Development of On-line Instrumentation and Techniques to Detect and Measure Particulates

Quarterly (Final 12th Quarter) Technical Progress Report

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Abstract

In this final quarter, we have continued to collect more field data. Here, in this report representative data collected in the field with turbine engine are presented. We also made substantial progress in calibration of standard particles using MOUDI.

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Executive Summary

During the 12th quarter of this project, we collected a myriad of field data at our industrial partner's test site. These data verified the system performances.

1. The system could detect light scattering signal for all 9 wavelength lasers under different load conditions
   - ➢ We verified that the ELIS1024 chip could reliably collect light scattering signal from the 9 wavelength lasers, even the weakest wavelength at 355nm, thanks to our effort in improving the signal to noise ratio of the detector.

2. The data collected for each wavelength channel under the same load is consistent and repeatable
   - ➢ Although different wavelength channel has drastically different signal to noise ratio, after certain averages, we are able to repeat the scattering signal under the same engine conditions.

3. The data collected for each channel under different load conditions are qualitatively consistent with prediction.
   - ➢ The data collected for each channel under different load conditions change according to the predictions.
   - ➢ We are conducting simulation models to simulate the data and use the model to predict the PM emission pattern.

Experimental

1. Improved signal to noise ratio benefits signal collection even for the weakest laser channel

In the past last quarter, we verified that the CCD array could not have multiple exposure capability, however the data could be read out many times after one exposure and averaged several times to improve signal to noise ratio. We successfully improve the signal to noise ratio and now the read out has an effective bit resolution of 14bits after some 20 readouts. This scheme, although improves bit resolution, comes at the sacrifice of effective sampling rate. We use this scheme only for weak signal channels, e.g. 355nm.

a. Develop single shot multi-readout process to improve signal to noise ratio

We have implemented the non-destructive read out (NDRO) mode, in which the signal stored in the charging capacitor could be read out and digitized many times. The average effects over the number of readouts could reduce the readout noise level for each exposure, and therefore improve the signal to noise ratio.

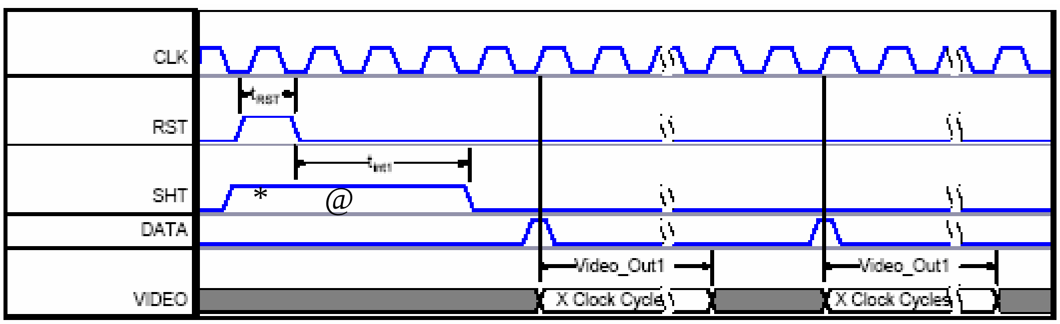
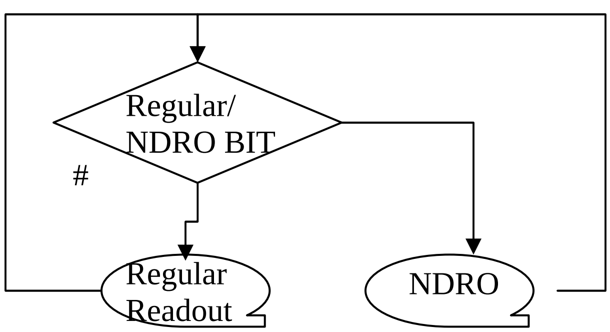


Figure 3: Non-Destructive Readout Timing Diagram.

We now developed the VHDL code for the USB + CPLD controller which will switch between normal readout, i.e. readout following RST and SHT, and nondestructive readout (NDRO). The NDRO command will be issued by the USB controller. And the CPLD will have two sets of VHDL code --- one for normal readout and one for NDRO.



2. Field experiments

We continue our effort to collect more field data, so that we could analyze, compare and model after this project ends.

We have added a blue diode laser at 403 nm which will give us the valuable wavelength to cover the gap between 532nm and 355nm. The power of the 403nm is 5mW, and could also be pulsed with external logic with rise/fall time of ~50ns. We added a combiner filter from Semrock (part # NF02-405S-25), and this forms our new 9 wavelengths lasers assembly that we will be using in the field.

We have developed data logging program that automates the scattering data collection with engine load adjustment. We have collected scattering data under different load conditions and with all 9 channels. The data will be analyzed in the Results section.

3. Calibration of our data with water jet standard

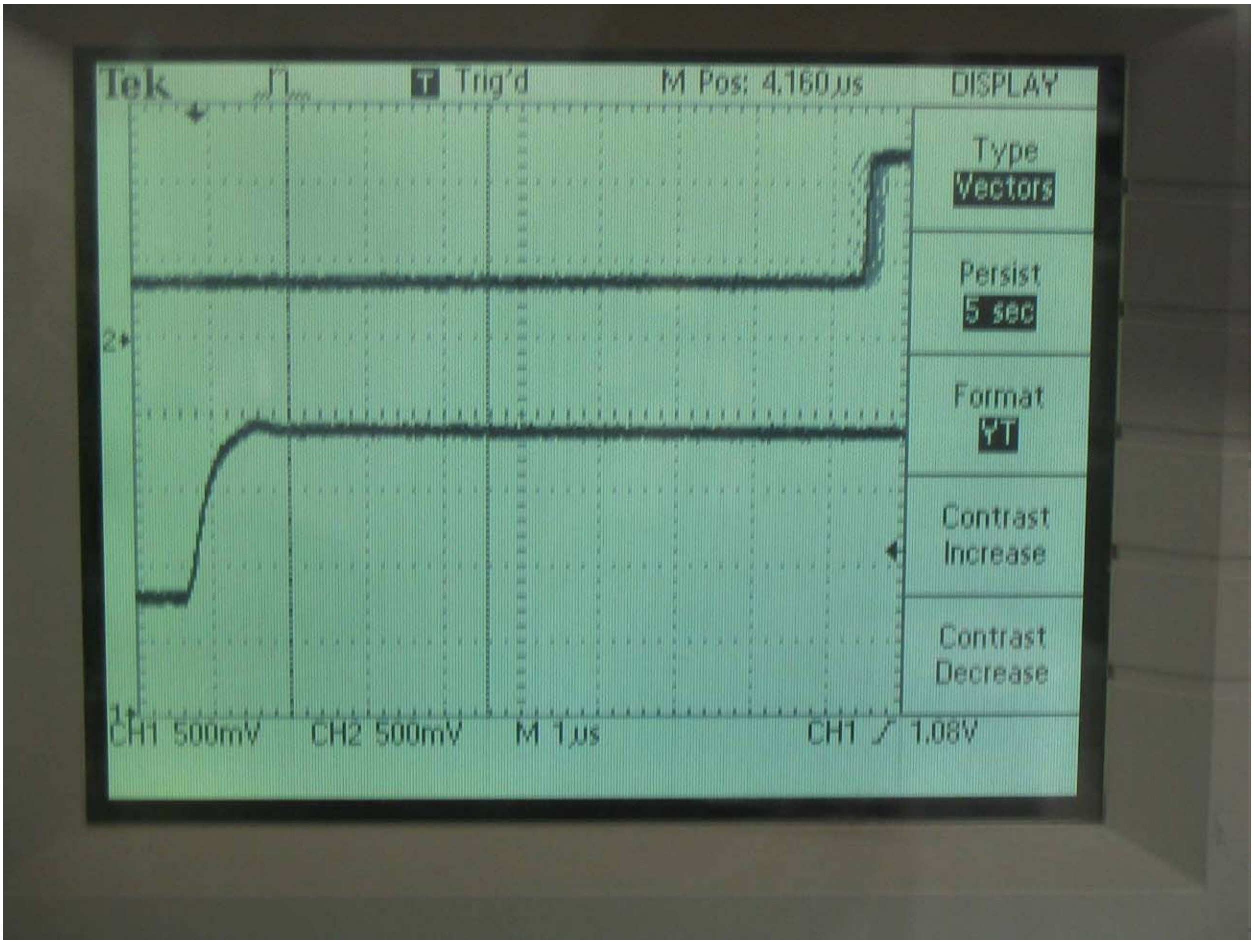
We have successfully generated mono-sized liquid particles before (see Q2 report and figure below), and verified with MOUDI. But, the liquid particles, although mono-sized, have a relatively wide size distribution due to the liquid particles' generation process. This provides us a good standard to calibrate, but we still need more standards with narrower size distribution to provide a more accurate calibration database like we have done with PSS particles in the liquid. One could generate the particles by disperse the mono-sized particles in evaporative liquid, and then form the particles in the air by blowing it through an expansion nozzle. Then, detect the scattering signals with the scattering instrument. But, before we start measuring the scattering signals, we need to verify that standard single particles without liquid could be generated in the region where the probing beam intercepts the expansion jet. We planned to use MOUDI to intercept the particles after expansion and then verify the particles on each plate and prove that standard particles are deposited on a single plate.

We are now working on the calibration of our system with standard particles in the air. More standard database will be collected to assist the interpretation of our field measurement data.

a. Improved timing accuracy in our DPPQS laser

We have successfully improved our Diode pumped Passive Q-switched (DPPQS) laser timing accuracy. The previous results have shown that free running DPPQS lasers has a timing jitter of 10s of micro-seconds, and with a delay of several milliseconds after a pulsed current is sent to the pumping diode. Past results with prepumping have successfully reduced the jitter below one micro-second, and delay as short as 7.7 micro-seconds after a pulsed current is sent to the pumping diode.

We have just demonstrated that we could reduce the jitter and delay further down to ±100ns and less than 3 micro-second. We achieved this goal because we have a custom designed LD driver that has fast-rising pulsing capability, the LD driver has a analog modulation depth of 2MHz, with a current amplitude as high as 5 amps. The rise time of the pump current pulse sent to the diode is as fast as 0.5 micro-second, and this gives room to further improve the delay below 1 micro-second. We are exploring using secondary pulse in prepumping to further improve the stability.



The trace at the bottom is the current pulse to the pump laser diode, and the trace above is the PQS laser pulse. Jitter is about 100ns in 5seconds (100 shots accumulated).

Results and Discussion

1. Setting up platform for field test

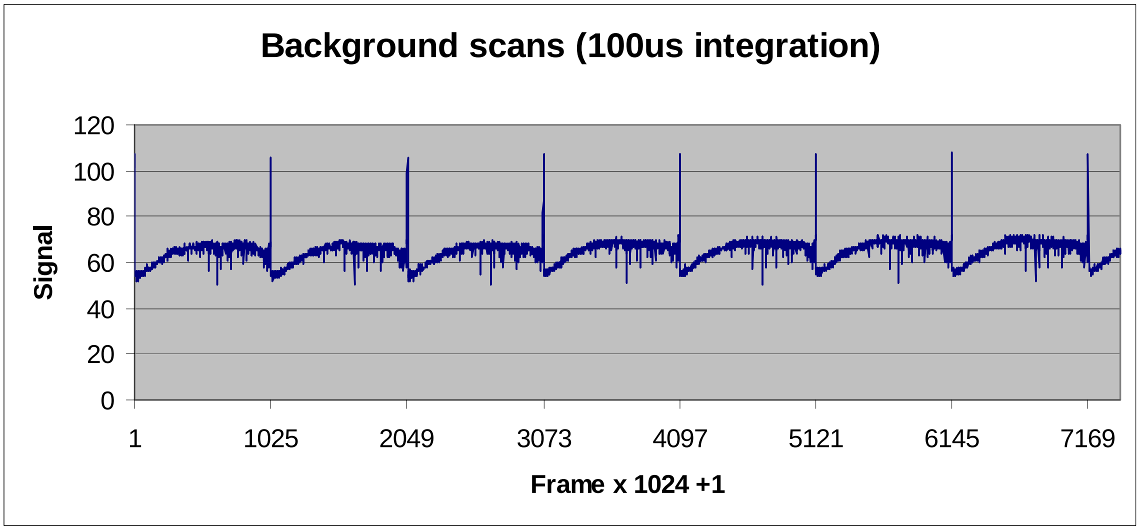
The setup consists of a multi-wavelength laser transmitter (now 2W and 9 wavelengths) box and an angular (15degrees) scattering CCD detection box. The engine is a Cummings Turbine with 160hp power, we could change the load conditions by changing the external current sink automatically or change the fuel air ratios manually.

We have set up the new lasers assembly with the 403nm wavelength laser at Alturdyne's test site, and initial results have shown that we have a signal to noise ratio of about 12 to 1 when the engine is running under normal load. We are improving the signal to noise ratio by adding the NDRO mode to the CCD detection system. We have installed our particles standards generator which could generate standard mono-sized particles in the air, and these particles include all the standard that we tested before in the liquid. We are now collecting the standard in the air as well, and will then compare and interpret the data collected from the engine's emission.

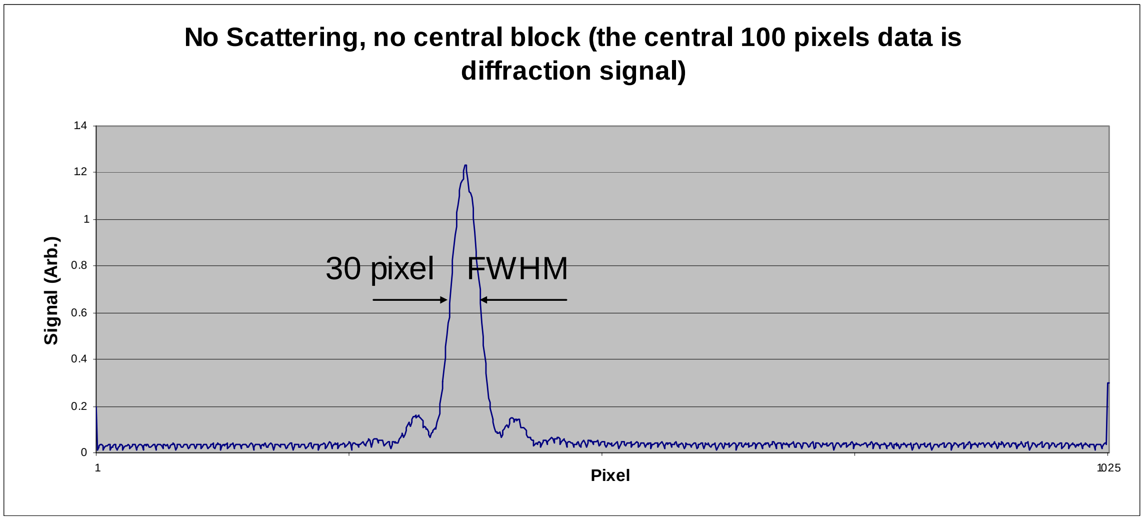
2. Repeatable scattering data consistent with load conditions and wavelengths

Below, we present the sample data collected from the field which demonstrate that the field is repeatable, and they are also consistent with load conditions and wavelengths' change.

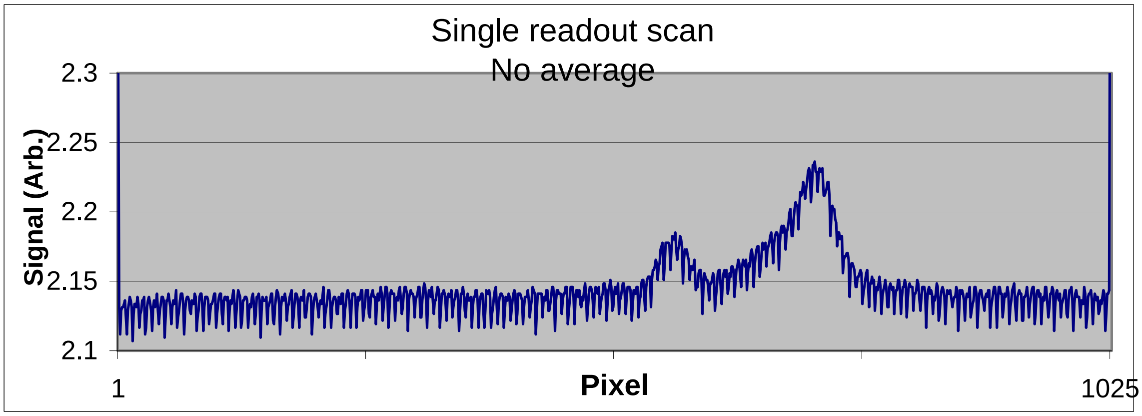
Some calibration data



This figure above is the scan of background, i.e. no laser probing, each frame is 1024 points and normal readout process is used.

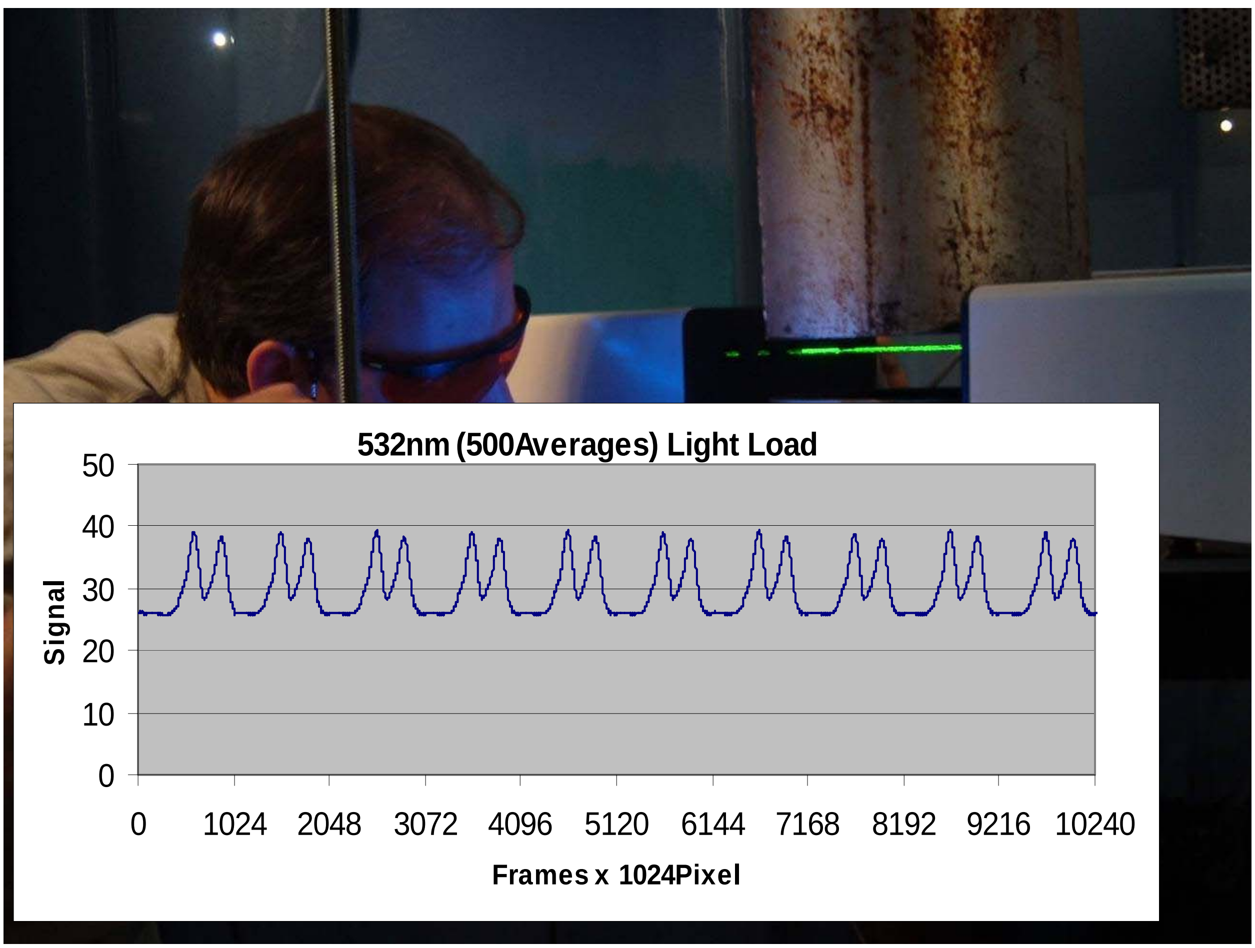


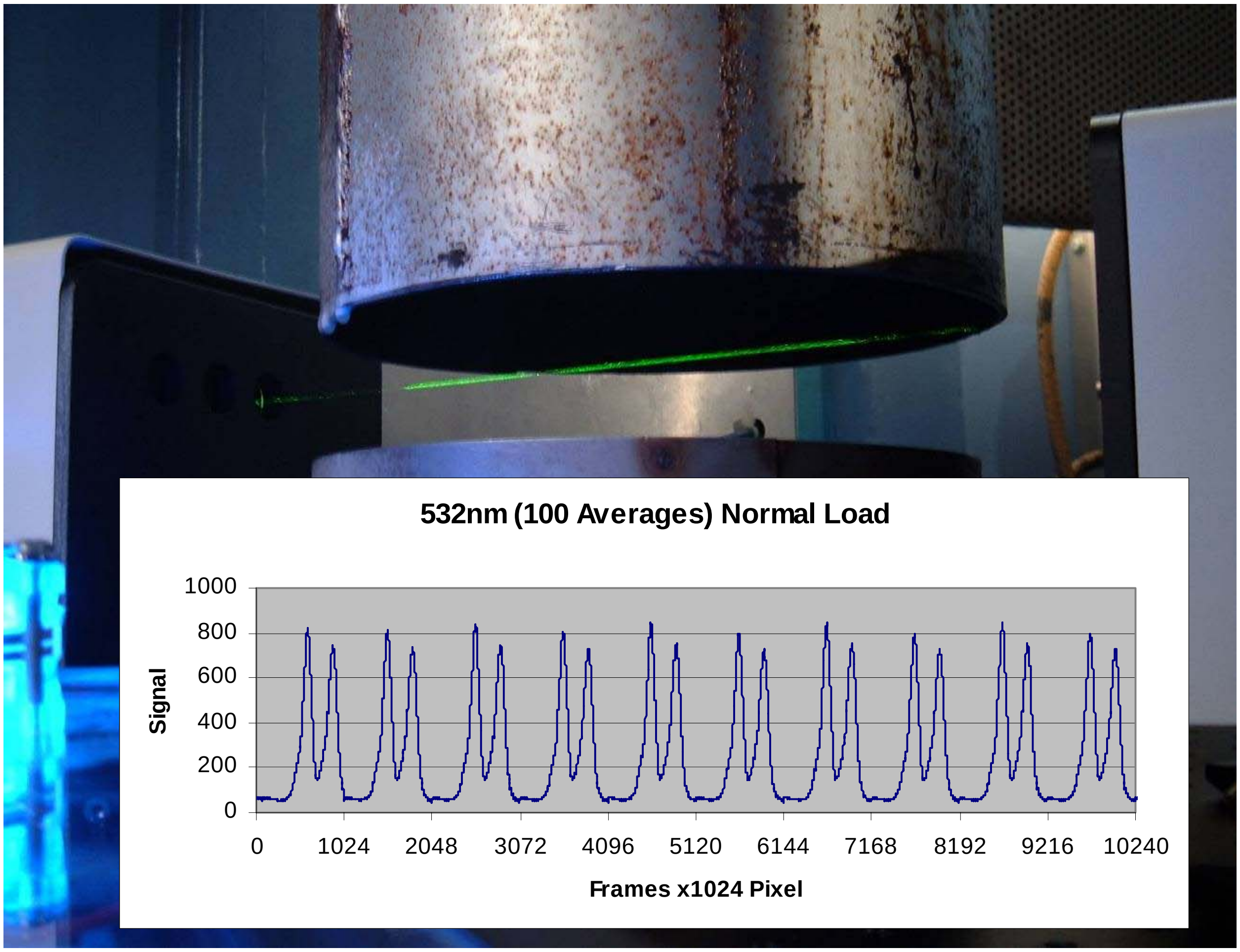
This figure above shows the intensity on the CCD array when there is no particulates in the beam path, and no beam block for the beam path. It is used as a zero degree calibration, where the center is determined for each wavelength (each wavelength has a slightly different zero degree pixel position).

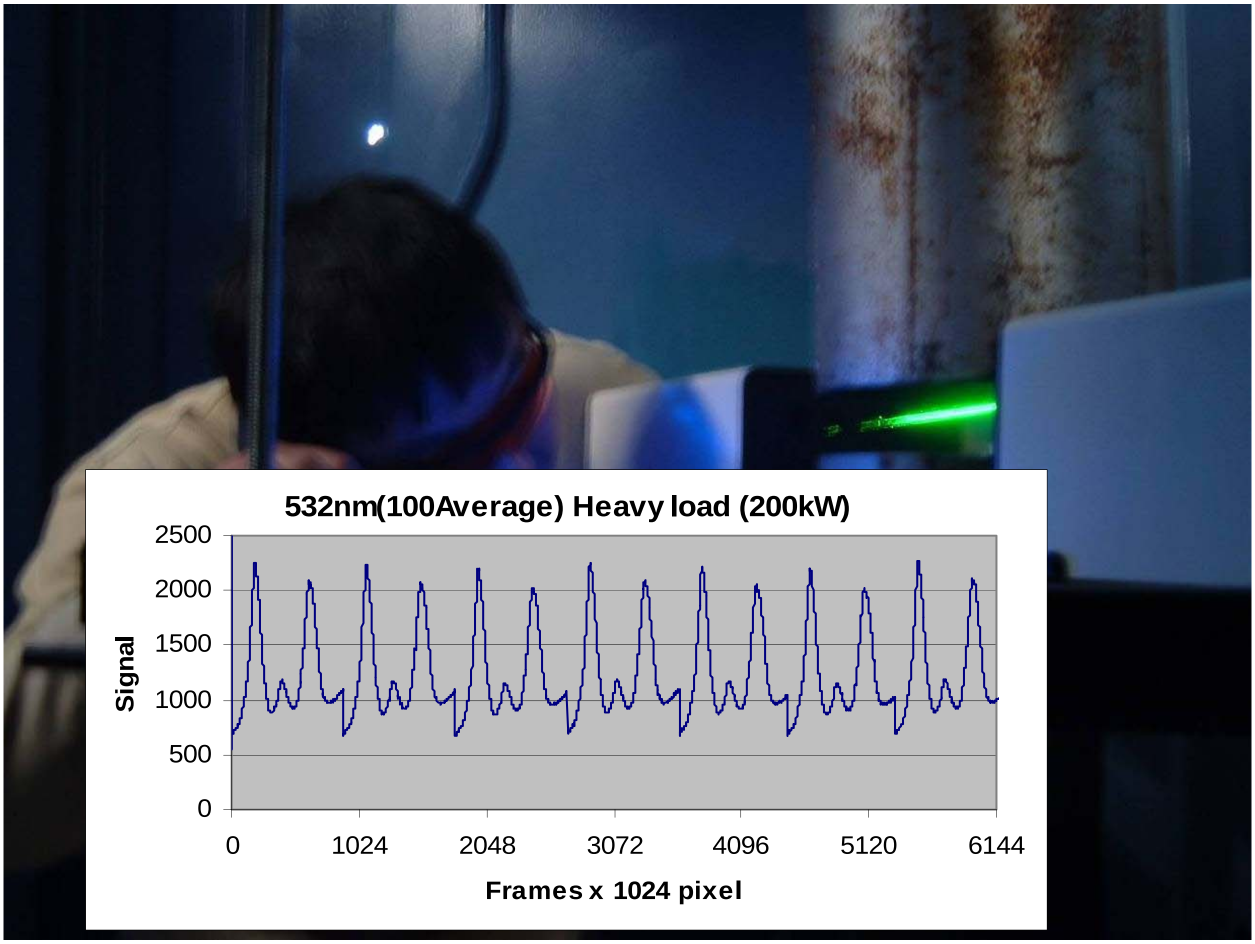


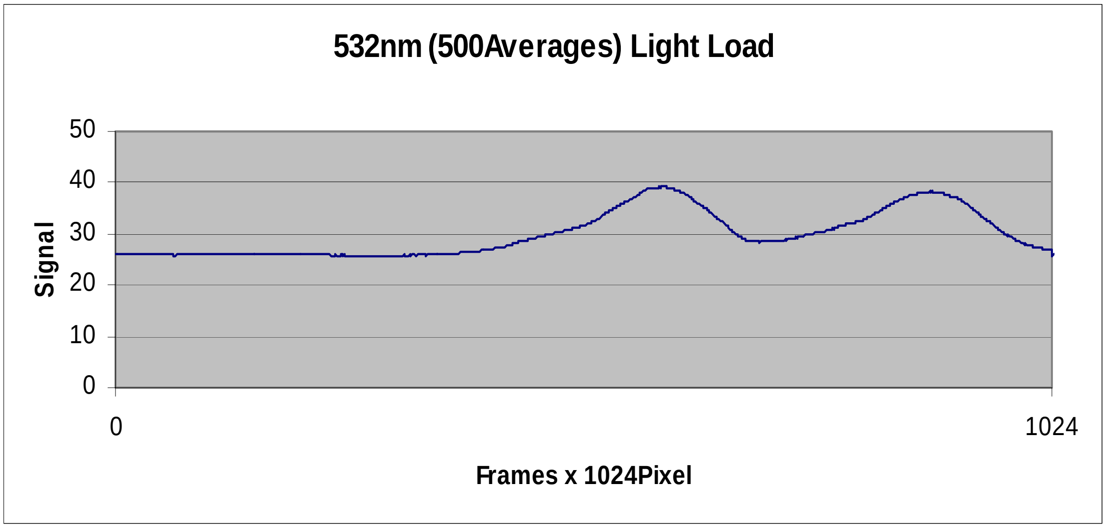
This figure above shows the single scan data with 532nm laser and light load conditions, single readout is performed and noise is obvious.

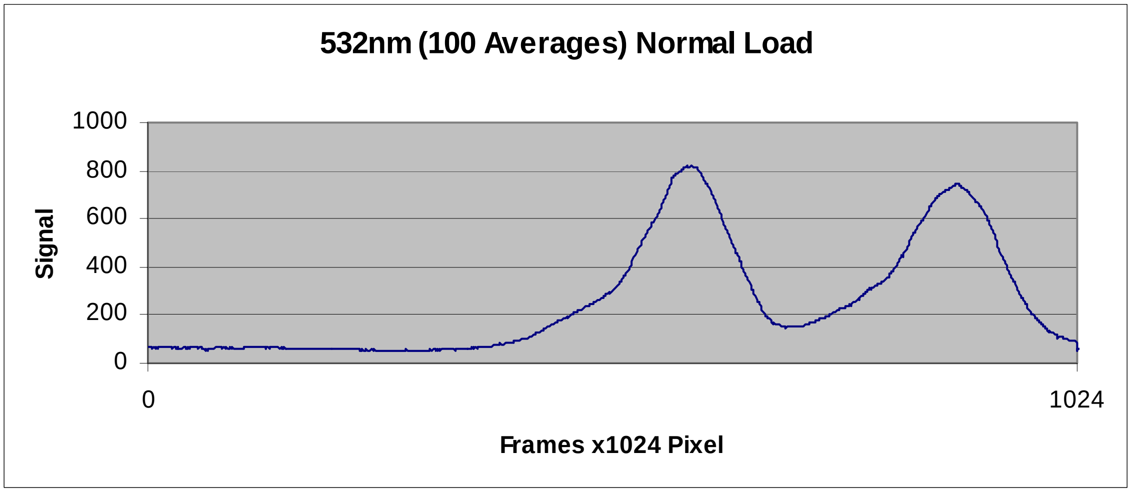
Single wavelength data under different load conditions

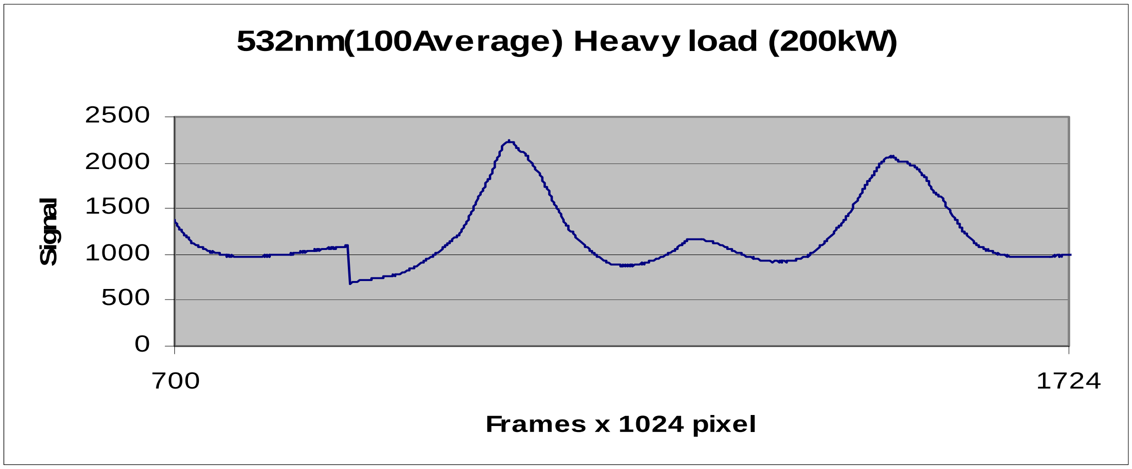



532nm (100 Averages) Normal Load
Signal
1000
800
600
400
200
0
0
1024
2048
3072
4096
5120
6144
7168
8192
9216
10240
Frames x1024 Pixel


532nm(100Average) Heavy load (200kW)
Signal
2500
2000
1500
1000
500
0
0
1024
2048
3072
4096
5120
6144
Frames x 1024 pixel



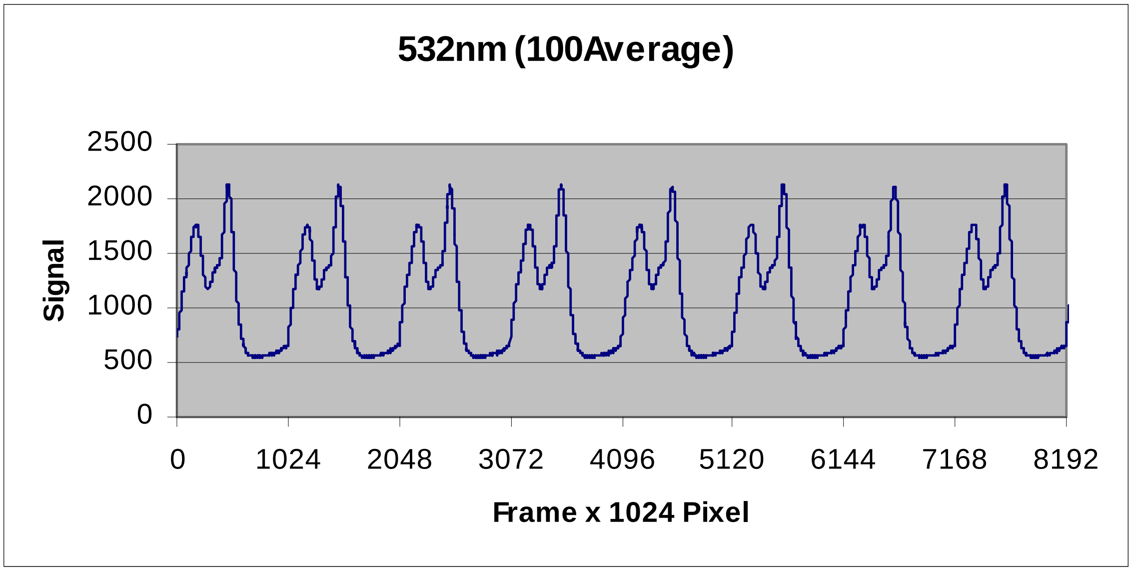


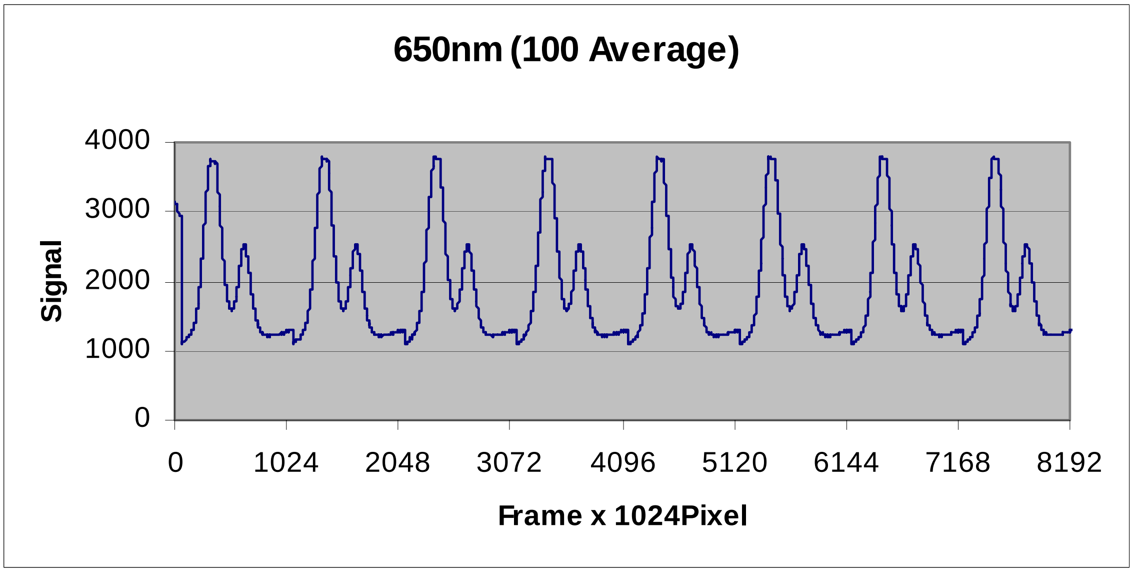


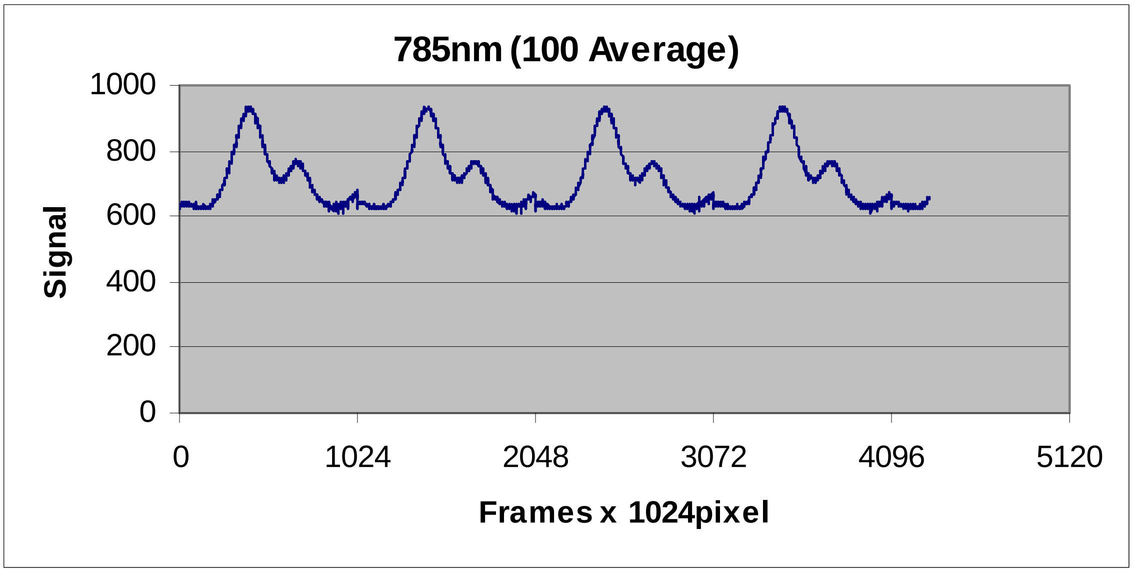
The above figures show the scattering signals under different load conditions for the same wavelength (532nm). The results demonstrate the following qualitative features:

1. Intensity increases as load increases
2. Slope getting sharper/larger, as load increases, indicating bigger particles
3. Location change at heavy load, indicating extra kind of particle generated

Change of wavelengths (light load 120kW)







The above three figures show that under light load conditions. When the wavelength changes, the angular distribution changes --- spreading to the larger angles, and there are also splitting in the longer wavelength scattering, which we attribute to resonance --- we could correct with another adjacent wavelength.

3. Conclusions

The field data shows repeatable patterns under the same load conditions and wavelengths. This proves the reliability of the instrument and concept. The total scattering signal and pattern change with load and wavelengths are also consistent with theory. Detailed simulation based on standard particles will further analyze the components in the emissions.

Work plan after the end of the project

We see our work has fulfilled our schedule as outlined in the Statement of Work (SOW) for this project.

We will continue the following work:

- We will finish collecting 9-channel scattering data for the standard particles, especially liquid phase particles, verified by MOUDI.
- We will simulate the data collected in the field with the standard particles' data collected in the lab after MOUDI.
- We will go back to the field and verify our field data with improved laser sources, especially with stronger 355nm laser source.
- We will seek opportunities to test this instrument at coal firing power plants.
- We will work with local Southern California AQMD to have field test of this instrument at other particulate emission sources
- We will commercialize the instrument and subsystems developed during this project.

Appendix:

Planed schedule from the statement of work

Task	Technical Milestone	Schedule
1. Assembly of the multiwavelength light source	Ready diode & DP chip lasers, drivers	Month 1-6
	Ready beam combination system	Month 1-6
2. Construction of the PM synthesizer	Verify that monosize PM are generated	Month 1-6
3. Simulation of Ralyeigh and Mie Scattering	Literature review	Month 1-3
	reviewComputer program that could generate simulated scattering spectrum	Month 1-6
4. Laboratory demonstration of instrument	Experimental scattering spectrum database for different PM sizes	Month 7-18
	Compare with theory and conventional PM monitoring data	
5.Application of the PM analyzer to a combustion environment: engine intake area	Correlation of our instrument data with conventional PM monitoring data	Month 13-24
6.Application of the PM analyzer to a combustion environment: engine exhaust	Correlation of our instrument data with total PM mass emission, new data (PM size and chemical composition) about in-situ PM monitoring	Month 13-24
7. Applicability assessment for PM emissions from coal fired power plants	Design/modify our PM instrument for smoke stack PM monitoring	Month 24-30
8. Instrument design optimization	Optimize the instrument during different experiments	Month 13-36