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

Quarterly Technical Progress Report

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Abstract

In this quarter, we have rebuilt a new multiwavelength light source which boasts over 300mW combined output from 10 different wavelengths and loss of less than 15% for each wavelength and it is much more flexible than the previous version too. Compared to the previous version, the efficiency and construction complexity have been dramatically improved for field use. We also have refined the diode pumped laser which now could give out more pulse energy than before, and this will improve the signal to noise ratio. We are also using the water jet we built in the 2nd quarter to calibrate our laser scattering outside the engine exhaust, and water jet calibration data is used to simulate the scattering results in the exhaust line.

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Executive Summary

During the 10^{th} quarter of this project, we continued to make several major upgrades to the laser sources. In this report, we detail all the efforts and changes we have made. We also collected some field test data using the previous system, and compare it with past results.

1. The improvements in the laser source
   - Before, we used dichroic mirrors at 45º AOI for coupling different lasers, this design although has the advantage of low cost because only low precision dichroic mirror is used, it has quite low coupling efficiency due to large remaining reflections outside reflection band. We finished the construction of a light source based on small Angle Of Incidence (AOI) dichroic filters, which could couple 9 wavelengths with efficiency over 80% for each wavelength. Besides high coupling efficiency, it also has high flexibility in changing configurations to different wavelengths and combinations of multiwavelength input and output.
   - We improved the PQS laser system used in our laser source --- we solved the problem of using large pulse energy laser head because of the bulky size of the thermal electric cooling used before for the PQS laser system.

2. On-going field test
   - In the laser Quarter we have problem correlating the data we collected with our simulation data, we have been working to collect the calibration data using our water jet system that we built in Quarter 3.

3. Improvements in data logging
   - We have automated the logging the generator’s conditions along with the particulate emission data process for faster and reliable data collection, retrieval and achive.

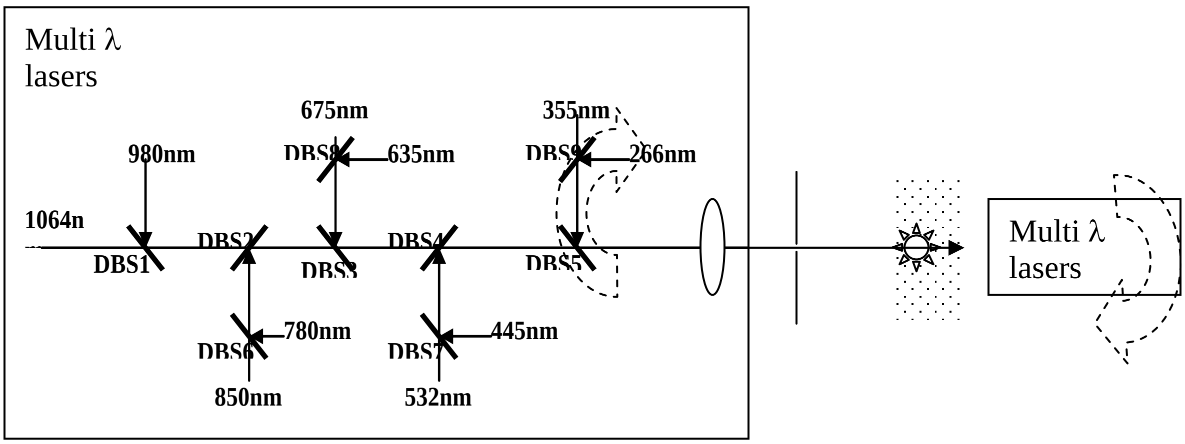
Experimental

1. On the new multi-wavelengths laser source

a. Previous design

The laser source used in our project requires the coupling of 9~10 wavelength in the collinear fashion. Our previous coupling design was based on using dichoric mirrors which reflects at 45º Angle of Incidence (AOI).

Below is the block diagram of our old design, we used 9 dichroic mirrors at 45º to couple the light. This design is complicated although technically more readily available before, because optics at 45 AOI are quite mature, and all the optics below are readily available. But the trouble



here is that the 45 AOI optics introduces quite some loss for the transmitting wavelengths, because there are at least 1 45 AOI mirror (for 266nm/355nm), and as many as 5 mirrors (for 1064nm), used in the transmitting mode in the system, the residual reflectivity for each of the mirror could introduce loss at large as 15%. This translates into a loss as large as 60% for the 1064nm wavelength. Also, the wide transition bandwidth for 45 AOI mirrors means that the separation of the closest wavelengths has to be over 7% of the wavelength (from 99% to 10% reflectivity), i.e. at 800nm, the closest 2 wavelengths have to have a difference of ~60nm. If we need to compare the scattering of the closest wavelength, e.g. separated by 20nm, it is almost impossible.

The telecom boom several years ago brought many innovative technologies developed at the same time. One of these technologies is the dielectric filters. Originally developed for Dense Wavelength Division/Multiplexing (DWDM), nowadays, dielectric filters with high transmission (over 90%) or reflectivity (over 99%) over very wide transmitting/reflecting wavelength band (spanning from UV to IR, i.e. 350nm to 1100nm), and at the same time very narrow reflecting/ transmitting band (less than 1% of the total wavelength) are becoming more and more mature and readily available in the UV-visible-IR band.

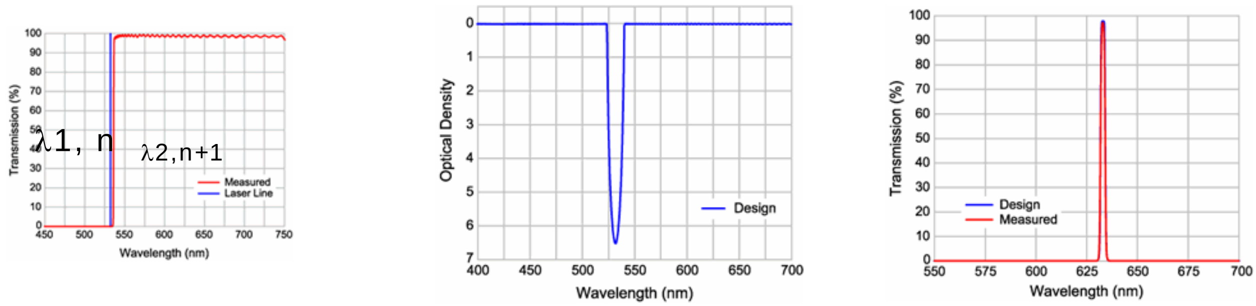


Figure 1. Typical spectral curves of the new dielectric filters (www.semrock.com)

The above figure (courtesy Semrock, Inc. www.semrock.com) shows some of the typical reflectivity and transmitting curves of the dielectric filters now available. The left one is the long pass filters, it features a sharp rise feature (from 99% to <5% reflectivity change in less than 0.5% of wavelength); the middle one is a typical narrow band blocking filter, and it has a narrow blocking band --- only 2% of the bandwidth, and transmits well over 95% from 350nm to 1100nm; the right one is a transmission curve of the typical narrow band pass filter, and it has a narrow passing band (over 90%) --- only 0.5% of the bandwidth, and blocks 99% from 350nm to 1100nm. We decided to use the long pass filters and the narrow band pass filters to construct our new multi-wavelengths light source, see figure 2 for schematic when only use long pass filters.

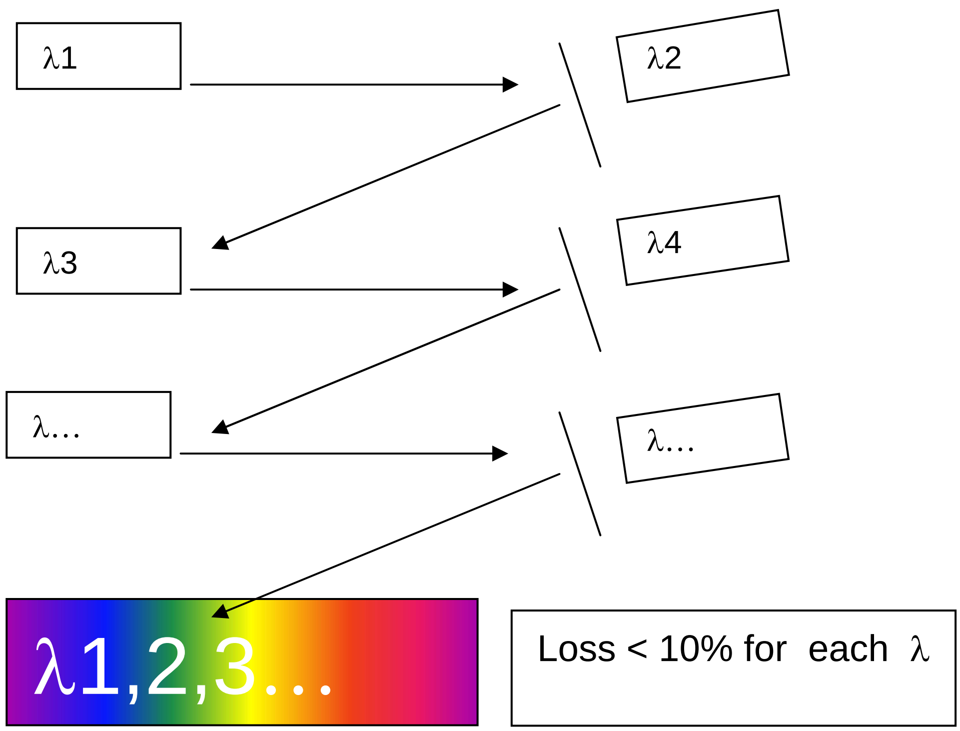


Figure 2. Multiplexing different wavelengths from short wave (starting from $\lambda 1$) to long wave (λn)

In February, we first built a smaller scale one which also uses narrow band pass filters, and it multiplexes 4 wavelengths together.

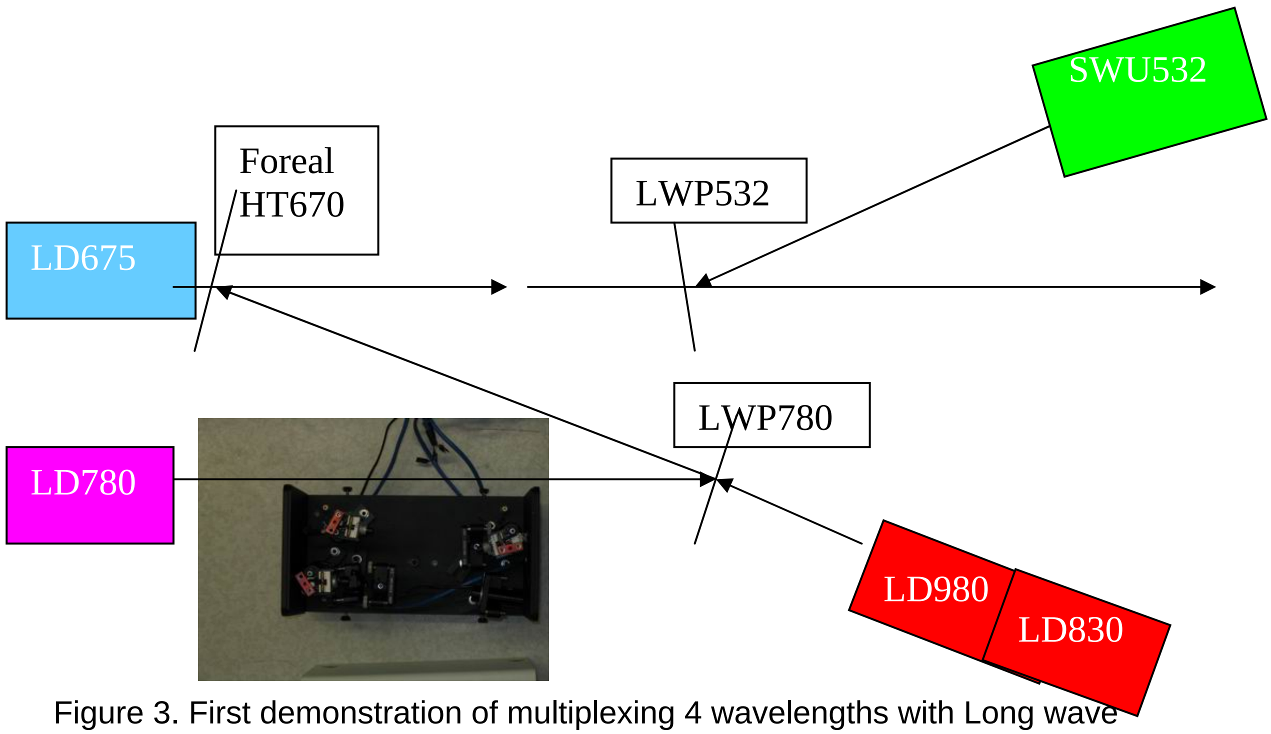


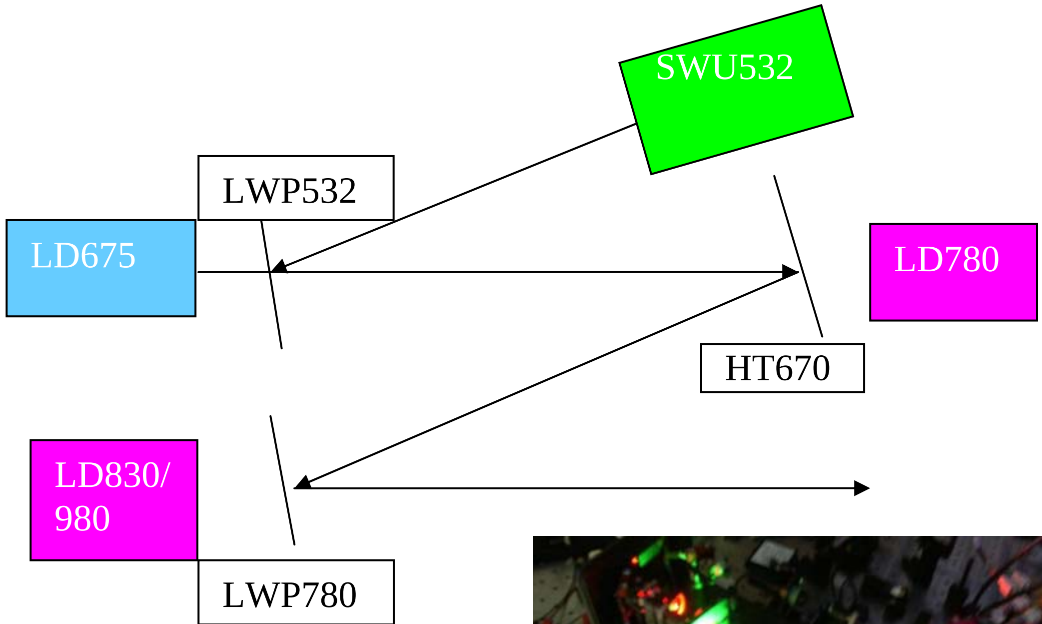
Figure 3. First demonstration of multiplexing 4 wavelengths with Long wave pass (LWP) and narrow pass (HT670) filters

We first measured the output power from each diode laser directly at a given current, and then measured the power of each diode laser at the output port after multiplexing by turning on only one laser on at a time. Table 1 lists the direct power output and the multiplexed output,

Table 1. Direct power output and multiplexed power output of the 4 laser system in figure 3

	830nm	780nm	675nm	532nm
Direct Power	120mW	85mW	32mW	16.0mW
Multiplexed Power	97mW	74mW	28.5mW	15.8mW

In our previous multi-wavelengths laser source using 45 AOI optics, we could not efficiently couple the 830nm and 780nm as their separation is too narrow (the loss is as high as 40%). Now, it is possible thanks for the new dielectric filters. However, we could see that the loss is quite high for the 830nm band as it has to pass through 2 mirrors.
Now, we are using the light source which uses the schematic in figure 4 right now and has less than 10% loss for each and every wavelength (Table 2).



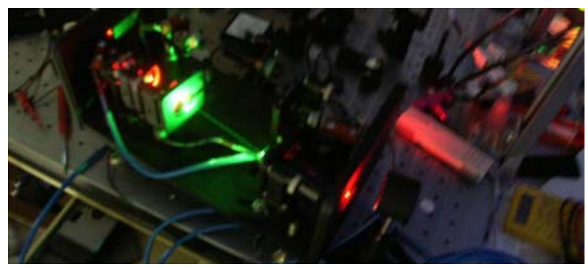
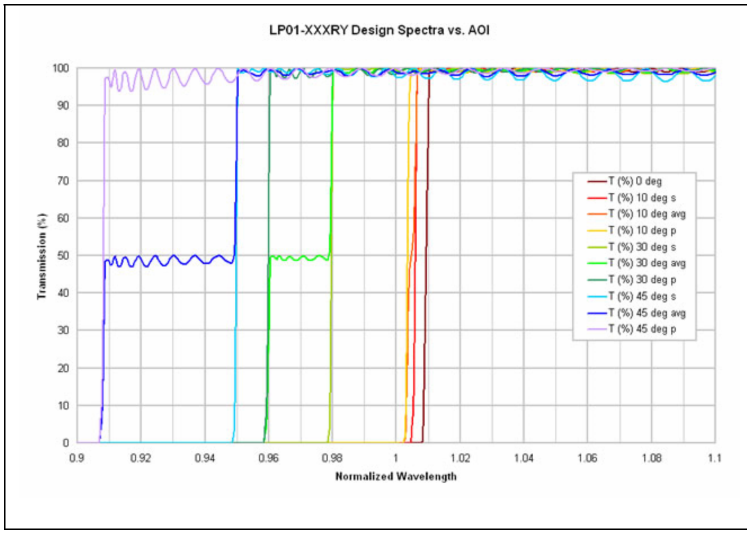


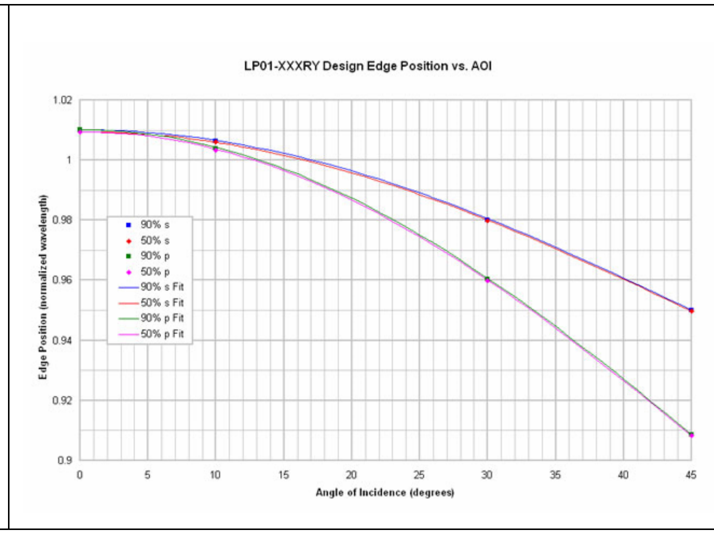
Figure 4. A variation of the scheme used in figure 3, which produces less than 10% loss for the wavelengths multiplexed.

Table 2. Direct power output and multiplexed power output of the 4 laser system in figure 3

	830nm	780nm	675nm	532nm
Direct Power	120mW	85mW	32mW	16.0mW
Multiplexed Power	117mW	84mW	31mW	15.0mW

When using the dielectric filters, they are used at small angle of incidence, and this small AOI creates shift in the original specification curves of the filters which are designed at 0 degree AOI. Figure 5 from the manufacturer gives the guidance in predicting the shift when used at small AOI and larger AOI. As we could see when used at larger AOI, e.g. 45 deg, the difference in shift for S and P polarizations create large transition bandwidth for the optics, therefore compromising the filters' ability in multiplexing the narrowly separated wavelengths.





In our setup, the filters are used at small angle of incidence, i.e. 8º AOI, and this creates shift less than 0.5% of the shift, and for LWP532 (~2nm shift) and LWP780 (~3nm), the optics still work perfectly for multiplexing 532nm and 780nm as shown in figure 3 and figure 4.

b. Improved DPSSL now could output more power in the multiplex platform

Up to now, we are limited to use the low pulse energy DPSSL laser (10µJ/pulse at 1064nm) in the multi-wavelengths laser source because the more powerful DPSSL requires two-stage TEC cooling when the pump laser diode is over 2W. Two-stage TEC makes the TEC power supply quite bulky and quite inefficient. The low pulse energy at 1064nm translates into even lower pulse energy at 532nm and much tinier energy at 355nm after harmonic conversion. In our current 10 wavelengths laser setup, we are using a CW 1064nm and a 532nm laser source, and the 355nm laser source has only 0.5µJ/pulse. Therefore, the signal to noise ratio is quite poor when probing the sample area with 355nm laser, due to the number of photons at 355nm is just too limited. We tried to improve the signal to noise ratio by reducing the integration window (shutter time) of the ELIS CCD camera, but it is still quite poor. The response of the ELIS at 355nm is also only about 40~50% of the peak response at ~675nm, and it is also much lower at 1064nm (see figure 6). The signal to noise ratio at 1064nm is barely acceptable because the number of photons at 1064nm is a lot more than the photons at 355nm. Therefore, it is very important that at the same time while we reduce the shutter time, we also improve the probing laser energy and power.

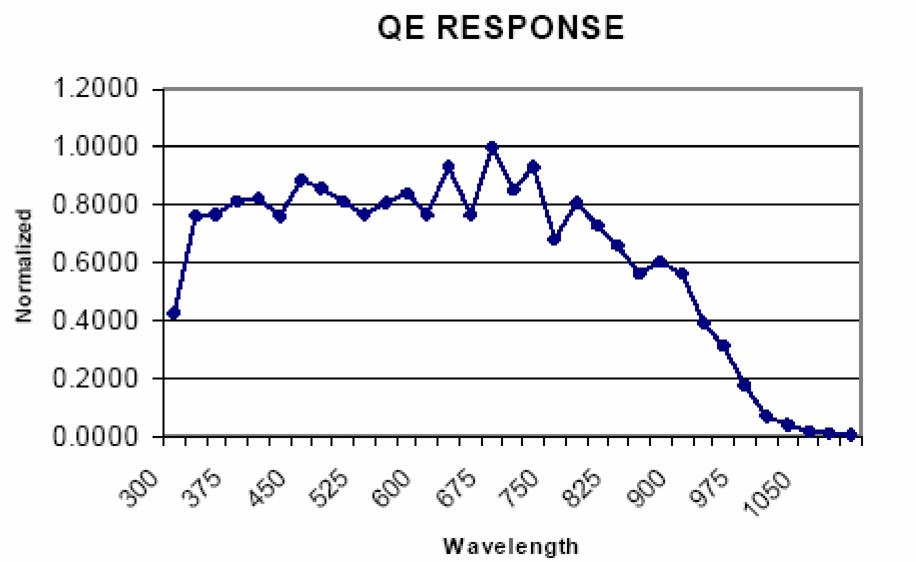


Figure 6. Quantum efficiency of ELIS1024 at different wavelengths

For the previous DPSSL laser with 5W pump diode, we first mount the pump laser diode on the same platform where our 2W pump diode is mounted. The platform has a TEC peltier cooler with a power of only 5.0W. This peltier cooler is running at the limit for the 5W laser diode, since the 50% efficiency 5W laser diode has a heat dissipation of at least 5W. To keep the temperature constant, we have to use 2 x 40 W peltier cooler underneath the platform base to keep the base temperature under 10ºC. This setup requires a complete 200W switching power supply to power the 2 x 40W peltiers, and also makes the platform too bulky to fit into the system. Therefore, we have been stuck to the lower power DPSSL source.

In March, and into April, we changed the original 2W pump diode design by using only one 35W peltier for the platform. This 20W peltier is powerful enough to keep the pump diode temperature at 25ºC even when the external temperature is as high as 50ºC. This upgrade is still in progress. We hope to include this in the next laser source which feature <10% loss for each wavelength.

c. Upgrade the integration of laser pulsing sequence and data acquisition

After we migrate our ELIS1024 CCD controller from USB1.1 to USB2.0, we are using the Xilinx 95XC288 CPLD both for controlling the logics for ELIS1024 CCD chip, but also for controlling the pulsing of the ELIS1024 CCD.

Before, we have been using the I/O ports of our National Instrument E6023 multi-function board to pulse the lasers. The speed is only limited by the PC program which controls the E6023 multi-function board. We did a test program and found that the shutter time is also limited by the capability of the PC program, and it is limited to 20µsec due to the minimal time to set the I/O ports from the program. There is also extra overhead in executing the loop code, which is measured to be about 16msec. This means that we could not fire our laser faster than 60Hz. One way to solve this bottleneck is to pulse the lasers faster and bypass the current multi I/O lines in the PC program.

Now, since the CPLD has extra I/O ports for laser pulsing, we have been working to use these unused I/O ports for pulse the 10 different lasers.

Our initial VHDL code for the CPLD and the firmware for the USB2.0 controller shows that we could reduce the loop time down to 0.2msec while the shutter time for each laser is set at 0.1msec. Now, the bottleneck is only the speed in the PC program to read in the waveforms from the ELIS. We did a preliminary test and found that it is possible to have a maximum repetition rate of 120Hz. This is quite consistent with our design goal, i.e. able to collect 8~10 complete wavelengths scans in one second.

This is still an on-going progress and we hope to use it in late June.

d. Calibration of our data with water jet standard

We still have trouble correlating the engine emission scattering data with our simulation. So, from January, 2005, we have been working on to turn on our water jet again to generate mono-sized water particles. We also need to use the impact particulate analyzer again, which we used in the first year (Quarter 3) to demonstrate that the water jet was generating mono-sized distribution.

We also found that the difficulty in interpreting our scattering data with simulation is related to the weak signal at 355nm. The signal level is close to the noise level, after we did the baseline subtraction (see field test in section 2 below).

Steve at Alturdyne has been working to construct a duplicate water jet which allows us to check the size distribution with the impact analyzer (MOUDI) at PEER Caltech. We have also found another application for our multi-wavelengths laser scattering instrument --- using it to characterize water liquid content in gas pipelines.

2. The field test platform and the field test setup

a. Upgraded laser source at the test site

We have installed the upgraded laser source at the test site, and gave a demo to visiting officers from DOE. Our test results show that the signal is still weak, although repeatable, for several wavelengths, i.e. 355nm. Thus, we are working to integrate the more powerful DPSSL laser to improve the signal to noise ratio there. This wavelength is very important, because it is quite far away from other probing wavelengths, and its data is quite important for simulation and particularly important for sub micron particles.

Results and Discussion

1. Setting up platform for field test

We have set up the test platform at Alturdyne's test site, and lots of results have shown our instrument could repeatedly detect changes during engines's normal load, overload, and fuel/air mixing ratio changes. But we have inconsistency between the data we collect and the simulation data. Particularly for data at 355nm, its signal to noise ratio is still quite poor, i.e. close to one. Since 355nm laser is the only wavelength below 532nm right now, and it is quire important for data simulation and crucial for submicron particle measurement. We have to improve the power output at 355nm. We are also considering getting a laser at 470nm or 400nm (blue diode laser) to replace 355nm wavelength if we could not successfully integrate the more powerful 355nm DPSSL lasers in our laser source. We have installed our standard mono-sized water droplet generator into the field, and test it along with our instrument. We are comparing the differences between the two, and waiting for the data at shorter wavelength, i.e. 355nm to become more meansingful.

2. Improved laser power output and wavelength flexibility for the probing lasers

In this quarter, we have upgraded our laser power output for the probing laser. The power is now improved by 10% to 30% for individual lasers. We are also now able to multiplex narrowly separated lasers, e.g. 830nm and 780nm, and also as narrow as 650nm and 635nm.

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

In this 10^{th} quarter, we have finished the upgrade for the fast scanning linear CCD camera. The upgraded CCD detection system has all digitally controlled timing circuitry with gating as short as 100 ns, and as long as 6 seconds with minimal increment of 21 ns.

We are adding I/O functions to the firmware and CPLD to drive the laser diode too, and this will help us to improve the scanning speed from 50 lasers/sec to over 100 laser/sec. This means that we could finish over 10 complete scans of all 9~10 wavelengths.

Work plan for the rest 2 quarters of the project

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

Currently, we are finishing the following tasks:

- We will improve the power output at 355nm and integrate it into our probing laser source.

- We will add a wavelength at 400nm to complete the data collection at shorter wavelengths
- We are adding extra I/O ports on the USB+CPLD board to have faster data collection.
- Improve the detection system using USB2.0 which gives us over 100 scans/sec or over 10 scans/sec for 9~10 lasers;
- Finish the upgrading on 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