WHITE PAPER

Particle Synchronization Number (PSN) for the Next Generation I/M Program

Mr. Andrew Burnette, Dr. Karl Ropkins, and Mr. David Miller

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1. Brief Introduction: PM measurement for Inspection/Maintenance (I/M) program

1.1. CARB roadside I/M – the California Air Resources Board (CARB) Heavy-Duty Diesel (HDD) Vehicle Inspection Program was established in 1990 to regulate excessive particulates from HDD vehicles and was last updated in 2013. From the beginning, the pass/fail cut-points needed to consider the inherent variability of HDD emissions.

1.2. CARB conducted a pilot study in 1989 where they measured the exhaust opacity of many diesel vehicles and determined which of them had repairable malfunctions. They then determined opacity levels that would maximize "true fails" (i.e. a malfunctioning vehicle with a high test reading) while minimizing "false fails" (i.e., an engine without malfunction that had an unusually high reading for some random reason).

1.3. As is the case for all I/M programs, the resulting pass/fail cut-points are somewhat less strict than the new vehicle emissions standards, but they are more enforceable because if a vehicle fails the test, CARB is confident there is a malfunction which when fixed will lead to reduced emissions.

1.3.1. Current tests and methods (Opacity) – Most I/M smoke tests are based solely on measuring the opacity of the exhaust while the engine is revved in a controlled way, as described in the SAE J1667 protocol [www.arb.ca.gov/enf/hdvip/saej1667.pdf]. When this testing method was first introduced it was effective because opacity provided a good measure of the larger, courser, visibly opaque particulate material that then dominated exhaust smoke emissions. Three advantages of the opacity test are that: (1) it can be conducted easily on the side of the roadway; (2) it is possible using relatively inexpensive equipment; and (3) it's accuracy can be easily confirmed using an optical filter with a known opacity level.

1.3.2. Current tests and methods (Filter Smoke Number) – A few I/M smoke tests in Asia and Europe use a test based upon the aethalometer method. This method draws a sample through a white filter paper, then measures how dark the remaining stain is as compared to the unstained paper by reflecting and detecting light from the filter paper surface. Several relative indices of the darkness of the particulate stain have been developed for use in I/M programs, with the Filter Smoke Number (ISO/FDIS-10054) being the most prevalent. Although aethalometers are slightly more complicated than opacity meters, they too can be used roadside and can be easily calibrated or checked for accuracy.

2. Shortcomings of current tests and methods

2.1. Recent improvements to vehicle engine management systems and exhaust particulate emissions control systems have both reduced the amount of particulate emitted by vehicles and the size ranges it is typically emitted in -- even when those control systems are not functioning as they should. The opacity measurement is not sensitive to the smaller amounts of finer material that modern vehicles can emit when the particulate control system has been partially compromised, such as when small cracks form in the particulate filter. The Filter Smoke Number measurement can be more sensitive than the opacity measurement, but it is not sensitive to portions of smoke that are not black, such as liquid aerosols formed by organic carbon. As a result, a faulty modern vehicle can emit *relatively* large amounts of particulates, often well above regulatory limits, but still pass an opacity or Filter Smoke Number test because the particulate it is producing is too fine or light to be detected by a single method. Therefore, a new technology, that is relatively inexpensive, easy to use on the roadside and has a calibration standard, is required in order to meet the next generation of CA roadside requirements.

3. Overview of the parSYNC® iPEMS

3.1. Integrated Portable Emissions Measurement System (iPEMS) – the parSYNC® Unit provides a real-world emissions measurement system that is affordable, ultra-portable, and easy to use/maintain for field testing. The dimensions are 27cm h x 22cm w x 13cm d (10.6" x 8.7" x 5.1"), weight is 3.3 kg (7.3 lbs), and the unit is powered by a 10-volt Lithium Ion Battery for up to eight hours of continuous run-time.

3.2. The parSYNC® Unit

3.3. The small size and light weight allow for jobsite simplicity, low power consumption translates into testing reliability, and a rugged, watertight, weather proof construction ensures an increased "MTBF" (Mean Time Between Failures). The parSYNC® includes wireless duplex communication with a Windows touch-enabled tablet running fully automated LabVIEW®-based control and visualization software.

3.4. The PM/PN multiplex approach (3+ sensors) – the 3DATX iPEMS intellectual property and patent(s) for Particulate Matter/Number (PM/PN) utilizes a miniaturized multi-chamber and replaceable "Sensor Cartridge" design to obtain second-by-second PM/PN data in either a dedicated, "pass/fail" lane-testing configuration, or a field unit PEMS/PAMS approach. The use of a "Compound Sensing Technique" (e.g. Opacity, Scattering, Ionization) ensures that multiple, dissimilar sensors provide a unique sensing perspective while helping to “cancel-out” some of the sensors’ specific weaknesses. Each sensing technique uses a different approach and has a different bias with the PM/PN that is being sensed and recorded. Unlike some regulated pollutants such as carbon monoxide, PM/PN is not one chemical species. The exact constitution of emission PM/PN includes complex structures, such as a solid phase carbon particle with liquid phase hydrocarbons attached to its surface, and both of these phases can incorporate, ad/absorb numerous species. Furthermore, PM/PN exists in a wide range of sizes, and health concerns have been associated with PM/PN of aerodynamic diameter from 10 micrometers to less than 100 nanometers. Any one measurement technique will provide results that are biased by the type of PM/PN the measurement technique is most sensitive to, and no one measurement technique can be sensitive to the complete range of PM/PN chemical and physical structures. Thus, PM/PN, by its very nature, cannot be fully characterized by any one sensing technique, however accurate it may be. Therefore, the compound surrogate capabilities of the 3DATX 3+ sensors provide unique benefits of PM/PN Sizing, “Future proofing" (utilizing multiple methods in the present, so as to redefine and recalculate results in the future, based upon potential changes in methodology acceptance) and other significant data presently not recorded by traditional methods.

3.5. Calibration capability – in order to be used in a federal, state, or local I/M program, it is critical that multiple field units are able to be calibrated or compared to a reliable, external standard. Otherwise, their data would be seen by the regulated public as unreliable and could not be defended in court. Therefore, a benchmarking system, called the CA/GE™ System (particulate calibrator and generator), has been designed by 3DATX to ensure that multiple parSYNC® Units have been properly calibrated to an exact, predefined tolerance so as to ensure that in-use emissions standards can be accurately enforced and any fines or other legal actions are justified and defensible. Also, the continued accurate operation of parSYNC® Units can be easily confirmed in the field using the CA/GE™ System.

4. Proposed solution: the Particle Synchronization Number (PSN)

4.1. Theory – The multiplex parSYNC® outputs described above are combined using a fit algorithm that maps the three+ sensor outputs onto a conventional instrument output. The fit model typically has the form:

$$CONC = f(V_{S,t=-1}, V_{S,t=0}, V_{S,t=+1}) + f(V_{I,t=-1}, V_{I,t=0}, V_{I,t=+1}) + f(V_{O,t=-1}, V_{O,t=0}, V_{O,t=+1}) \qquad (E.1)$$

Where CONC is the output of the reference method; V_S, V_I, and V_O, are the light scattering, ionization, and opacity sensor response voltage outputs from the parSYNC®, t=-1, 0, and +1 are the sampling time increments relative to the measurement point, and f(…) is the fitting term.

This procedure is currently carried out off-line as a post-processing step, using a procedure similar to the end-of-run processing step many commercial PEMS systems employ to align exhaust gas concentration and flow rate measurements when calculating second-by-second mass emissions. The step provides a significant improvement in measurement accuracy and typically generates reference measurement agreements of the order of 95%. While highly accurate, using this approach alone does hinder users that would like to follow PM/PN trends in real-time as only raw sensor voltages would be available in real-time. Therefore, **Particle Synchronization Number (PSN)** has been introduced as a real-time diagnostic.

PSN for the parSYNC® is analogous to Filter Smoke Number for the aethalometer (described above). It is a relative index by which one can take the abstract measurement output and express it in simple and understandable form. Thus, it is the parSYNC® output to be used for measurements that require simplicity, such as I/M testing. It takes the form:

$$PSN = f(V_{S,t=0}) + f(V_{I,t=0}) + f(V_{O,t=0}) \tag{E.2}$$

Where PSN is calculated based on only instantaneous sensor outputs, and the f(...) terms are linear, so it further simplifies to:

$$PSN = C_b + (C_S * V_S) + (C_I * V_I) + (C_O * V_O) \tag{E.3}$$

Where C_b is a baseline correction term, and C_S, C_I, and C_O are constants used to scale light scattering, ionization, and opacity sensor outputs, respectively.

The accuracy of the instantaneous PSN model (*E.3*) is typically over 80% (as compared to various reference methods) and it is available to users as a real-time diagnostic. The end-of-run data and reports are based on the higher accuracy (90-98%) of the multiplex model *(E.1*)

4.2. Advantages over existing methods – In the case of I/M programs, a single PSN cut-point could be determined (through a pilot program) that would minimize false-failures, ensuring that any vehicle which failed the inspection would indeed have a malfunction whose repair would result in emissions reductions. The combination of PSN and an optimized off-line measurement provides a highly flexible toolset. PSN provides a real-time feedback which allows the user to quickly gauge vehicle performance and decide if that vehicle is a clean pass, definite fail, or a borderline case. The user can decide if they want to just post-process and report using the more accurate off-line calibration methods, rerun the test, or run further diagnostics, for example using the ternary plots to investigate PM distributions and possibly even characterize the nature of any emission issues.

4.3. Limitations – Currently, only PSN is available in real-time. Ideally, optimized outputs would also be available in real-time, and a diagnostic like the ternary plot would be integrated into an expert/wizard system so the user/vehicle tester is guided through the fault identification process.

5. Future direction: expansion of the PSN ecosystem

5.1. In its current form, the parSYNC® satisfies criteria for use in an I/M program and as a research tool. However, we can already envision future upgrades which will further leverage the advantage of the multiple, simultaneous measurements of PM. Naturally, with the collection of more data from I/M and research, the off-line fitting models will be incrementally made more robust. Also, we expect to refine the software so that what is now done during post-processing could be done in real-time. Finally, we envision innovations based upon the unique "view" of PM emissions provided by the parSYNC® instrument. For example, since the parSYNC® provides a "multi-dimensional" measurement of PM, it may be possible to relate the responses of each sensor to a given type of emissions control system malfunction. Given that capability, it would be possible to work with garages to create a “faulty vehicle” PSN database and expert system repair diagnostics that use the measurement itself to diagnose the malfunction that is causing the excess emissions.

5.2. A Statewide/National PSN troubleshooting database from vehicles with previously diagnosed PM emission issues could be developed. Current measurement results can be ‘matched’ with the database to provide a more simple yet descriptive and accurate pass/fail judgement to a diagnostic system to rapidly identify productive repair options. Example:

> A diesel vehicle is tested, fails, and the cut-off results are stored. Additionally, the specific repair(s) to the vehicle are also stored, and catalogued. Given enough data over a period of time, CARB would be in a position to recommend potential solutions, based on how the individual sensors have responded, how the PSN has scored the vehicle, as well as the historical repair records based on previous results.

5.3. Develop a gasoline particulate matter (GPM) parSYNC® system based on the unique signature of ultrafines from gasoline direct injection (GDI) vehicles.

6. Demonstration of the parSYNC® and PSN using real-world data

6.1. In August of 2015, 3DATX gave a demonstration of a prototype parSYNC® to CARB in El Monte, CA. CARB had prepared for the presentation by supplying a diesel truck for the parSYNC® to measure emissions from. The exhaust system of the truck was modified by CARB with a variable DPF exhaust bypass system. The range of DPF exhaust bypass levels on the truck can be accomplished in 16 increments. This allows the accurate simulation of a range of DPF malfunctions, from no malfunction (no DPF bypass) to a removed DPF (full bypass). During the demonstration, the truck was tested as it simulated three states of DPF malfunction. The first test simulated a truck with no DPF malfunction (Mode 1). The second test simulated a significant malfunction that should be repaired, but would not be detected using an opacity test alone (Mode 2). The third test simulated a truck with a malfunction severe enough to be detected using opacity alone (Mode 3). These settings had been determined by CARB in advance and were not revealed to 3DATX until after the demonstration was finished.

6.2. Figures A.1 to A.3 show associated parSYNC® plots. Figure A.1 shows parSYNC® opacity, scattering and ionization sensor outputs, stacked and weighted to provide a summed output analogous to the PSN number. Here, the three test modes (Modes 1-3) have been annotated in red. Figure A.2 shows the same data as ternary plots. Here, the three sensor outputs are plotted on the three axes and the size of each point is scaled according to the PSN value of that point. Separate ternary plots are also generated for each mode and an additional subset (labelled Mode -1) has been included containing data collected when the vehicle was not running. The plots demonstrate both the different magnitudes of response of PSN and the difference in the response distribution from the different parSYNC® sensors associated with data collected in Modes 1, 2 and 3. Finally, Plot A.3 demonstrates the predictive power of the parSYNC® analysis. Although a clean vehicle exhaust (Mode 1) is actually very hard to tell from no vehicle (Mode -1), modes that simulate a failing or failed DPF (Modes 2 and 3, respectively) are correctly assigned with high confidence after several seconds of data collection.

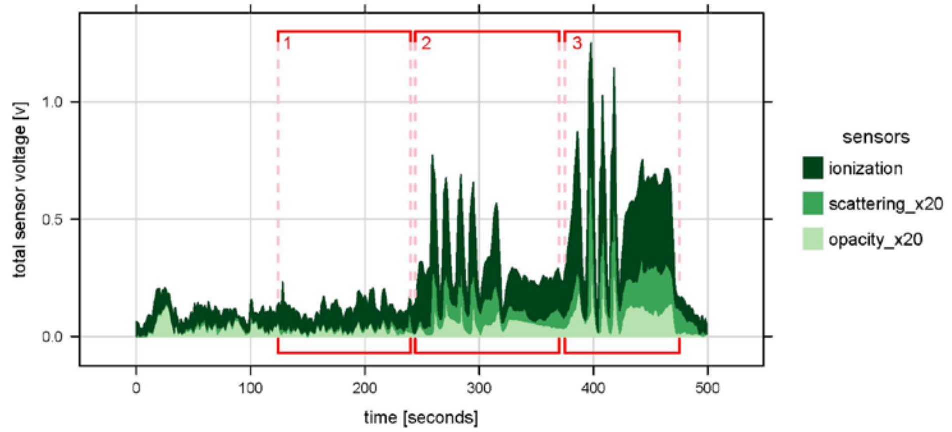


FIGURE A.1: Weighted sum of scattering, ionization, and opacity sensor data from CARB truck with variable DPF bypass

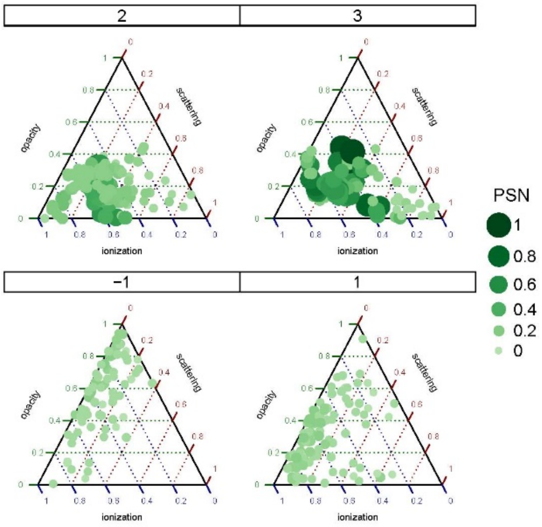


FIGURE A.2: Ternary plots showing change to PSN distribution due to variable DPF bypass

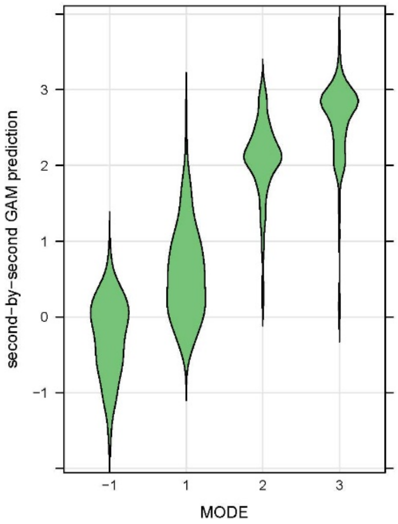


FIGURE A.3: PSN based synthesized predictive power plot showing DPF failure modes

7. Solution centric customization of parSYNC®

7.1. As CARB becomes more familiar with the parSYNC® system, existing features can be customized or new features can be added that would improve its utility to the state. For example, we foresee the following possibilities.

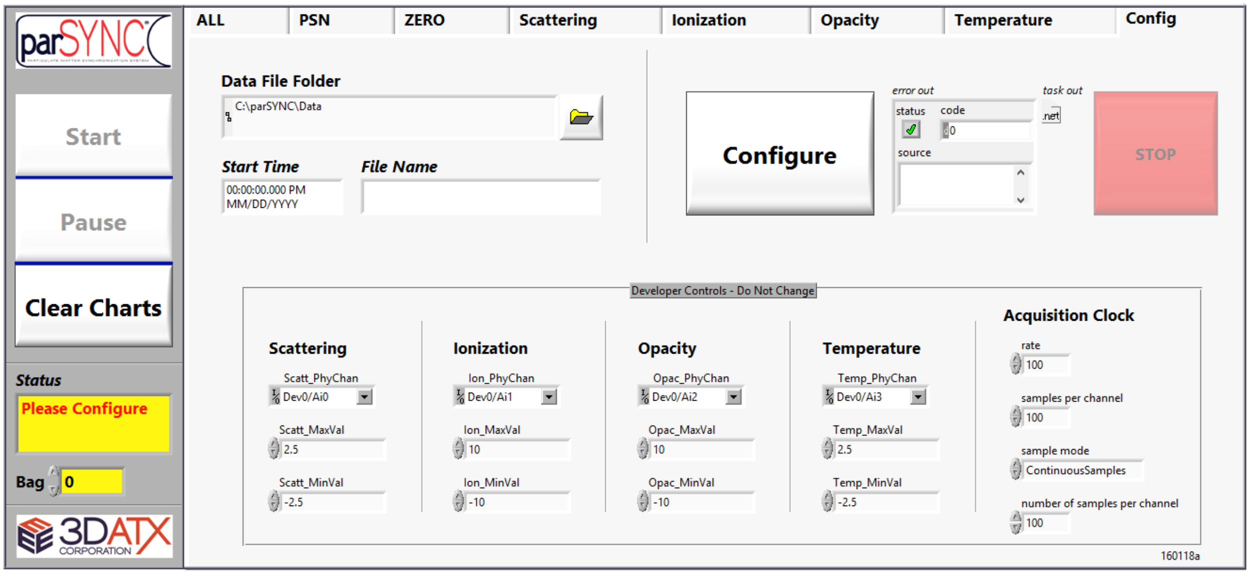
7.1.1. The parSYNC® I/M system end-user custom settings can be adjusted to facilitate "learning" as the pass/fail database grows. For example, referring to equation E.3, the constant multipliers C_O, C_S and C_I can be changed to make the system more sensitive to a certain PM size range, such as greater ionization weightage for higher sensitivity to finer particles.

7.1.2. Software modules can be added that will differentiate between roadside tailpipe measurements versus trucks driving through an instrumented shed arrangement. Higher sampling rates, which also help reduce random noise, can be added.

7.1.3. The software can be made to allow for development of more robust and case-specific PSN pass/fail criteria. For an example case of a roadside tailpipe measurement that lasts 60 seconds, pass/fail criteria could be either of these two options: (1) total number of 1 Hz PSN values that exceed a threshold; (2) a rolling window of 3-5 seconds will generate window-average PSN and each window will be judged as pass/fail based on a window-average PSN threshold. The failed window count will then decide the vehicle as pass/fail. Individual PSN threshold, rolling window width, window-average PSN threshold, and window count can all be user defined. This gives the user the flexibility to deal with real-world uncertainty and a future-ready system.

7.1.4. A gaseous measurement module could be added to measure CO_2, NO, and NO_2. Such a module is now under development. Over time the additional information added by the gaseous data would likely provide insight into other emissions control system failure modes (e.g., via the well-known NOx/PM trade off) and enhance the quality assurance of the PM measurement (via expected CO_2 concentrations during measurement) and other applications that will only be discovered as the I/M data are amassed and analyzed.

7.2. PSN Software design for CARB roadside I/M – the parSYNC® software proposed for CARB introduces a simple and straightforward pass/fail and cut-point approach that will operate similar to the existing Opacity program. The PSN software is designed so that "true fails" are clearly identified and "false fails" are minimized; screens can be designed to incorporate specific requirements based on specific field conditions.



Data File Folder: C:\parSYNC\Data

Start Time: 00:00:00.000 PM MM/DD/YYYY

File Name:

error out: status ✓, code 0, source

task out: .net

Status: Please Configure

Bag: 0

Scattering: Scatt_PhyChan Dev0/Ai0; Scatt_MaxVal 2.5; Scatt_MinVal -2.5

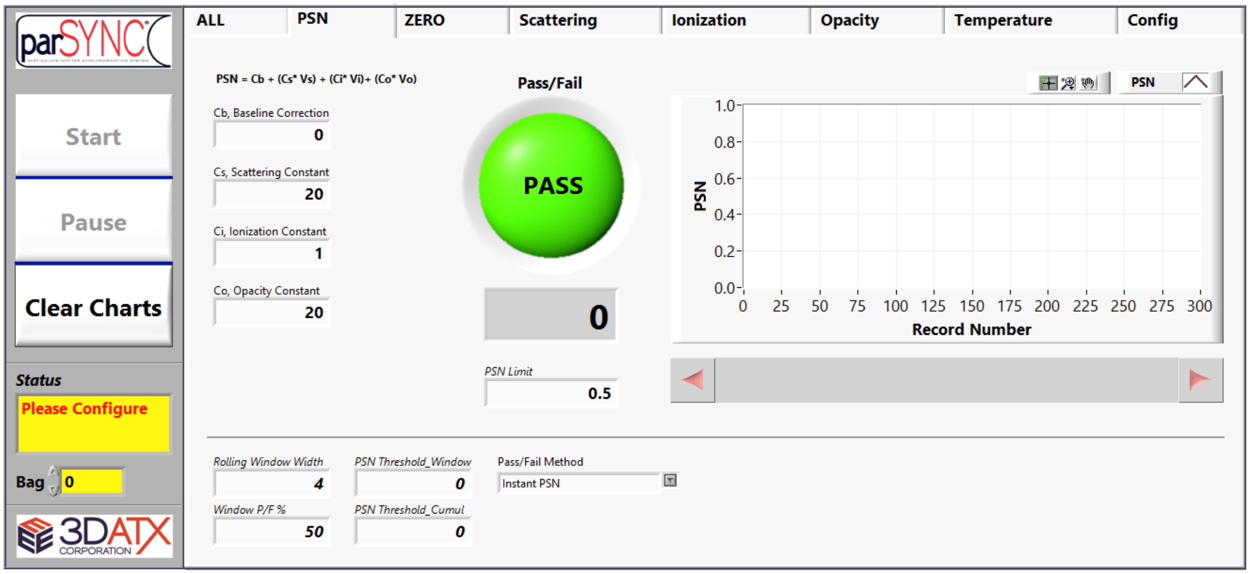
Ionization: Ion_PhyChan Dev0/Ai1; Ion_MaxVal 10; Ion_MinVal -10

Opacity: Opac_PhyChan Dev0/Ai2; Opac_MaxVal 10; Opac_MinVal -10

Temperature: Temp_PhyChan Dev0/Ai3; Temp_MaxVal 2.5; Temp_MinVal -2.5

Acquisition Clock: rate 100; samples per channel 100; sample mode ContinuousSamples; number of samples per channel 100

FIGURE B.1: parSYNC® configuration screen showing capability to control data acquisition rates to match the requirements of the application



PSN = Cb + (Cs* Vs) + (Ci* Vi)+ (Co* Vo)

Cb, Baseline Correction: 0

Cs, Scattering Constant: 20

Ci, Ionization Constant: 1

Co, Opacity Constant: 20

PSN: 0

PSN Limit: 0.5

Rolling Window Width: 4

PSN Threshold_Window: 0

Pass/Fail Method: Instant PSN

Window P/F %: 50

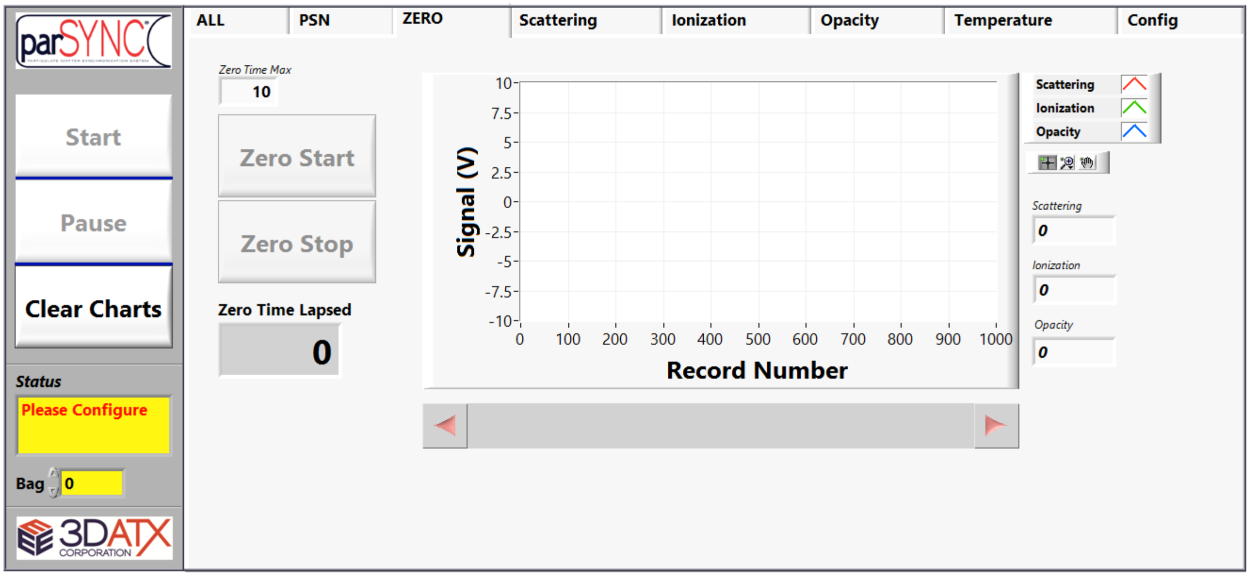
PSN Threshold_Cumul: 0

Status: Please Configure

Bag: 0

FIGURE B.2: parSYNC® PSN screen showing pass/fail criteria selection, settings, and test result notification

The parSYNC®/ CA/GE™ and their attached data/algorithms being provided by 3DATX are proprietary assets of 3DATX and shall not be transferred nor disclosed. Further, the parSYNC® or any related information related to the parSYNC® shall not be disclosed to any third party, except as expressly authorized by 3DATX. Finally, use of the parSYNC® or any related information for any purpose other than to evaluate the parSYNC® shall not occur.



Zero Time Max 10

Zero Time Lapsed 0

Status: Please Configure

Bag 0

Scattering 0

Ionization 0

Opacity 0

FIGURE B.3: parSYNC® zeroing screen showing control of zeroing procedure duration

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