SPECIFICATIONS / TECHNICAL DISCUSSION

Overview

3DATX Corporation develops and manufactures next generation emissions measurement technologies for the transportation and power generation markets. We manufacture a range of accurate, low-cost, and ultra-lightweight portable emissions measurement systems (PEMS) that make field testing, industry and academic research, and compliance screening practical on a mass scale.

The 3DATX parSYNC® iPEMS (integrated Portable Emissions Measurement System) and CA/GE™ (particulate calibrator & generator) equipment series provide an extensive utility and range of applications in the developing requirements of Real Driving Emissions (RDE).

The lightweight (4kg) parSYNC® utilizes multiple miniaturized sensors, packaged in patented, replaceable cartridges, designed to obtain real-time particulate matter and particulate number (PM/PN) performance data from both diesel and gasoline engines.

The advanced parSYNC® PLUS RDE unit, in addition to particulate measurement, also incorporates a removable GasMOD™ Sensor Cartridge for NO, NO2, CO, CO2, etc.

Most importantly, parSYNC® comes with a user-friendly software suite. The Graphic User Interface (GUI) has been designed to be intuitive – significantly reducing field training time. Post-processing data software helps to eliminate many of the bottlenecks associated with teasing out meaningful data from the numbers.

Next Generation: iPEMS

3DATX has developed the iPEMS self-contained solution platform. IPEMS is a class of equipment weighing less than 5kg – including power supply, and having the ability – at a minimum – to measure Particulates, NO, NO2 and CO2, with other Greenhouse Gas (GHG) and Criteria Pollutants as option-able. Our instrumentation is designed to be referenced against a traditional 1065 PEMS as well as traditional laboratory protocols. It provides a single technician or operator with the ability to hand-carry a device through airport security and into the field, to deploy and test within an hour of arrival to the test site, and to pack up and travel home within an hour of finishing the last test. A significant advantage of the 3DATX iPEMS design is the Modular Sensor Cartridge design.

Modular Sensor Cartridge Advantage: Particulates and Gases

The **3DATX parSYNC® PLUS** unit builds upon our core platform by incorporating both the Particulates (PM/PN) Sensor Cartridge offered in the parSYNC® and replaceable gaseous module (GasMOD™) cartridge combinations (e.g. NO/NO2/CO2, NOx/CO2/CO, etc.) to obtain gaseous data from all types of internal combustion engines. The small, easily replaceable Cartridges allow for field units to remain field deployed for continuous testing, re-calibration, and virtually limitless emissions data acquisition.

• Particulate Measurements - (PM/PN Cartridge)

The parSYNC® measures undiluted emissions using the response of three dissimilar particulate sensors. The sensors are sensitive to different histogram particle size fractions:

Sensor	Greatest Sensitivity
Ionization	Ultra-fine/Fine particulates, typically 0.01 to 1 micron
Opacity	Overall particulates, typically 0.1 to 10+ microns, peak@0.8microns
Scattering	Coarse particulates, typically 0.3 to 10+ microns, peak@3.5microns

Note that although their particulate size sensitivities overlap, their optimal particle size and concentration responsiveness is different between sensors. Thus, particle mass concentration and number can be extrapolated based on the evaluation of sensor modality and empirical references.

Multi-plex post-processing maps matched up with engine failure response modes may also enable prediction for engine trouble diagnostic/failed DPF applications.

• Gaseous Concentration Measurement Sensors (GasMOD™ Cartridge)

Nitric Oxide (NO) - 3-electrode electro-chemical

- *Linear Measurement Range: 0-5,000 ppm NO*
- *Filter: Remove effect of SO2 in gas stream*
- *Sensitivity: 0.05 ± 0.01 µA/ppm*
- *Response Time: <5 Seconds T90*
- *Baseline Offset (clean air): 0 to +12 ppm equivalent*
- *Zero Shift (0°C to 40°C): <30 ppm* *Operating Range: -20°C to 50°C*
- *Resolution: 1-2 ppm*
- *Repeatability: 2% of signal*

Nitrogen Dioxide (NO2) - 3-electrode electro-chemical

- *Linear Measurement Range: 0-300 ppm NO2*
- *Response Time: <15 Seconds T90*
- *Resolution: 0.1 ppm*
- *Zero Shift: <0.2 ppm equivalent* *Operating Range: -20°C to 50°C*
- *Repeatability: 2% of signal*
- *Linearity: Linear*

Non-dispersive Infrared Spectrometer (NDIR) – CO2, CO

Solid-state detector

Response Time: <3 Seconds
Operating Range: 0°C to 50°C

NDIR Carbon Dioxide (CO2)

Measurement Range: 0-20%
Accuracy: ±0.3% absolute or ±3% relative
Repeatability: ±0.1% absolute or ±2% relative

NDIR Carbon Monoxide (CO)

Measurement Range: 0-15%
Accuracy: ±0.02% absolute or ±3% relative
Repeatability: ±0.02% absolute or ±2% relative

TECHNICAL MEMORANDUM

The parSYNC® directly samples 2.5Liters/min from the engine exhaust, there is no dilution and thereby no extrapolation of sensor values to full concentration. Thus, the small lightweight device can be comparably responsive and accurate to a large PEMS device.

Moreover, the physics and chemistry are fundamentally identical to larger instrumentation. All the sensors behave in roughly the same fashion, regardless of size, shape, orientation, and composition (as large platforms). The only effective differences are relative accuracy, required volume, and responsiveness of the system. Therefore, from a scientific perspective, the small, inexpensive sensors can be comparably accurate with proper signal conditioning.

If the size of the device is potentially irrelevant to the overall accuracy of the device, what comparisons can we draw? The smaller design enforces a direct measurement of the exhaust gases and particles that does not happen with the current larger machines – the larger machines use dilutions, into which the incoming air mixes before analysis. Hence, we can expect that the direct measurement is more volatile, noisier, and more sensitive to external conditions; meanwhile, the indirect measurement smooths out the data, tends to be less sensitive to exterior conditions and minor variations in the reading – but genuinely useful, if transitory, sharp variations in output will be attenuated. (cf. parSYNC® versus DMM-3063 output.)

From a practical viewpoint, the more compact device permits greater flexibility in testing of multiple vehicles numerous times under real driving conditions which are very difficult with even the best large emissions testing devices (population statistics versus individual statistics). The portable device is only limited by the endurance of the user and the stability of its parts. Its compact size allows even critical parts to be replaced comparatively at will, whether they were dirty, broken, or just misbehaving.

Despite its size, parSYNC® also has sensors for the standard reaction products NO, NO_2, CO_2 and CO used by similar machines. Our measurements have shown similar behavior to more complex and expensive devices under identical conditions. (EEPS, Dekati, etc.)

The inclusion of the opacity, scattering, and ionization sensors in parSYNC® requires a greater explanation. **There are no other iPEMS devices that track all of these measurements simultaneously**. Thus, an obvious question to ask would be why parSYNC® has all three.

One reason for their inclusion is that they have been used individually in comparable situations. Note that although these functions are similar, each sensor reacts to different types of sizes of particles in identical situations. Their inclusion in a multi-sensor view allows parSYNC® to perceive changes in the distribution of the sizes of the particles.

This is important because, as documented in various papers, most PEMS devices compute particle number from particle mass by assuming that the particles are approximately uniform in size. This would be correct if we could assume that the engine's behavior is essentially uniform throughout its usage. However, the engines run in varying gears for various speeds under a variety of conditions and particulate filters. As parSYNC® evolves, we add functionality to draw greater inferences on the distribution of particles sizes from their combined output using reference data from the literature and laboratory dynamometer studies.

The parSYNC® device uses three different types of sensors to determine particle mass and particle number. Each sensor is sensitive to different ranges of particle sizes and can measure the particle throughput in real-time.

<u>Opacity</u>

Opacity, also known as extinction, is governed by the Lambert-Beer law. Measuring obstruction and diffusion, the greater the number of particles per unit volume and/or the greater the average size of the particles, the higher the opacity. More precisely,

Lambert-Beer opacity: $O = 1 - \exp(-n*a*q*l)$
n = number of particles per unit volume
a = mean projected area (a.k.a. attenuation cross-section or effective cross-sectional area)
q = particle extinction coefficient
l = path length of beam through the sample (technically, the length of effluent path)

The particle extinction coefficient varies versus wavelength and particle size. These numbers have been determined experimentally at different wavelengths for different particles. The standard wavelength of typical opacity sensors is in the green range, and parSYNC® follows suit by using gel filters. Opacity is measured by the change in the current within the circuit that the opacity meter resides.

There are known limitations with using green light, such as the cross-sensitivity to NO_2. However, merely changing the color will require other trade-offs; for example, red light is less sensitive to smaller particles and ultra-violet light is sensitive to methane.

The Lambert-Beer law applies over a wide range of concentrations and particles and thus is useful to get an overall picture of the particle mass flow. Thus, opacity sensors have a high sensitivity to changes in this range. However, opacity sensors are known to be less accurate when there is a lot of light scattering within the sample and when the particles are very small. To counter these issues, parSYNC® has included a scattering sensor (sensitive to larger particles and when large amounts of scattering occur) plus an ionization sensor (sensitive to ultra-fine particles).

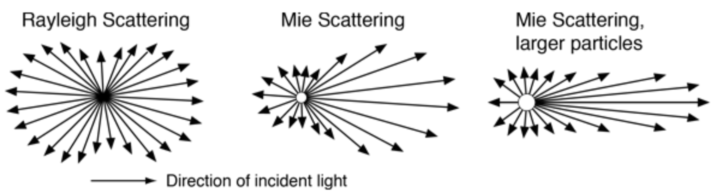
<u>Scattering</u>

A greater number of particles will result in a greater amount of scattering; different sized particles along with greater number of particles will affect the scattering profile, which in turn varies by angle.

For non-absorbing particles, a long derivation gives the following complicated formula for scattering sensor's response to the incoming light for Rayleigh scattering:

$I / I_0 = (\pi^4 / 8) * ((n^2 - 1) / (n^2 + 2))^2 * (D^6 / (r^2 * \lambda^4)) * (1 + \cos^2\theta)$
n = index of refraction
D = particle diameter
r = distance of particle from light source
λ = wavelength of incident light
θ = scattering angle

Experimental data show that for comparatively uniform particle geometry and particle mass, the mass concentration versus scattering is log-linear in the Rayleigh region. Hence, the electronics within a scattering sensor can convert its readings to a usable output. It is well-known that the scattering sensors are most sensitive with larger particles, as you might expect from the 6th power on the D factor in the above formula.



For large particles, we are in the geometric scattering region. The equation is modelled with an inhomogeneous wave equation with dissipation, as in:

https://omlc.org/software/mie/maetzlermie/Maetzler2002.pdf
http://www.thermopedia.com/content/158/
https://cims.nyu.edu/~corona/hw/nlgonotes.pdf

$u_{tt} - \Delta u - r^2 u = f(x, t)$

with the appropriate initial and boundary conditions. This has known closed-form fundamental solutions of the form

$e^{kx} (A(x, t) \cos(\omega t) + C(x, t) \sin(\omega t))$

where k is the spatial decay constant and ω is the frequency of the light source. This equation applies for large particles in the geometric scattering region.

(Note: Because of the dependencies on both angle and wavelength, varied incident angles and wavelengths can provide even more of a complete picture of the distribution.)

To complete the picture for the particle size distribution, parSYNC® also incorporates an ionization sensor.

Ionization

Ionization sensors are far more sensitive to ultra-fine particulates than opacity and scattering sensors. Ionization sensors have been an important part of emission analyses (see diffusion charging sensors).

If we assume that the particles in the air are of uniform size, then the diffusion motion of ions are shown to have a linear response to the particle surface area concentration detected in the sample. If not, then an approximation typically is be made over the range of particle sizes; typically, the models and experimental data show that particles' sizes would be in a log-normal distribution. For ease of use, virtually all ionization sensors have compensators to make their response linearly proportional to the particle size.

Specifically, the following system of equations govern the detector response:

Define $\Delta I = I_1 - I_0$
Where I_0 = original current in the detector
And I_1 = measured current in the detector

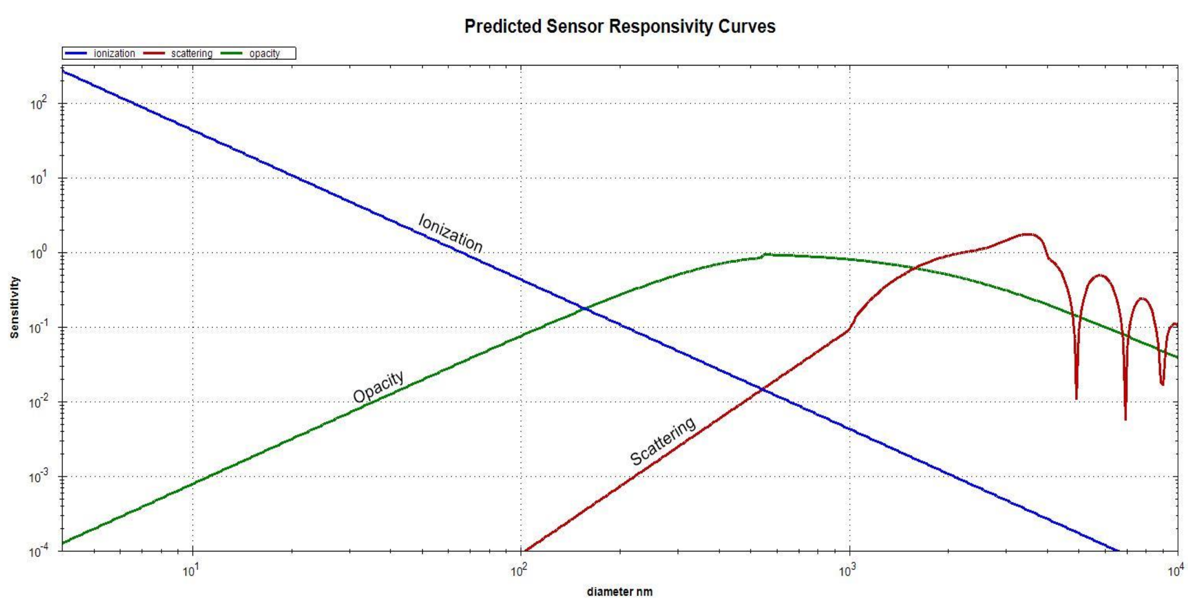
Define $x = \Delta I / I_0$
Where ΔI and I_0 are defined above

Define $N_t = f_v / (18.62 * r_m^2)$
Where N_t = total number of particles passing through the chamber
And rm = mean particle radius

Then $y = x * (2 - x) / (1 - x)$
And $y = k * N_t * rm$
Where y = detector response
And k = constant (determined empirically)

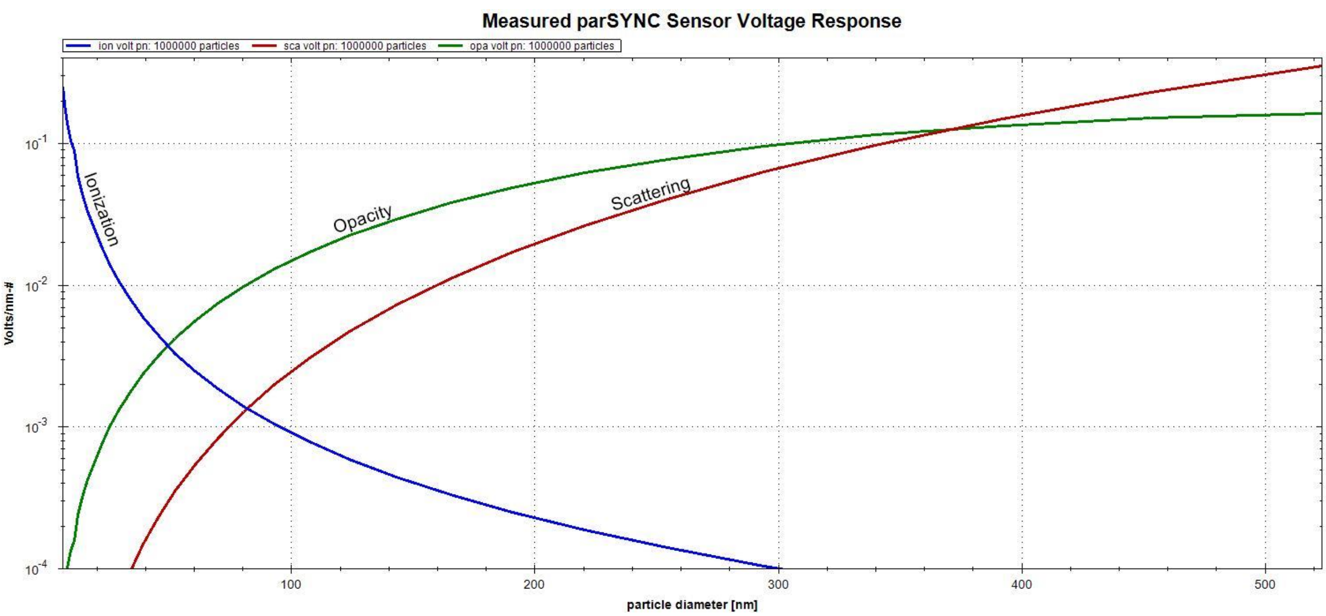
When we plot the theoretical/mathematical responses of the three sensor types against particle diameter in one graph (re-scaled each response to illustrate them all on the same graph, we get relative sensitivities as shown in the next figure.

Note: Wavelengths (and angles) of incident light used in the illustrated calculations match the 3DATX current sensors.



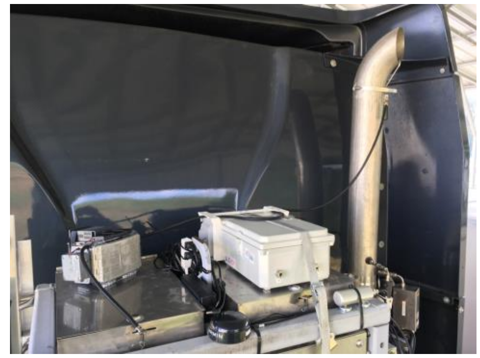
Note that each sensor type has a different peak sensitivity to particle size in identical situations. The Opacity sensor has a peak in the 0.8 micron diameter range (800nm) and Scattering sensor peaks in the 3.5 micron diameter range. The parSYNC® can perceive changes in the distribution of the size of the particles by using this physical property. These results have been quantified in the literature and in measured laboratory test.

Evaluating the response of the parSYNC® sensors in a laboratory FTP-75 dynamometer test cycle yields measured response characteristics that closely follows the theoretical responsivity. For example, a specific test of a light-duty diesel vehicle (with DPF) yields data below utilizing a TSI EEPS-3090 as a laboratory spectrometer reference was completed. When characterizing the measured voltage response of the sensors to the ultra-fine particles, an illustrated log-linear graph below was determined from laboratory data measuring up to 520 nm diameter.



C.U.B.E. – (Condensate Unit for Batch Emissions) Chiller/Water Trap (Sample Conditioner)

This sample conditioner/Water Trap weighs 1.5kg. The water trap collects condensation that forms within the tailpipe sample line and utilizes the Peltier "thermoelectric cooling" effect to create an additional condensation event to remove an additional amount of water vapor prior to entering the parSYNC® (where the sample exhaust is re-heated). The chiller method utilizes a significantly lower amount of energy compared to traditional heated sample lines (which attempt to keep all water in a gaseous form).



The unit ensures that water condensation does not occur within the sensors optics for the best instrument functionality. Furthermore, ongoing tests have demonstrated that the degradation of removed particulate is an insignificant amount that can be accounted for in final data output via software.