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

Quarterly Technical Progress Report

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Disclaimer

Abstract

In this quarter, we have finished construction of the first field deployable multi-wavelength PM measurement system. This system is retrofit from the system that we designed and tested in the lab, and by adding light blocking covers and rugged electronic boxes, we are now testing the instrument in our industrial collaborator’s site with a turbine power generator. We are collecting data on PM emissions from the engine under different load conditions and fuel/air mixing ratios.

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Executive Summary

During the 8th quarter of this project, we have finished building the field usable multi-wavelength PM monitoring instrument, and we are starting to collect the data in the field. During the development of this instrument, we have tailored our detection and probing subsystems for field application, and such improvements result in new features for several existing commonly used detector and laser driver systems.

1. The field test platform and the field test setup
    - ➢ We modified the exhaust line of a turbine power generator, so that we could conduct measurement in an enclosed container while keeping the exhaust out of container.
    - ➢ We then installed the field deployable instrument at the platform with laser beams crossing the exhaust line
2. The improvements in detection and probing subsystems
    - ➢ Our detection subsystem has the unique features which help our signal acquisition, i.e. fast gating and low noise when compared to comparable commercial detectors
    - ➢ Our probing subsystem has the fast sequential laser pulsing capability, and this help us reduce background noise and exposure in the detection subsystem
    - ➢ The integrated system could synchronize the firing of probing lasers and the exposure of the detector system
3. On-going field test
4. Improvements in data logging
    - ➢ We are adding capability in logging the generator's conditions along with the particulate emission data

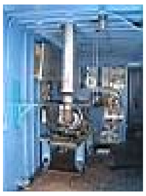
Experimental

1. The field test platform and the field test setup

a. Turbine power generator

Our field test setup is at Alturdyne, Inc., our industrial collaborator, in El Cajon, San Diego, CA. For the purpose of continuous test in a controlled environment, they set up the test engine, a 150hp T62-T32 gas turbine engine, in a container. This setup gives us the ability to adjust background light intensity. We hope that ultimately, we could collect the particulate emission data in an open environment.

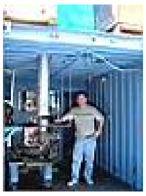
Field test at Alturdyne --- container lab



The test bed #1 looking from outside the container

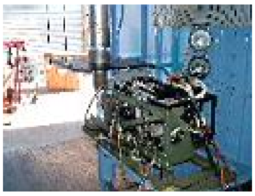
The test bed #2

The test bed #3



Test bed #4--- Steve Palm

The test bed #5 ---Lab in a Container



Test bed#6 looking from inside

The test bed is an Alturdyne 150 hp T62-T32 gas turbine engine generator set built for the Canadian Navy. The exhaust line is split using a jet eductor to accommodate the probing beam path. An optical breadboard is bolted at the appropriate height for mounting the PM detection instruments. The engine load (and consequently the bulk equivalence ratio) is controlled using a load bank which is operated from the control room in the rear of the container. Further pages and full size pictures could be found at http://peer.caltech.edu/Particulate/AlturdyneTest/page_01.htm

Field Test and Alturdyne --- test platform

PM box pair installed container door half closed.

PM box pair installed

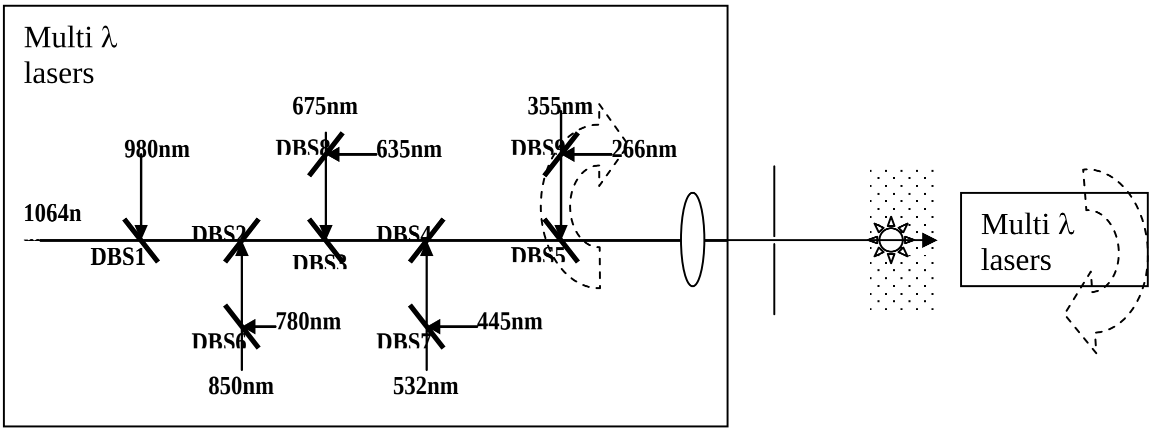
PM box pair installed looking from lower direction

PM box pair installed looking from inside the container

PM box pair installed looking from inside the container

PM box pair installed container door closed

The container could provide a relatively dark room conditions, and this provides a good start for PM detection when the signal is not very strong, i.e. particulates are not dense enough. As we enable the pulsed operation mode, we could detect PM scattering in flash mode and daylight might not be that critical.



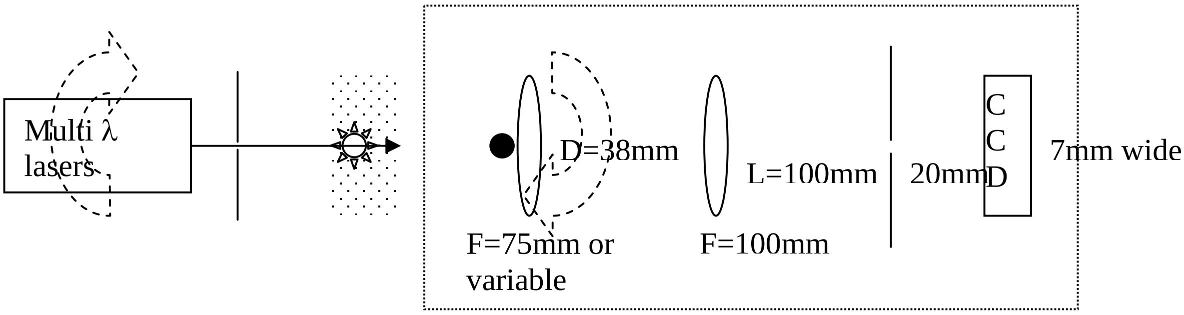


Figure 1a. Schematic of the 2 box setup with the detector box shown with detailed dimension and schematic

Figure 1b. Schematic of the 2 box setup with the multi-wavelength laser box shown with detailed dimension and schematic

Field test at Alturdyne --- close look of operation


Operator adjusting the instrument #3


Operator adjusting the instrument #4


Operator adjusting the instrument #5

Steve Palm is adjust the PM box during turbine operation , we could see light scattering at different intensities and distributions as a result of generator load and conditions.

2. Improvements and unique features of the current probe and detection system

a. Precisely triggered diode pumped passively Q-switched laser

In the probing laser beams, we use 10 different lasers listed below.
Table 1. The assembly uses 10 lasers at different wavelengths.

Wavelength	635nm	650nm	660nm	780nm	810nm	830nm	980nm	*355nm*	532nm	1064nm
Power (mW)	30	40	30	80	200	30	30	*14*	30	200
Package	TO	Cir. TO	Cir. To	Bare	C-mnt	TO	FC	*DP/PQS*	DP/CW	DP/CW

We could pulse each one of these lasers sequentially and finish firing them in a short period of time, e.g. each laser of a different wavelength pulses for only 500ns, and the fast CCD detector will only integrate in the 500ns of the laser pulsing period. Then, it takes about 1msec for the data to be read from the CCD and ready for the next laser pulse. These 10 lasers could finish firing and data from CCD all collected for them in about 12msec (~10msec for data acquisition, and ~1msec for 10 laser pulses). This process requires that all lasers could be triggered with a precision better than 500ns, i.e. the actual laser pulses come within ±250ns after the TTL pulse is sent in. This precise triggering capability is easy for the diode lasers, because the diode lasers respond to external modulation with a bandwidth well over 100MHz, i.e., less than 10ns. But, this is not straightforward for the diode pumped Passive Q-Switch (PQS) lasers, as we found out. We found that when the laser is operating at ~100Hz by applying an external current modulation at 100Hz, the delay between the TTL request, i.e. rise of the TTL pulse, and the actual laser pulse is about 4msec, and the jitter between TTL pulse and the final laser pulse is about ±2,000nsec. This makes the precise triggering of the PQS laser difficult, and therefore, we have to increase the integration window for the CCD detectors from 500ns to about 4,000ns. We are therefore collecting extra noise while the signal is not present.

We then found out that when we continuously pump the PQS laser, the pulse to pulse jitter is reduced significantly to about ±75ns. But, the repetition rate of continuously pumped PQS laser is only dependent on the pump laser power and can not be externally triggered or controlled.

This prompts us to explore the possibility of pre-pumping the PQS laser at a level just below threshold, and then when the TTL trigger comes in a higher current modulation pulse is sent to the PQS laser, triggering the Q-switched laser pulse. We then found out that we could improve the triggering precision significantly if we use this method. In this way, the delay between the TTL pulse and the laser pulse is reduced from 4msec to only 50μsec, and the jitter is reduced from ±2,000nsec to only ±50ns. This pre-pumping technique[1] could improve the performance of PQS in several ways --- first, it reduces the jitter significantly; second, it reduces the peak power needed for generating a laser pulse, which relief the diode laser driver's peak current specification; thirdly, it should save laser diode life time when the peak current is reduced.

Figure 2. For field use, integrated CCD controller and lower power diode laser and DPSSL laser controller with programmable pre-pumping capability.

We also expect that we could apply such technique to other diode pumped PQS laser variants. We noticed that mode-locked PQS lasers consists of Nd:YVO4 and Cr:YAG[2] has similar problem of accurate triggering, and this technique could be used to further improve the precision in triggering.

A paper has been authored on this innovation, and will be presented at Photonics West 2005 and Optics Communications.

b. Improve CCD detection system with nanosecond gating and ultra low noise

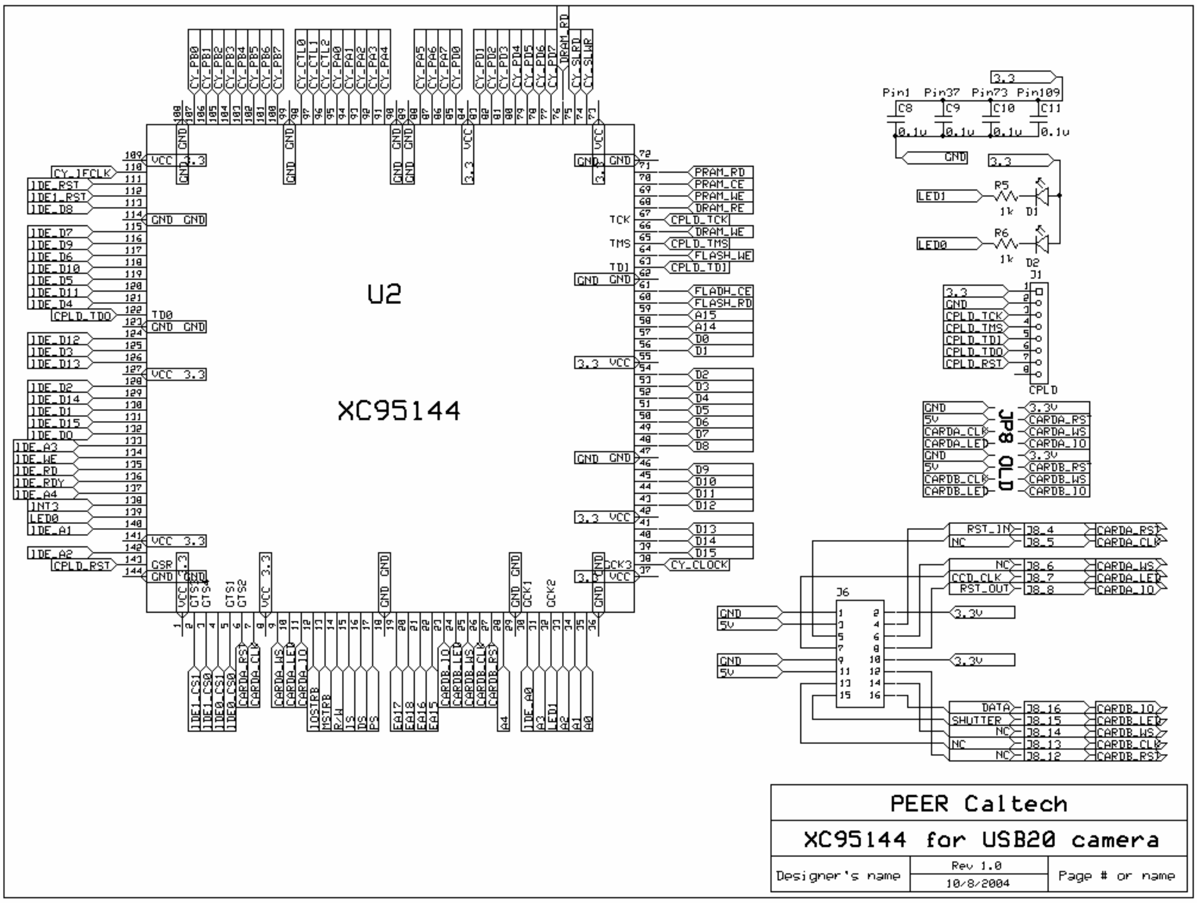
Table 2. Comparison of low cost linear array detectors

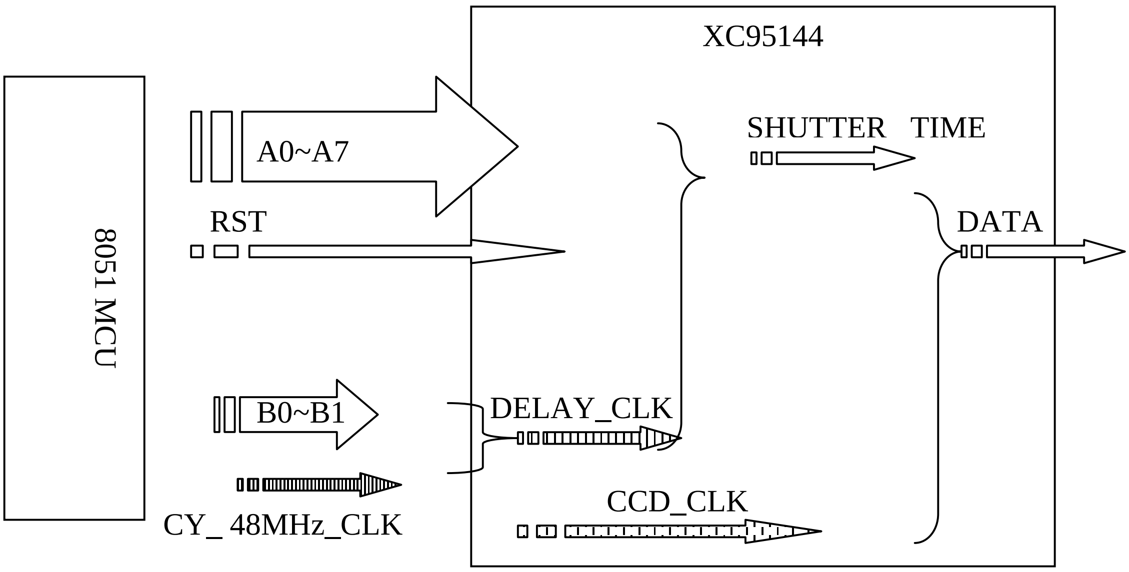
	Dark Current	Sensitivity (μV/e-)	Dynamic range	Well capacity	Shortest Gating	Saturation – Dark Voltage
SONY511	3mV integrate 10ms,	2.0μV/ν @ 400nm, or ~5μV/e-[*5]	267, 49dB	62.5Ke-[*4]	2.048msec[*1]	0.8V
ELIS1024	8mV/sec,	0.51(μV/e-)	71dB	800Ke-	<21nsec[*2]	3.3-0.74=2.4V
LIS1024	19mV/sec	0.32(μV/e-)	>84dB	8Me-	35μsec[*3]	4.8-2.1=2.7V

Note:
*1: Decided by the time needed to scan through 2048 pixels at a pixel clock rate of 1MHz.
*2: Decided by the time resolution available of the controller which in our case, could be as short as 21nsec.
*3: Decided by the time needed to scan through 1024 pixels at a pixel clock rate of 30MHz.
*4: From Ocean Optics S-2000 spectrometer specifications (2004 catalog)
*5: From Ocean Optics S-2000 spectrometer specifications (2004 catalog), 0.8V/4096/90ν*3(~ QE @ 400nm)

Our CCD linear array detector is based on the ELIS1024 detector from PanaVision. Compared to other widely available CCD detectors, e.g. SONY511, it is a high performance detector with extra low noise, high sensitivity, and large dynamic range (see table 1). It also offers two unique features ---- the synchronized integration for all pixels and the integration time, i.e. shutter time, could be as short as 1 nanosecond (ns). In our system, we just added a FPGA (XC9144) design that allows us to increase the shutter time from 21nsec to several seconds with a minimal increment of 21nsec. This kind of gated timing enable use to capture laser pulses within the shortest time period, therefore reducing dark current noise accumulation. We also upgraded our USB camera design from USB1.1 (based on Cypress AQ2131) to USB2.0 (based on Cypress CY68013). Now, our USB2.0 system could conduct 500 scans/sec for 1024 pixels at 12~16 bits resolution for each pixel, this compares favorably with the previous USB1.1 protocol which conducts only 8 scans/sec. We have spent past 2 months working on the upgrade, and need another month to fully modify the data acquisition program.

We expect this kind of camera system could find great application in spectroscopy experiments where gating under μsec is critical, such techniques include RAMAN, LIBS (Laser induced breakdown spectroscopy) and time resolved LIF (laser induced fluorescence), just to mention a few.


U2
XC95144
PEER Caltech
XC95144 for USB20 camera
Designer's name
Rev 1.0
10/8/2004
Page # or name


8051 MCU
XC95144
A0~A7
RST
B0~B1
CY_ 48MHz_CLK
SHUTTER TIME
DATA
DELAY_CLK
CCD_CLK

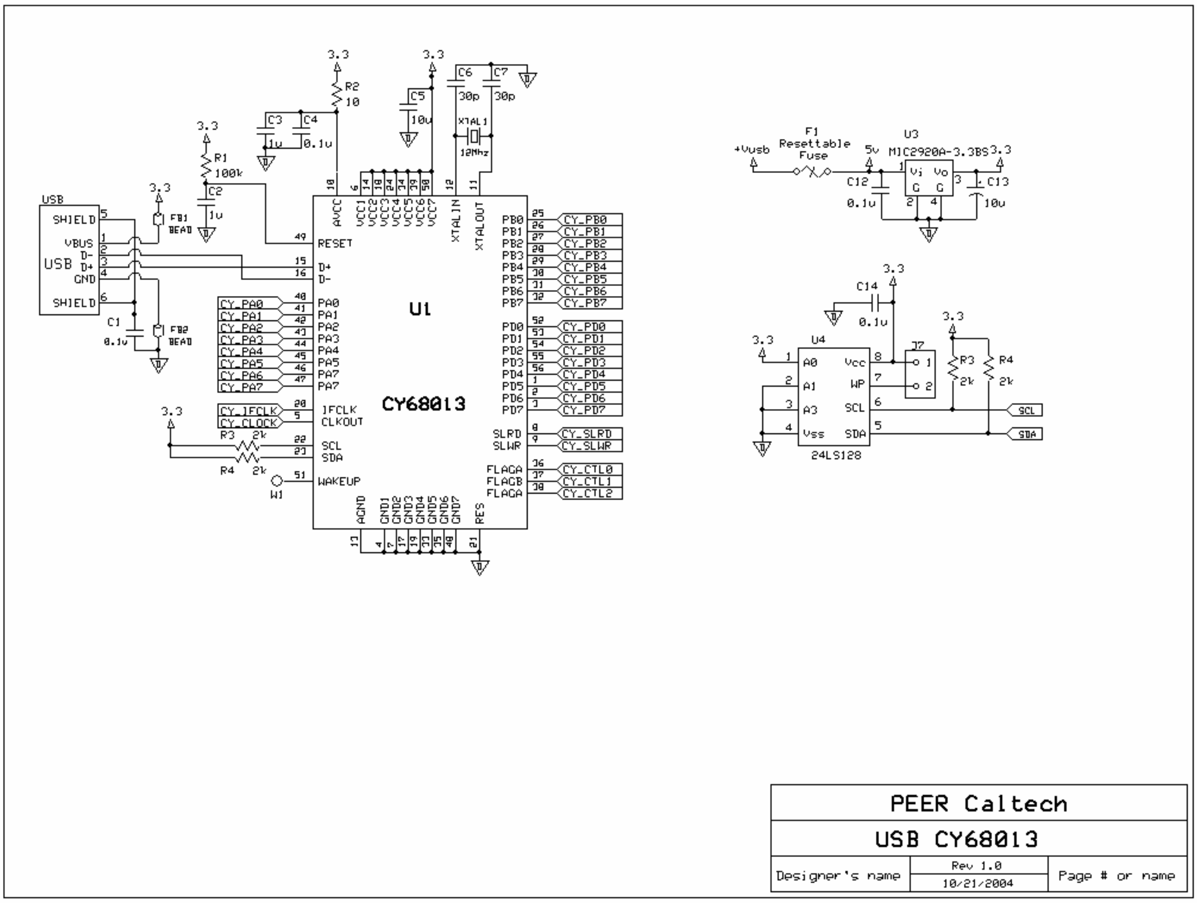


Figure 4a. XC95144 and USB20 schematics for fast scan and ultrashort pulse gating linear CCD camera

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CASE (B0~B1)                                                'BASE_UNIT 2 bits 4 combinations
        =  00 Then
                DELAY_CLK = CY_48M_CLK / 1                  '1 x 1/48M = 20ns time base unit
        = 01 Then
                DELAY_CLK = CY_48M_CLK / 256                '256 x 1/48M = 5.12µs time base unit
        = 10 Then
                DELAY_CLK = CY_48M_CLK / 256 / 256          '64K x 1/48M = 1.33ms time base unit
        = 11 Then
                DELAY_CLK = CY_48M_CLK / 256 / 256 / 256    '16M x 1/48M = 0.33 sec time base unit
END CASE (B0~B1)

CASE (A0~A7)                                                'generate SHUTTER_TIME with 1 unit increment
        =  0000 0001 Then
                SHUTTER_TIME = 1 x DELAY_CLK
        =  0000 0010 Then
                SHUTTER_TIME = 2 x DELAY_CLK
        =  0000 0011 Then
                SHUTTER_TIME = 3 x DELAY_CLK
…… …..
        =  1111 1111 Then
                SHUTTER_TIME = 255 x DELAY_CLK
END CASE (A0~A7)
```

Figure 4b. VHDL Logic for the shutter time generation in the XC95144 CPLD chip with control from the Cypress USB 2.0 MCU. This gives minimal shutter time of 20ns and as long as 6 seconds and a minimal increment of 21ns.

Results and Discussion

1. Setting up platform for field test

We have set up the test platform at Alturdyne's test site, and preliminary results have shown our instrument could detect changes during engines's normal load, overload, and fuel/air mixing ratio changes. We are collecting more data, and then also adding automatic data logging capability for the load conditions, fuel/air ratios, and the particulate emissions. This will help us systematically log the data and analyze it over long period of time.

2. Fast laser switching capability

We have upgraded our diode pumped PQS laser by improving its precise triggering capability. Now, we are able to reduce the jitter between the TTL pulse and the actual laser pulse to less than 20ns, and this value is already good enough for many applications previously only possible with EO Q-switched laser (jitter 1ns).

3. Digitally controlled fast scanning and ultra-short integration linear CCD detection

We have finished design and almost finished the upgrade for the fast scanning linear CCD camera. The upgraded CCD detection system will have all digitally controlled timing circuitry with gating as short as 21 ns, and as long as 6 seconds with minimal increment of 21 ns.

Work plan for the rest 4 quarters of the project

We see our work is within our schedule as outlined in the Statement of Work (SOW) at the start of this project.

Currently, we are finishing the following tasks:

- We are adding extra I/O ports on the current system to enable us to simultaneously log the engine conditions such as load, fuel/air ratio, along with the PM emission data;
- Upgrade the detection system using USB2.0 which gives us 500 scans/sec or 50 scans/sec for 10 lasers;
- The electronics for the data acquisition so that we could control and instrument with notebook computers and therefore use it in the field.

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

References

1. Z. Hong, H.Z., J. Chen, J. Ge, *Laser-diode-pumped Cr4+, Nd3+:YAG self-Q-switched laser with high repetition rate and high stability.* Applied Physics B., 2001. **73**: p. 205-207.
2. Yung-Fu Chen, S.W.T.a.S.C.W., *High-power diode-pumped Q-switched and mode-locked Nd:YVO4 laser with a Cr4+:YAG saturable absorber.* OPTICS LETTERS, 2000. **Vol. 25,**(No. 19): p. 1442.