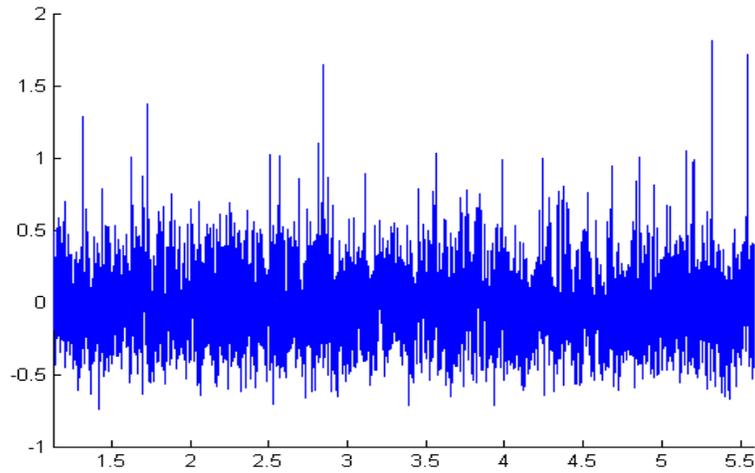


# Laser Doppler Velocimetry

Afif Elghraoui & Yuan Hung Lo



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**University of California, San Diego**

## Introduction

Laser doppler velocimetry (LDV) is a technique in which the velocity of a fluid is calculated from the measured doppler frequency shift of a laser beam scattering from tracer particles in the fluid. The relativistic doppler shift is given, for particles traveling much less than the speed of light, by

$$f_d = \frac{f_0}{1 - \frac{v_{pr}}{c}} = f_0 + \frac{v_{prb}}{c} = f_0 + \frac{v_{prb}}{\lambda_0}$$

In this formula,  $f_d$  is the frequency of the scattered light,  $f_0$  is the frequency of the incident light,  $\lambda_0$  its wavelength,  $v_{pr}$  is the component of the particle's velocity in the direction of the receiver, and  $v_{prb}$  is particle's velocity along the line from the receiver and the incident source. While there are multiple possible configurations for the LDV technique, one that is more convenient and used in this particular experiment is the so-called dual beam configuration

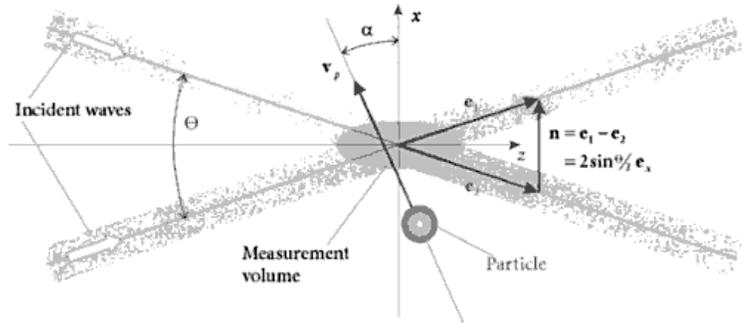


Figure 1: Dual-beam configuration for LDV

(Fig.1). Using this configuration, the position of the receiver becomes irrelevant since the two beams positioned in this manner create a third wave whose origin is not defined in the traditional sense. This is shown mathematically as follows.

$$f_1 = f_0 + \frac{v_{prb1}}{\lambda_0}, f_2 = f_0 + \frac{v_{prb2}}{\lambda_0}$$

$$f_D = f_2 - f_1 = \frac{v_{prb2} - v_{prb1}}{\lambda_0} = \frac{2 \sin\left(\frac{\Theta}{2}\right)}{\lambda_0} v_p$$

In the above formula,  $v_p$  is such that the angle  $\alpha$  is zero, and  $\Theta$  is as shown in Figure 1.

Because the frequency shift is negligible compared to the frequency of the incident light, it is advantageous to superpose the two beams on the detector such that it registers beats. The beats have a

more easily detectable frequency that is equivalent to the difference of the frequencies of the two beams that formed it.

### Experimental Methodology

Fluid flow is achieved by a gravity pump. The velocity of the flow is regulated by either changing the initial height of the fluid or by tightening or loosening a clamp at the end of the hose. A 2mW 633nm He-Ne laser was the light source used in this experiment. As seen in the setup (Fig. 2), a prism is used to divide the beam into two beams with roughly equal intensities. The two beams made parallel by use of a mirror pass through a first lens whose focal point is aligned with the center of the flow tube. A second lens is positioned so that its focal point also coincides with the center of the tube so that the lens acts as a collimator. Finally, a third lens focuses the light onto the detector. Unscattered light is blocked from entering the detector by an iris, and a red filter is placed on the detector to block the majority of light from other sources in the room. The amplified and DC-coupled signal from the detector is recorded and analyzed using MatLab using Chronux ([www.chronux.org](http://www.chronux.org)) software.

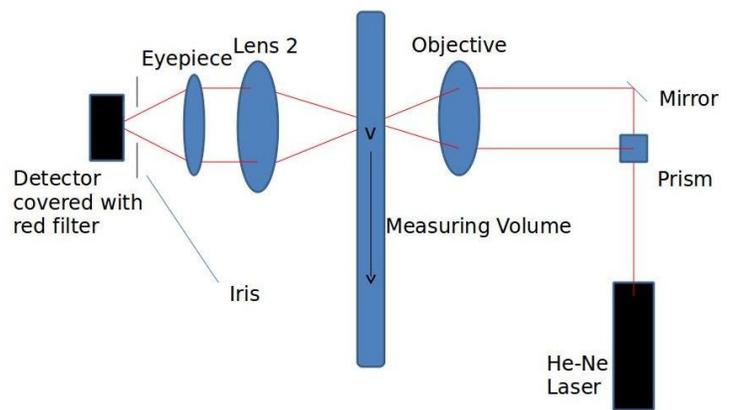
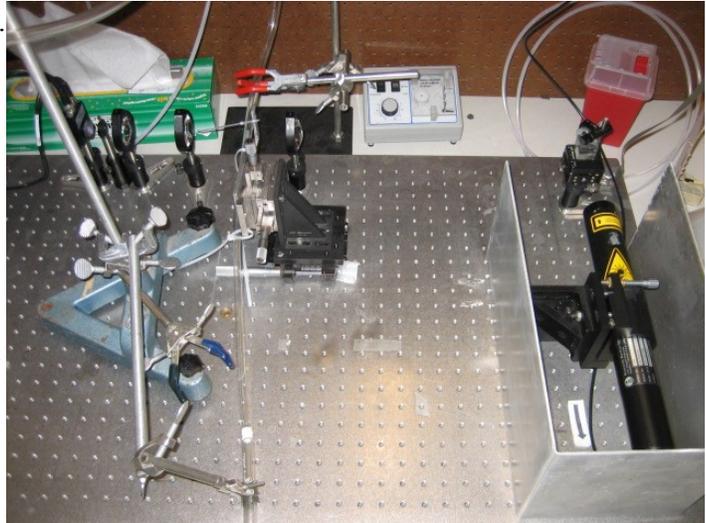


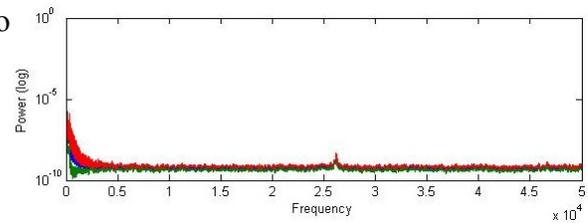
Figure 2: (above) Experimental setup. (below) Schematic depiction of experimental setup

The data were analyzed using multitapered spectral analysis implemented in MatLab by Chronux. In this method, a Fourier transform of the raw data is taken and multiplied to each of several tapers. The resulting spectra are averaged, which allows for safer interpretation of the results due to the statistical reliability it introduces.

## Results

### *Baseline*

Multiple data sets were taken of stationary fluid to measure the electronic, ambient light noise, and other unaccounted for noise that incurred in the laboratory environment. Fig. 3 shows one such trial of baseline recording. There is an unknown distinct frequency peak at roughly 27 kHz and it is systematic throughout all recordings. This noise peak may be the result of high frequency cut-off built into either the DAQ card or the computer electronics. Results from previous years have also shown a significant noise peak arising between 20 kHz to 30 kHz range, thereby suggesting that the source of error is inherent in the lab equipment. Furthermore, in the 0 to 5 kHz frequencies range, there is a pronounced high amplitude systematic noise band of unknown origin. Both peaks were neglected while analyzing actual bead flow data.



*Figure 3: Semi-log plot of Power vs. Frequency for stationary fluid*

### *Flow Tube Variation*

Two measurement volumes were used during the course of the experiment – one was a 25 ml clear plastic pipette (diameter 1.0 cm) and another was a clear flexible plastic hose (diameter 1.0 cm). The plastic hose measurement volume was able to conduct the necessary laminar flow for consistent bead flow because the entire channel has a constant diameter, so there was nothing to disrupt the flow and consequently the signal.

### *Bead Size Variation*

Two different bead sizes – 4.5  $\mu\text{m}$  and 5.8  $\mu\text{m}$  – were utilized throughout the experiment. While most data was collected using 5.8  $\mu\text{m}$  beads, results obtained using both bead sizes showed no obvious disparities.

## Flow Velocity Variation

In the first series of experiments, the polystyrene bead flow rate was measured consecutively with seven different fluid velocities in multiple trials. Fig. 4 shows the beat frequency shift as fluid velocity increases from top to bottom. Interestingly, another frequency peak roughly 20 kHz higher than the expected signal was recorded in every trial, suggesting the presence of another systematic noise that was only present when the beads were flowing.

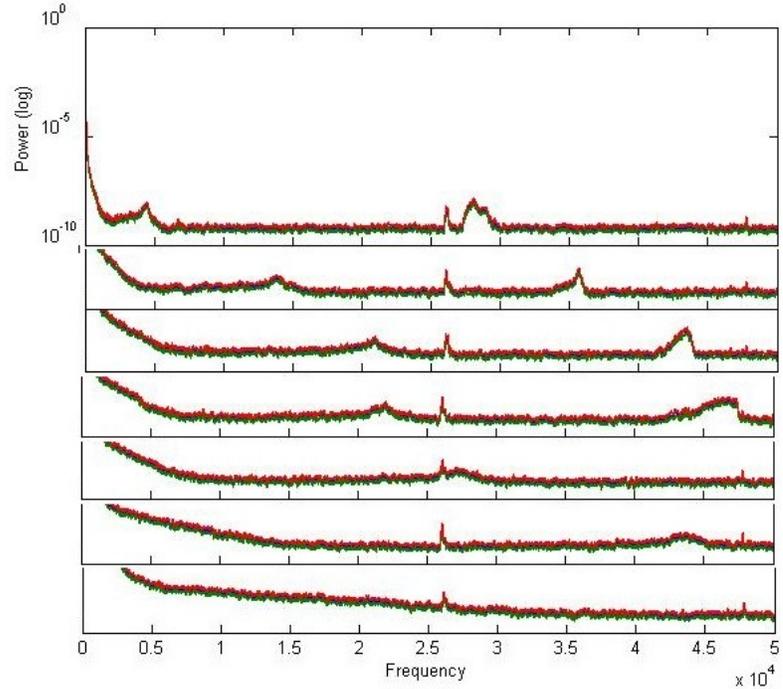


Figure 4: Semi-log plots for fluid flow at various velocities

An estimated beat frequency was calculated by measuring the fluid output per unit time and using that value to calculate an expected beat frequency. For the second trial in the series, the bead velocity was measured to be  $4.1 \pm 0.1$  cm/s, and the theoretical beat frequency turned out to be 17 kHz. The observed beat frequency registered by the photodiode was 14 kHz. Since the bulk fluid velocity was not representative of the actual bead velocity – beads colliding with one another may randomly reduce their speed – the velocity component in the Doppler shift equation overestimated the bead velocity, and it was therefore safe to assume that the theoretical frequency will be larger than the observed value. In the 7<sup>th</sup> trial, no peak was observed because the fluid velocity exceeded the Nyquist frequency of 50 kHz. The highest beat frequency that was used in our setup was 50 kHz, which translates to a fluid flow velocity of roughly 10 cm/s. The computer was unable to process over 5MB of data using the inefficient Chronux software, so the graphs below were generated using 1 second of data.

Another series of four frequencies were recorded to reinforce the previous set of data. Fig. 5 shows once again the frequency peaks that changes with respect to fluid frequencies. The second trial was picked to compare the observed and theoretical beat frequency. This time the measured bead velocity was  $0.76 \pm 0.1$  cm/s, which translated into a beat frequency of 3 kHz. The observed frequency was 1.6 kHz. Once again, the theoretical value was larger than the observed one. This verified that the

observed peaks were indeed beat frequencies generated by the flowing beads in the solution.

### Discussion

Our experiment successfully demonstrated that the velocity of micron-sized particles inside a bulk mobile fluid could be measured and quantified using the principle of Doppler shift. It further suggests the possibility of using LDV as a viable medical tool in non-invasive measurements of flow velocities of micron-size particles in a dynamic fluid such as the circulatory system.

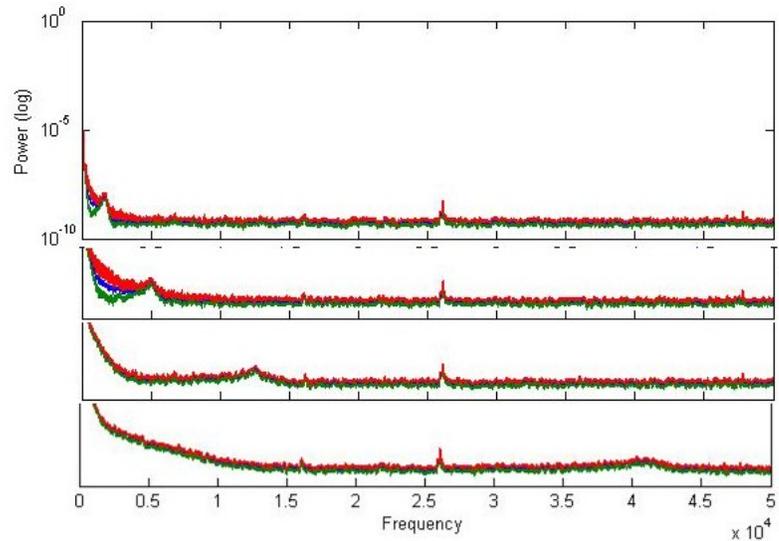


Figure 5: A second trial of varying fluid flow velocities

While we have successfully registered changes in beat frequency peaks as we varied the fluid velocity, the linear relationship between beat frequency and bead velocity, as predicted by the Doppler shift equation, was not observed in the actual experiment. The  $f_b/v_b$  ratio for first and second analyzed recording was 3.4 and 2.1 respectively. The different ratios indicate a non-linear relationship in the Doppler shift formula. This difference may be resolved to obtain a linear relationship by analyzing more accurate trials and calculate and compare their respective  $f_b/v_b$  ratios.

One of the most difficult challenges we faced was in collecting consistent data. Not enough time was spent to systematically construct an experimental system that generates consistent results, so in many of the trials, the frequency peaks would either fluctuate or fail to register altogether.

### Future Direction

Due to the limited amount of time we had to work on this project, we had very little time to push the project forward once the system was set up. However, there are many interesting questions that we would like to investigate. How do the experimental parameters such as laser beam intersection angle or the laser beam wavelength and intensity influence the measured beat frequency? Changing these parameters can potentially yield more pronounced and accurate frequency signals that better reflect the movement of the micro particles. In addition to the instrumentation itself, how does bead concentration and size affect the frequency signal? Could higher concentration generate a higher

intensity peak, which can make beat frequency detection easier by visualization? Also, is there an optimal particle concentration that can yield the maximum amount of scattering light? Are other experimental setups – such as one with the photodiode in the same enclosure as the laser beam or a system where one beam is shifted and another reference beam is not shifted – generate more consistent and accurate results than the setup employed in this experiment? All these parameters and a myriad of other can be tested and optimized to turn LDV into a truly viable system in medical applications.

Perhaps in the future, more emphasis can be placed on the medical applications of LDV by introducing biological systems containing dynamic fluid flow that can be measured and quantified using LDV. Not only will this be more interesting, if successful it will also greatly demonstrate the proof of principle of LDV and its potential application in the practice of medicine.

### **Acknowledgements**

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