, detectors and sensing electronics from the ground up.

The result is that airborne particles will be illuminated by laser cavity powers in excess of 40 Watts at a low wavelength of 633nm. The advantage of this combination is that it delivers at least 50X more scattered light than the same particle illuminated by a laser diode. This is the starting point for an excellent signal to noise ratio. It is not the whole story though, the side effect of high laser cavity power is a high background optical noise caused by molecules of air scattering light. How we overcome this steady state background optical noise is covered later in this document, for the moment we will continue to focus on the optics.

Figure 2 shows how historically two sets of Mangin mirrors were required to collect scattered light from the particle. Shown are two detectors which were needed in the past to facilitate a large dynamic size range and noise cancellation.

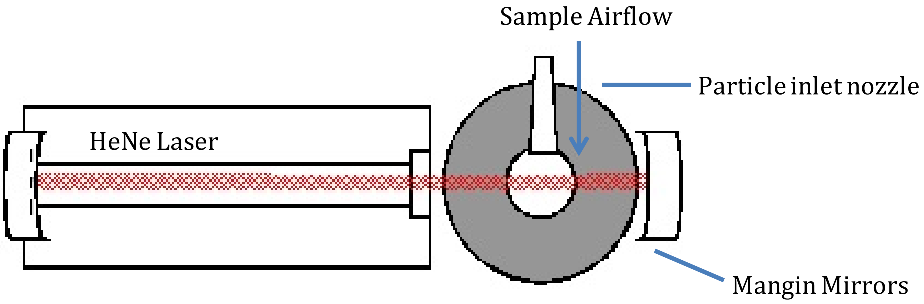


Fig 1. HeNe Active Cavity Optical Bench- Top View

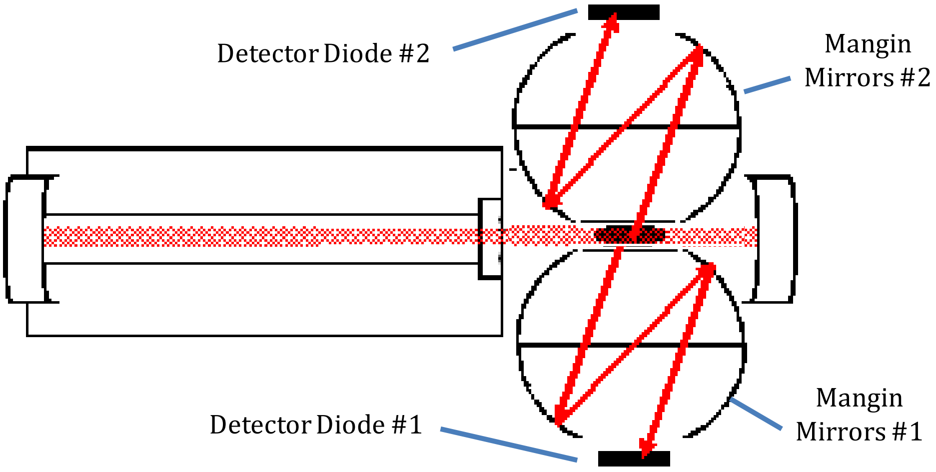


Fig 2. HeNe Active Cavity Optical Bench- Side View, (air flow is towards the reader)

In the past detector diode #2 handled sizing of ≥0.1 µm particles and detector diode #1 sizing of ≥0.2 µm particles. Twin detector systems as shown in figure 2 have been used to inhibit false counts from high energy particles. Typically, but not always exclusively, a high energy particle would be detected by only one of the detectors, not both, enabling the high energy or dark particle count to be rejected, more on this later.

The challenge with twin detector systems is that they are costly, and are complex to manufacture and maintain. Aligning both detectors and crisply focusing the part of the laser beam through which the particles travel onto both detectors simultaneously is difficult and time consuming.

Based on these lessons learned, TSI has redesigned the HeNe optical bench of the AeroTrak 9110 particle counter from the ground up. We have reduced the complexity and the number of components needed, see figure 3. There is only one set of Mangin mirrors and only one detector in the latest design. The Mangin mirrors collect scattered light over 80° and deliver excellent image quality to the detector.

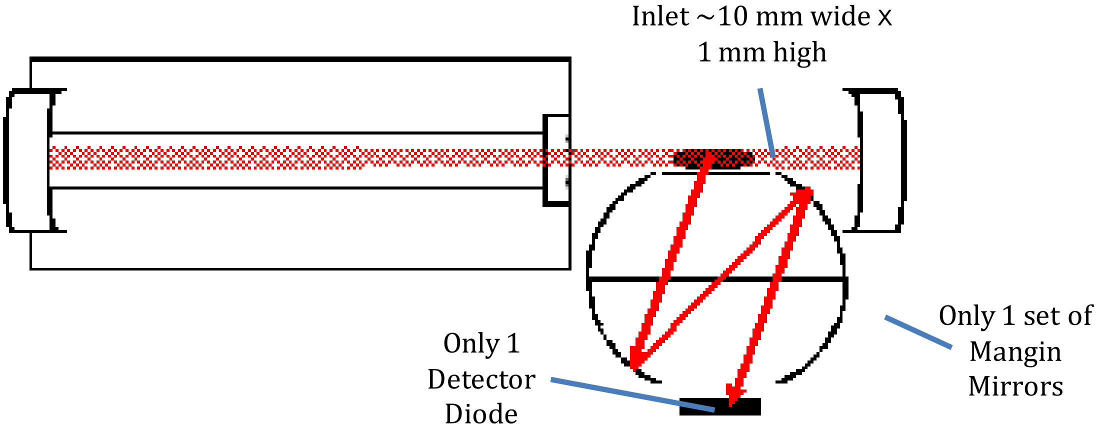


Fig 3. AeroTrak 9110 HeNe Active Cavity Optical Bench- Side View

The resulting improvement to particle image quality and optimal laser cavity power improves our signal to noise ratio and size resolution, enabling the Model 9110 to meet the requirements of the ISO 21501-4 calibration standard.

In recent years 0.100 µm instruments have claimed to be able to count and size 0.100 µm particles. The reality was that in fact the particles being used to calibrate these instruments were not exactly 0.100 µm in size, in some cases they were calibrated using 0.107 µm particles. At first glance this may not seem to be a big problem; we are talking about only 7nm here. However, examining the Rayleigh scattering curve in figure 4 below, it is clear that a 0.107 µm particle scatters 50% more light than a true 0.100 µm particle. This means that a 0.100 µm particle counter that only measures down to 0.107 µm will count ~13% less particles than a particle counter that actually measures down to 0.100 µm.

In order to meet ISO 21501-4 optical particle counter calibration standard the instrument must have a counting efficiency of 50% ± 20% at the first particle size threshold, 0.100 µm in this case. It was clear that a significant improvement was needed in optical power and signal to noise ratio to deliver the extra signal and performance needed to meet the ISO 21501-4 requirement. The good news is that the AeroTrak 9110 particle counter easily meets and exceeds this requirement, typically achieving a first size channel counting efficiency of 60%. See figure 5 for an oscilloscope screen shot showing a 0.100 µm calibration particle being detected.

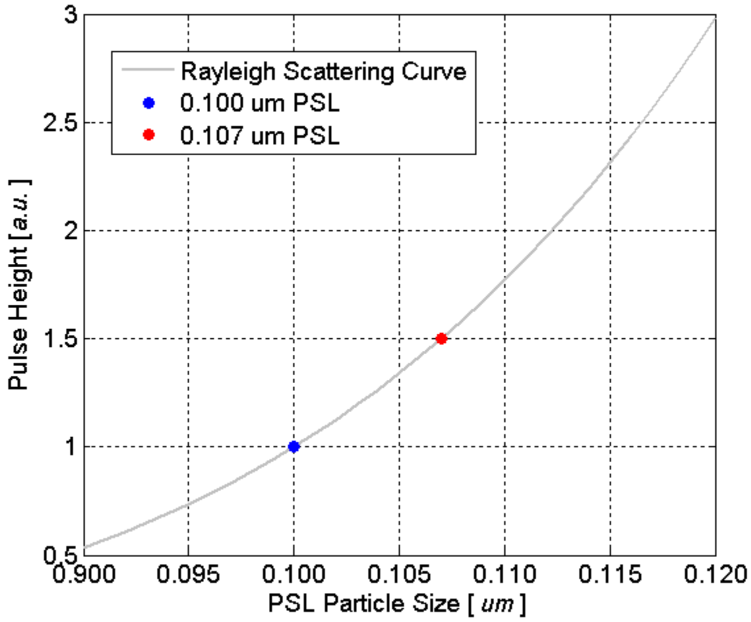


Fig 4. Rayleigh Scattering Curve or 0.100 and 0.107 µm Particles

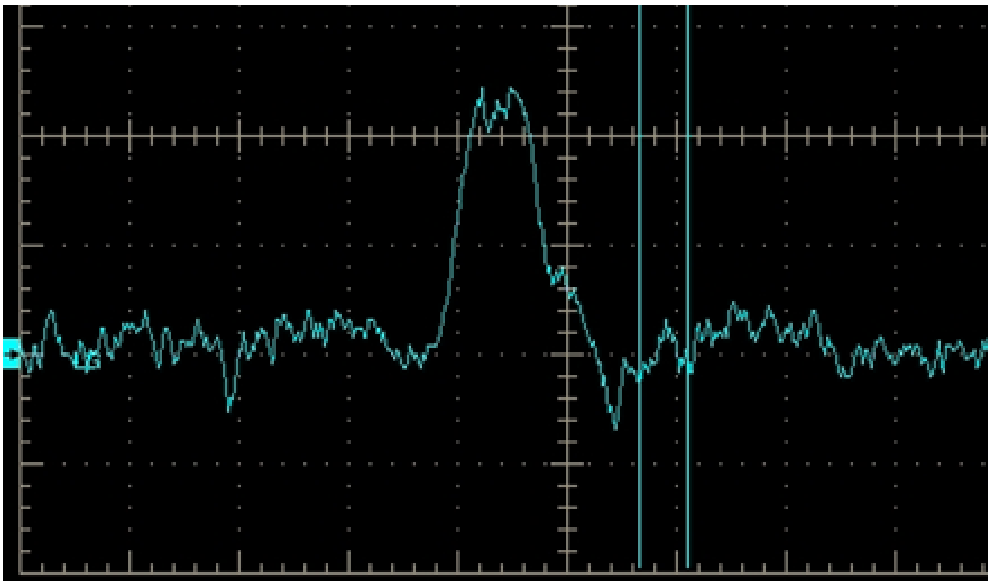


Fig 5. A typical 0.100 µm Particle Signal Pulse Taken from a Single Detector Element

An additional advantage of the excellent image quality onto the detector is excellent size resolution. The minimum requirement for size resolution per ISO 21501-4 is 15%, we regularly achieve ≤5% resolution @ 0.2 µm, easily exceeding the ISO 21501-4 requirement. Excellent size resolution means reduced size calibration errors when determining position of a peaking calibration particle during instrument calibration, leading to consistent year on year instrument calibration. Additionally, as a result of the excellent sizing resolution of the AeroTrak 9110, we are able to count and report particle size at 8 individual size thresholds across our measurement range. End users will now have more information about airborne particulate contamination in their environment.

The concentration limit of the AeroTrak 9110 particle counter per ISO 210501-4 is 100,000 c/ft^3 or 3,500,000 c/m^3 at a 10% coincidence level. This is the number of particles sampled by the instrument at which there is a 10% probability that there will be two particles present in the laser beam at the same time. A significant factor that influences this specification is the physical size of the laser beam. All optical particle counters assume that there is only ever one particle in the beam at any given moment in time. If two particles are present in the laser beam an optical particle counter cannot tell, it simply assumes that there is one particle and sizes the particle count event as one large particle, see figure 6.

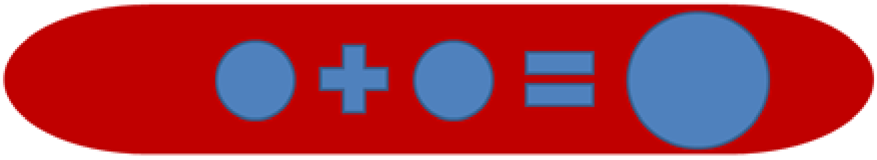


Fig 6 Particle coincidence, two particles in the laser beam

A concentration limit of 100,000 c/ft^3 or 3,500,000 c/m^{3}means that the AeroTrak 9110 particle counter easily meets the requirements per ISO 14644-1 ISO Class 6, see figure 7. For environments that contain large numbers of airborne particles, such as ISO 7-9, ISO 14644-1 guides end users towards more suitable instruments with a minimum sensitivity of 0.3-0.5 µm.

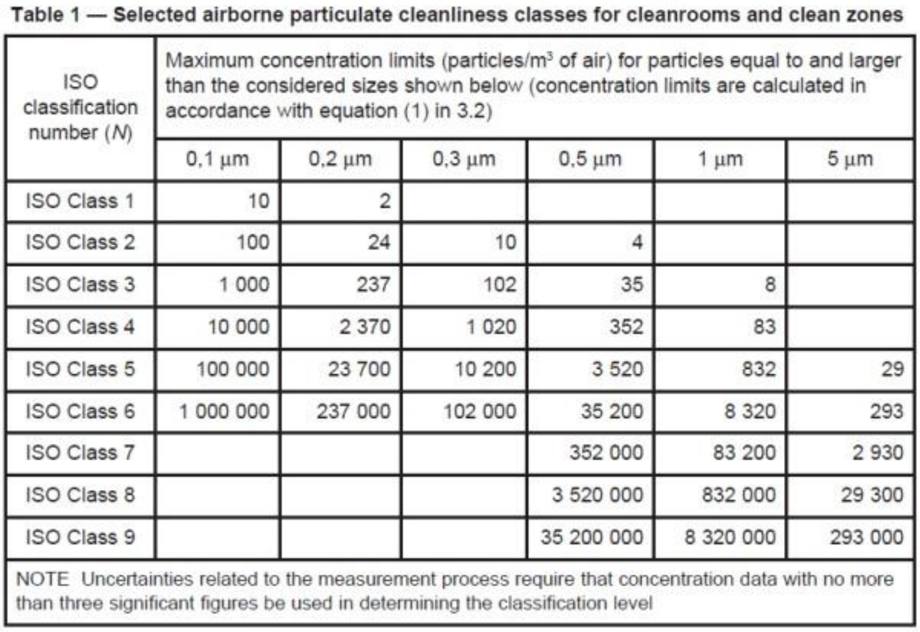


Table 1 — Selected airborne particulate cleanliness classes for cleanrooms and clean zones

ISO classification number (*N*)	Maximum concentration limits (particles/m^3 of air) for particles equal to and larger than the considered sizes shown below (concentration limits are calculated in accordance with equation (1) in 3.2)					
	0,1 µm	0,2 µm	0,3 µm	0,5 µm	1 µm	5 µm
ISO Class 1	10	2				
ISO Class 2	100	24	10	4		
ISO Class 3	1 000	237	102	35	8	
ISO Class 4	10 000	2 370	1 020	352	83	
ISO Class 5	100 000	23 700	10 200	3 520	832	29
ISO Class 6	1 000 000	237 000	102 000	35 200	8 320	293
ISO Class 7				352 000	83 200	2 930
ISO Class 8				3 520 000	832 000	29 300
ISO Class 9				35 200 000	8 320 000	293 000
NOTE Uncertainties related to the measurement process require that concentration data with no more than three significant figures be used in determining the classification level						

Fig 7. ISO 14644-1 1999 Airborne Particulate Cleanliness Classification Table

The most common cause of technical problems when using high sensitivity optical particle counters is optics contamination. Running a 0.100 µm optical particle counter in an environment where there are high levels of airborne particles will increase the risk of optics contamination. This is why TSI has ensured that the advanced HeNe optical bench can be easily cleaned on site if needed. There is no need to send the AeroTrak 9110 particle counter off site for cleaning.

In the next section we will detail other technical advances that have enabled TSI to use a single detector optical system in the AeroTrak 9110 particle counter.

State of the Art – Advanced Detector Diode

In the late 1980s detector diodes were developed that facilitated optical noise reduction. Up until then the part of the laser beam through which the particle travels was imaged onto a single detector diode. This image is rectangular in shape because the inlet nozzle of 0.1 µm 1CFM instrument is also rectangular in shape, ~ 1mm high by about ~10mm wide, see figure 3. The technical challenge was that the detector diode was viewing a very large area of a high cavity power laser beam. This meant that it was detecting a large amount of steady state scattered light, another name for this scattered light is optical noise. The result is that the small amount of light scattered by a 0.100 µm particle is masked or hidden by this background optical noise.

To overcome this problem detector diodes were developed that had many smaller elements. These are called Array detector diodes. Because each element is small it is only exposed to a small area of the laser beam thereby reducing background optical noise. The number of elements within the detector has advanced over the years. See Fig 8 below to see this evolution.

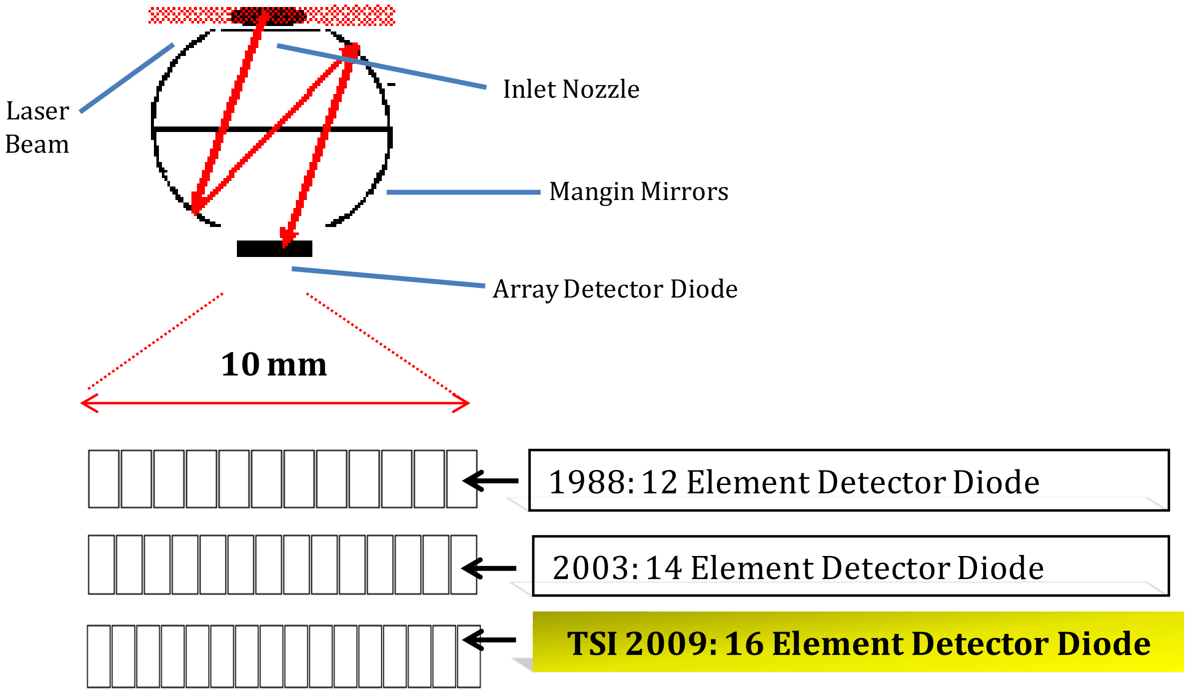


Fig 8. Detector Diode Evolution

The advantage of the TSI AeroTrak particle counter is that it utilizes a 16 element array detector diode, instead of having 1 detector we now have 16 very small detectors. This means we are getting a ~16X reduction in background optical noise resulting in very low detector electronic noise. The whole area of the laser beam through which the sample air flow passes is imaged onto the 16 element detector diode, see figure 9, and is another factor that leads to an excellent signal to noise ratio.

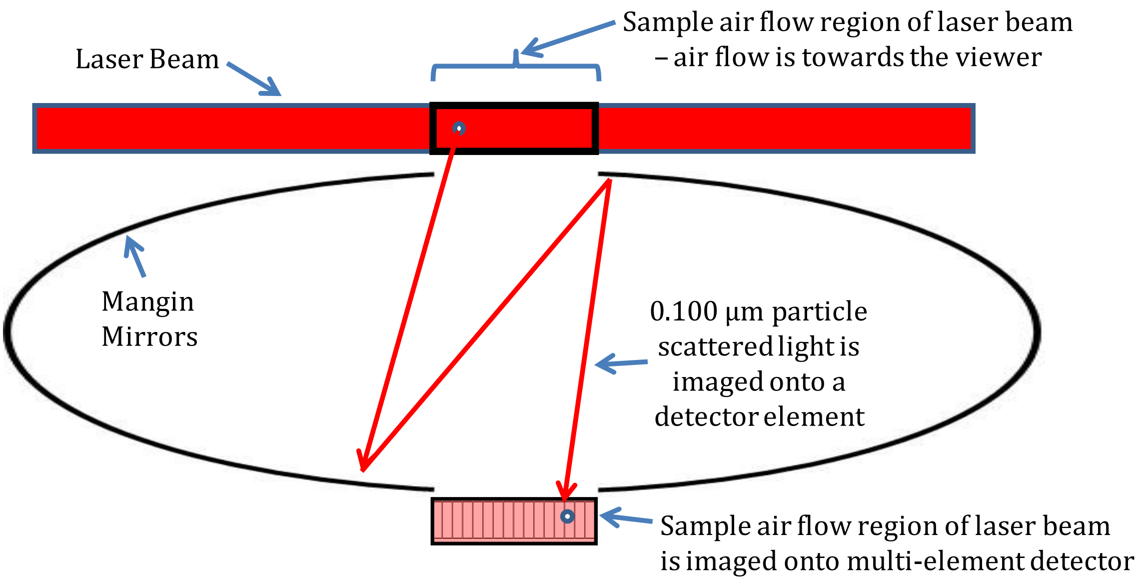


Fig 9. Laser Beam is sharply focused onto the Multi Element Detector

In order realize this optical noise reduction benefit each of the individual detector elements has to be processed individually. In the next section we are going to examine the important role of signal processing when counting 0.100 µm particles in air.

State of the Art – Signal Processing

We can process each array detector element individually to help us reduce electronic noise, and facilitate a wide dynamic size detection range. Signal processing technology and techniques have evolved over the last 25 years. It is this foundation of lessons learned, and what works best that have inspired us to develop and enhance signal processing methods to deliver an excellent measurement performance.

Interestingly, many patents have been generated over the last 25 years to facilitate optical and electronic noise reduction and thereby improve the signal to noise ratio, many of these are currently owned by TSI. However our new detector design and signal processing perform so well we do not even need to use this older intellectual property in the AeroTrak 9110 particle counter.

Electronic Noise Cancellation

High levels of electronic noise will severely impact a signal to noise ratio. As discussed earlier, electronic noise can be caused by optical noise inside the measurement optics, although this is not the only cause. Other components of this noise are inherent in the detector diode itself and the associated electronics. The optical signals are extremely small and the electronic amplifiers are needing to work hard to amplify them, and will be contributing towards electronic noise.

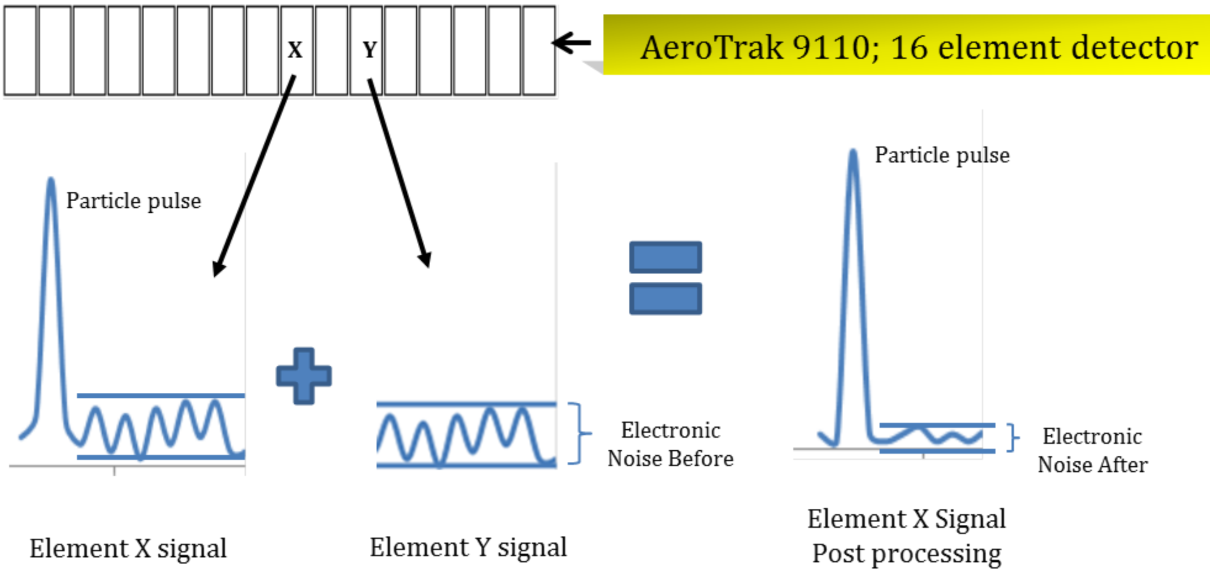


Fig 10. Electronic Noise Cancellation by Cross Feeding

To reduce electronic noise TSI takes individual element signals and Cross Feeds them with other elements, see figure 10. Cross Feed is a term used to describe the practice of combining two individual element signals to significantly reduce the electronic noise component of each signal. The technique of Cross Feeding individual elements is not new, what is new is that way we are doing this. We have taken a tried and tested foundational technique and improved it.

Because a very large amount of light is scattered from larger particles we can also choose not to use all the detector elements when sizing large particles. This means we do not saturate the detector electronics with huge amounts of scattered light signal when sizing large particles. This delivers an excellent sizing performance of 100:1 dynamic range from 0.100 µm through to 10 µm.

Analog to Digital Conversion

The analog signals from each individual detector are then converted to digital signals to allow us to perform a more complex analysis. This analysis will determine whether or not the particle is a true particle count or a false count due to high energy particles such as cosmic rays.

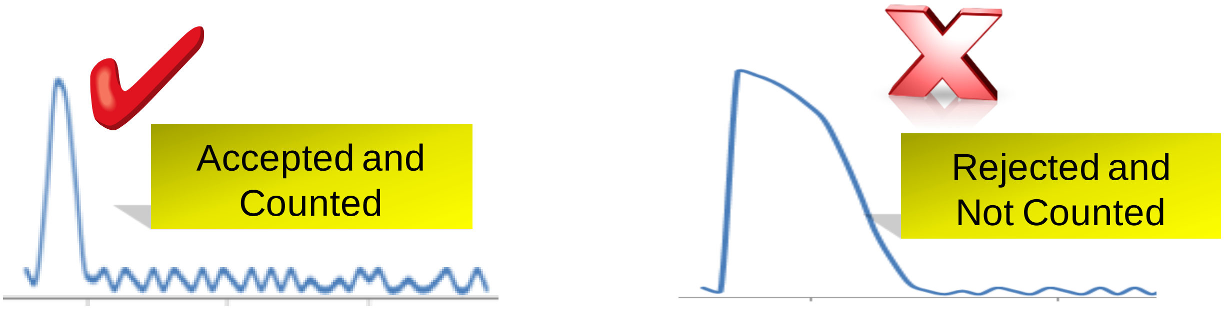
False or Dark Particles

The main sources of false or dark particle counts are typically Cosmic Rays. These are high energy particles that originate from outside the Solar System. When they pass through a solid state detector such as a photo-diode detector they will generate a pulse that could be counted as a real particle. The frequency of Cosmic Rays is not constant; they are influenced by Earth's magnetic field. The incidence of Cosmic Rays can vary depending on your location on the planet surface. The glass within the array detector itself can also be a source of dark particle counts due to radioactive decay,

Different approaches have been used in the past to prevent 0.100 µm 1 CFM optical particle counters from counting dark or false counts. One approach has been to use 2 physically separate detectors, see figure 2. This is based on the principle argument that the same Cosmic Ray is unlikely to pass through two physically separate detectors at the same time. Simply, if one of the detectors sees a pulse and the other does not then the "particle" is rejected and not counted.

Another approach used utilizes statistical filtering algorithms. This is an algorithm in the particle counter firmware that artificially subtracts particle counts over a period of time. It makes assumptions that dark counts occur at a typical frequency. The side effects of statistical filtering algorithms are more significant in very clean environments as they may eliminate significant percentage of actual particle counts, giving end users a false sense of security.

Because TSI has now digitized the signals within the AeroTrak 9110 particle counter we can perform some detailed analysis on the particle signals using a Field Programmable Gate Array or FPGA. These dark particles are high energy particles and so their signal characteristics are different from an airborne particle signals. We analyze the signal for many characteristics, rise time, transit time and shape, to determine if the signal is a result of airborne particulate contamination, see figure 11. TSI does not use statistical algorithms to reject dark particles and we do not use a second separate detector. We analyze each individual signal.



True Particle Signal

Cosmic Ray or High Energy Particle

Fig 11. Dark Particle Rejection using Field Programmable Gate Array FPGA

Conclusion

The TSI AeroTrak 9110 Particle Counter meets and significantly exceeds the ISO 21501-4 particle counter calibration standard. TSI has built on technological advances over the last 25 years and has used them as a solid foundation to develop new and innovative ideas. The result is a 21st century 0.100 µm particle optical counter that is easy to use and maintain, and delivers an accurate and reliable measurement each and every day.

UNDERSTANDING, ACCELERATED

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