

AE3051 Experimental Fluid Dynamics

UNSTEADY VELOCITY MEASUREMENTS IN A JET USING A LASER DOPPLER VELOCIMETER

Objective

In this lab, you will learn the basic principles of laser Doppler velocimetry. You will use a laser Doppler velocimeter to measure velocity across a jet in a coflow; this is the same flow used in the hot wire anemometer lab. You will obtain similar data to that measured with the hot wire and compare the results for the two systems.

Please note the following safety precautions very carefully:

- 1. Your eyes, and your friends' and instructors' eyes, can get hurt by lasers. Take no chances or shortcuts: laser beams travel a lot faster than you can react! To ensure safety, no one who has not read the instructions thoroughly can be allowed near the experiment. Anyone disobeying safety rules will be ordered out of the lab immediately.**
- 2. Remove all rings and watches when working in the vicinity of lasers.**
- 3. Do not go to the back side of the test section unless directly supervised by a TA.**
- 4. Do not open the curtains if they are closed. Only the person in charge may do this.**
- 5. Do not lean over the laser beam, or stick your head between the laser transceiver and the test section when the laser is on.**
- 6. Do not touch the laser or fiber optic coupler, whether the laser is on or off. If they go out of alignment, the TA will realign the system. Also, do not touch the transceiver unless instructed to.**
- 7. Be very careful where you move the traverse: you must know clearly where all the reflections are (if any)!**

Background

In many flows of interest, it is not desirable to use intrusive probes to make measurements. There may be several reasons for this. First, it may be physically difficult to design a probe that can survive in the flow to be measured. For example, consider the problem of measuring velocity inside the passages between the blades of a jet engine compressor while the engine is operating. In other situations, the presence of the probe itself can greatly change the flow field

that is being measured. As an example, consider a Pitot tube inside the test section of a small supersonic wind tunnel, or a probe inside a vortex that is shed from a wing. A third problem occurs when several properties are varying simultaneously, as in a turbulent flame (e.g., inside an engine combustion chamber). For example, the velocity, pressure, and temperature may all be changing from one instant to the next. Most probes, such as Pitot tubes and hot-wires, respond to changes in several of these properties, and so it may be quite difficult to separate out the part due to velocity alone. Still another problem arises in two-phase flows (not all gas): there may be liquid droplets, e.g., liquid oxygen in the Space Shuttle main engine turbopumps and jet fuel sprays in engine combustion chambers, or solid particles, as in the exhaust from a solid rocket motor. Droplets and particles can clog or even instantly destroy sensitive probes.

The laser Doppler velocimeter (LDV, also known as a laser Doppler anemometer - LDA) is a non-intrusive measurement device that is sensitive only to velocity. Thus, it is one of just a few techniques that can be used in complex flowfields to measure velocity. This is why, despite the greater cost and difficulty usually involved in making measurements with this technique, laser velocimeters are highly regarded instruments.

Principles of Operation of LDV

When electromagnetic waves are scattered from moving objects, the scattered light has a frequency which is different from that of the incident waves. This is similar to the phenomenon that we have all observed: The horn of an oncoming car changes pitch suddenly as it passes us. The difference in frequency is known as the Doppler shift, and is proportional to the relative velocity between the moving object and the observer (or receiver). This principle is also used in radar and laser speed detection.

A laser is a source of radiation that *generally* has most of the following properties; it is: 1) well-collimated, which means the beam will not diverge or change in size much; 2) highly coherent, meaning its electromagnetic wavefronts are all in phase; and 3) nearly monochromatic, which means that the radiation is composed of a very narrow range of wavelengths. Thus, it is ideal for making measurements of Doppler shift; you can precisely and easily calculate what the shift should be for a given velocity. Unfortunately, the frequency of light is very high, and the Doppler shift caused by the kinds of velocity that we encounter is

extremely small by comparison. So, if one were to shine a laser beam at a moving object, measure the incident light frequency and the scattered frequency, and try to find the difference, one would probably find that one's measuring instrument cannot make out the slight difference between these frequencies. The solution to this problem is to find the difference in Doppler shift caused by two beams, hitting the same object at slightly different angles. If one tries to measure only this difference, one can get good accuracy. This is the principle of the dual-beam interferometer-type LDV that is widely used today (see Figure 1).

Dual-Beam Laser Velocimeter

When two laser beams of the same frequency cross in a small region, stationary interference fringes are formed, as shown in Figure 2. This is because light behaves as a kind of wave, with an amplitude and a phase. At some points, the two beams are in phase and the amplitudes add together; there the light's amplitude is large. At other points, the amplitudes cancel each other out (out-of-phase), and you get nothing at all. Thus, fringes are formed, with each bright fringe being a thin disc inside which the light intensity is large. The bright fringes are separated by dark fringes, where there is hardly any light intensity at all.

As seen from Figures 2 and 3, the region where the fringes exist is an ellipsoid of revolution. Consider a small solid or liquid particle moving perpendicular to the fringes (as shown in the figure). At the same time, imagine that a highly sensitive light detector is looking straight at the light being scattered from the ellipsoid. As that particle enters the first fringe, it starts scattering more light. The detector sees the received light intensity increasing. The intensity reaches a maximum when the particle is centered on the fringe, and decreases thereafter. As the particle reaches the center of the first dark fringe, the intensity sinks to a minimum, and the slowly starts increasing again as the particle approaches the next bright fringe.

As the particle crosses the ellipsoidal region (the measurement volume of the LDV), the detector sees the light intensity oscillating in a sinusoidal fashion; this is known as a **signal burst** (as seen in Figure 3). If the particle moves faster, the same number of fringes will be crossed in less time, so that the **frequency** of the sinusoidal signal will increase. Thus, the frequency of the signal received at the detector is proportional to the speed of the particle along the direction perpendicular to the fringes. Note that it does not matter, as far as the

frequency is concerned, how fast the particle is moving in other directions. Only the speed at which it crosses the fringes is important. Thus, the dual beam LDV is sensitive only to the component of velocity that is perpendicular to the bisector of the two laser beams, and in the plane of the beams.

Let us try to quantify this relationship. The frequency of the detected signal (which can be rigorously shown to be exactly equal to the Doppler shift) must be directly proportional to the velocity component, and inversely proportional to the **fringe spacing** (the distance between the middles of two successive bright fringes). The fringe spacing, d , for two beams of wavelength λ , intersecting at a half-angle θ , is given by:

$$d = \frac{\lambda}{2 \sin \theta} \quad (1)$$

Thus, the Doppler shift frequency f_D is simply,

$$f_D = \frac{U}{d} = \frac{2U \sin \theta}{\lambda} \quad (2)$$

where U is the velocity component perpendicular to the fringes.

As an example, consider an Argon-ion (Ar^+) laser such as the one used in our LDV system. The Ar^+ laser can output various wavelengths; the wavelength used here is 514.5 nm (the corresponding frequency of the laser light is 583.1 THz). If particles in an air flow are moving at 10.0 m/sec and the half-angle between the laser beams is 4.0° , then the fringe spacing is 3.69 μm , and the Doppler shift is 2.71 MHz (a frequency of 1 MHz means that the time between two successive peaks of the signal is 10^{-6} sec).

Focal Length, Beam Spacing, and Fringe Spacing

Notice that in the above calculation, the only parameter that depended on the flow was the flow velocity; the other parameters (laser wavelength and half-angle) depend on the instrument. Thus, the LDV requires no calibration, unlike the hot-wire anemometer. The half-angle (θ) between the beams is determined simply by the optical set-up, i.e., by the spacing (D) between the two beams when they come out of the front focusing lens of the LDV, and the focal length (f) of the lens, which is the distance from the middle of the lens to the focal point where the beams cross.

Bragg Cell and Moving Fringes

While the simple dual-beam LDV system (such as that shown in Figure 1) is able to isolate and measure a single component of the flow velocity, it can not differentiate between positive and negative velocities. If the flow were to change direction, e.g., from forward to backward, a particle moving through the fringes with the same velocity magnitude would produce the same Doppler shift frequency f_D for either direction of motion. To overcome this, one of the two laser beams in a dual-beam LDV system can be passed through an acousto-optical modulator* (called a **Bragg cell**) that can shift the beam's frequency slightly (e.g., by 10's MHz). When the two laser beams intersect, the fringes that are created are no longer stationary in space. The fringe pattern (i.e., the locations of the peaks and valleys) moves at a rate determined by this frequency shift. Now the detector will see a signal with an amplitude that oscillates at a frequency (f_{signal}) that is different than f_D . Assuming that the fringe pattern moves in the "forward" or "positive" flow direction, the signal frequency is given by

$$f_{signal} = f_{shift} + (\text{sign}(U) \times f_D) \quad (3)$$

For example reconsider the particle describe above, which was moving at 10.0 m/s through a fringe pattern with a spacing of $3.69 \mu\text{m}$ ($f_D=2.71 \text{ MHz}$). If the second laser beam was shifted by 10.0 MHz, causing the fringe pattern to move at 10 MHz in the negative direction of the flow, then the light scattered by the particle as it moved through the measurement volume would have an amplitude that oscillated at a frequency of $10+(+2.71)=12.71 \text{ MHz}$ if the particle was moving in the forward direction, or 7.29 MHz if it was going backward.

Dual-Beam, One-Component, Backward Scatter LDV System

The LDV system for this lab uses a 300 mW Ar^+ laser, fiber-coupled to a transceiver unit (see Figure 4). The light coming out of the laser goes to a fiber-coupler unit that first uses a beamsplitter to separate the original beam into two beams. One of these beams is then passed through a Bragg cell. The two beams are then sent to the transceiver unit through fiber optic

* In the acousto-optic modulator, the laser beam interacts with sound waves generated (typically by piezo-electric transducers) in an optically transparent material. The laser beam is diffracted off the index-of-refraction pattern caused by the pressure waves in the material.

cables. The laser beams pass through a lens in the transceiver, and are focused down, so that they cross at the focus of the lens and form the measurement volume.

Light Collection and Signal Processing

The back-scattered light from the focal volume is collected by a lens located in the transceiver, and focused in front of a photomultiplier, a light sensitive detector that can detect even very low light levels. The photomultiplier, when activated by a high voltage across it, converts incident light (photons) to an electric current (electrons) with a significant gain. Typically, a single input photon striking the photomultiplier can result in a large number (e.g., 10^4) output electrons. This electron current, when passed across a high resistance, produces a voltage that we measure (see Fig. 4 in the Unsteady Combustion Lab). The photomultiplier output goes to the Photodetector Module (PDM), which also controls the photomultiplier input voltage (and thus the detector's gain).

Since the receiving optics are located on the same side of the tunnel as the transmitting optics, our LDV uses the **backward scatter** (or **backscatter**) configuration. It turns out that when the diameter of a scattering particle is about the size of the wavelength of the light, most of the light scattered by the particle goes right past the particle, for example a typical value would be 90% of the light in this forward scattering direction. Only about 1% of the light comes straight back along the path of the incident beams, in the backscatter direction. On the other hand, our usual experience of looking in mirrors tells us that, when the size of the scattering object (say, a mirror) is much larger than the wavelength of the light, the light will not go around the object, but gets reflected right back. Thus larger particles will scatter a larger fraction of the incident light in the backward direction.

The Digital Burst Correlator

The output from the PDM goes to the **FSA** (Frequency and Size Analyzer) digital signal processor. The burst signal is first sent through an 80 MHz low pass filter, then downmixed with a user-chosen frequency; essentially the user-chosen frequency is subtracted from the signal. You can use this to subtract part of the shift in the signal frequency that was added by the Bragg cell. For the example given above ($f_D=2.71$ MHz, 10 MHz Bragg shift), a downmix frequency of 5 MHz would convert the 12.71 MHz burst frequency to 7.71 MHz.

Then the signal is sent through a bandpass filter to remove content at frequencies that are nowhere near the expected frequencies based on the estimated flow velocities; this is required because there are many possible sources of spurious electrical signals (“noise”). If what remains is the true (Doppler shift) signal caused by the particle crossing the fringes, the remaining signal would ideally just have one frequency. After being filtered, the digital signal processing units digitize the signal and determine the frequency embedded in the burst (similar to what could be achieved with a discrete Fourier transform). This part of the FSA electronics is called the **burst correlator**.

The system also includes a **threshold** for detection. Unless the burst signal has an amplitude of at least some minimum value, say 30 mV, the electronics can reject it. For example if the signal is too weak and buried in noise, no useful velocity measurements can be made. This fact puts the burden entirely on the operator of the system to ensure that the signal *going into the correlator is of good quality, (good visibility)*. *In other words, if you can not see a clear Doppler signal on an oscilloscope, do not expect the burst correlator to see one either.* Of course, if you amplify a noisy signal enough, the unit will faithfully find some frequencies in the noise signal, and may output useless data. The frequency counted may be that of the nearby radio station instead of the Doppler shift, and you may get supersonic flow velocities from your low-speed flow!

Seeding

Note that a valid signal results only when a solid or liquid particle crosses the measurement volume. *The velocity measured is actually of these particles, not of the air itself!* Thus, care must be used in ensuring that the particles present in the flow are those that are so small that they move at essentially the same speed as the flow. In other words, they must have very small mass, and comparatively low density. If they move at speeds different from the local air flow velocity, the drag force exerted on them must be far greater than the inertia due to their mass, so that they are again very rapidly accelerated or decelerated to the local air velocity. You can easily convince yourself that as the diameter of a particle gets smaller, this becomes a better approximation, since the mass of a sphere is proportional to the cube of the diameter, while the surface area is proportional to the square of the diameter.

Usually, in a laboratory, the air is supposed to be clean and free of dust particles. Hence, the flow must be artificially seeded with particles of the right diameter range. This is done here by means of an atomizer, which works essentially like a paint spray can. A high-pressure air supply is expanded through a small orifice or nozzle to high speed. On the way out, it hits a thin stream of liquid (mineral oil) and shatters it into tiny droplets. This flow is then rapidly decelerated and turned around a sharp corner, and forced to go upwards. All the large droplets hit the walls (low drag, high inertia - they can not turn quickly enough) and drip back down into the oil reservoir. The remaining droplets, with diameters in the range 1-10 μm , go with the air stream and mix with the main flow. If done properly, a uniformly seeded flowfield can be created.

Data Acquisition

i) **The velocity histogram** - The velocity may be expected to vary from one data point (i.e., one particle) to the next. The computer collects, say, the first 5,000 points to be measured, converts the time values to velocity, and then sorts these values into “bins” or velocity intervals. Thus, if the highest velocity that you expect is 20 m/s, and the lowest is 10 m/s, and you divide this range into 100, then all the data points which show velocity values between 10.0 and 10.1 m/s will go into the first “bin”, all those between 19.90 and 20.0 m/s will go into bin #100, and everything else will go somewhere in between. The mean velocity can be calculated from the binned data with the formula

$$U = \frac{\sum n^i U_i}{\sum n_i} \quad (4)$$

where n^i is the number of samples in the i 'th bin, and U_i is the center velocity of that bin. The root-mean square (or the square-root of the variance) is calculated as:

$$u_{\text{rms}} = \sqrt{\frac{\sum n_i (U_i - U)^2}{(\sum n_i) - 1}} \quad (4)$$

These results are usually displayed on the computer, along with a graphical display of the distribution of data points over the velocity intervals. Such a graph is called a *histogram*. The number of points in each interval has been divided by the total number of points collected. If it were a continuous function, instead of being a series of discrete values for a finite number of

intervals, it would be called a *probability density function (PDF)*, whose integral, over the entire range of velocities, should thus be equal to unity.

ii) **Averaging** - Usually when this procedure is used, at least 10^3 points are needed to yield a good result for the average velocity, and at least 10^4 - 10^5 for the root-mean square. This is if you collect data for a sufficiently long time, so that you have seen all the likely kinds of fluctuations that occur. However, if the flowfield is fluctuating slowly, the average calculated from just one set of data as above may be insufficient. Instead, you may have to average over many data sets, each taken at a different time. For example, suppose there are 6000 data points arriving every second, and you collect the first 3,000. This should take only 0.5 seconds. Suppose now that the flow itself is fluctuating so that the magnitude of velocity goes up and down again once in 2 seconds. Your calculated mean velocity will not be the true mean of the flow. To find the true mean, you will have to average many such data sets. Note from Eqs. (3) and (4) that you cannot just average the rms values to get a better estimate for the rms; this would have to be done inside the summation sign.

The Jet Flowfield

One feature of the laser velocimeter to bear in mind is that one must have a good idea of the flowfield before attempting to make measurements using it. Very precise measurements can be made by a careful and alert experimentalist, but not without some consideration of the flowfield. Figure 5 shows a schematic of the flow set-up in your laboratory. A fan downstream of the tunnel diffuser creates a pressure difference that induces the tunnel freestream, and forces it out of the laboratory. A circular pipe brings air output from a centrifugal blower to the upstream edge of the wind tunnel test section. The flow comes out of the pipe as a jet, with a velocity that can be significantly higher than that of the test-section freestream. This is the same flow system used in the hot-wire anemometer lab. In this new experiment, both the test section freestream and the flow inside the pipe are to be seeded with atomized mineral oil.

If the jet flow leaves the pipe with a high velocity, the effect of viscosity at the edges of the jet causes the surrounding test section flow to accelerate, and the jet flow to decelerate. In fact, the flow at the edges of the jet is forced outward as it is “pulled” by the slower-moving test section air. Thus, some of the jet flow “rolls up” into vortex rings around the jet, so that some air which originated in the test section flow goes into the jet, and vice versa. Thus, there is a

mass transfer and *momentum transfer* across the jet boundaries. Things rapidly become confused and unsteady at the jet edges, so that the velocity fluctuates. The fluctuations are largest inside the *shear layer* at the edges of the jet. Near the center of the jet, there is still a region where the fluctuations have not reached. This is called the *potential core*, and the fluctuation level should be quite low here. The shear layer grows quickly, so that the potential core rapidly disappears as the jet goes downstream. At the same time, the mass and momentum transfer force the time-averaged velocity profile across the jet to become smoother and to gradually disappear, as the jet merges with the test section flow.

Preliminary

The following items must be turned in at the start of your lab session.

1. Calculate the fringe spacing of the LDV using the distance between the beams when they go into the focusing lens, the focal length of the lens, and the given formula (Eq. 1). For our LDV system, the distance between the beams is 50 mm and the focal length of the lens is 363 mm. (Also, the measurement volume of our LDV is $\sim 1.3 \text{ mm} \times 90 \text{ }\mu\text{m}$.)
2. Determine the lowest and highest values of instantaneous velocity expected during the experiment, based on your hot-wire anemometer results. Convert these velocities to the maximum and minimum expected Doppler frequencies for your flow, assuming the Bragg cell did NOT shift the frequency of the second beam. Also determine the Doppler frequency that would correspond to the mean freestream velocity of the wind tunnel.

Procedure and Data to be Taken

Operation of the Laser

1. Turn the FSA on (power switch at rear of unit).
2. Turn the laser power supply on and turn the key to horizontal.
3. Turn the **Discharge** switch to “On” and wait until the laser has warmed up. You will know it is ready when the reading on the LCD display changes from approximately zero.
4. When you are ready, switch the laser to **Run** and set the laser power to $\sim 280 \text{ mW}$. Notice that in Standby mode, the laser is still ON, it is just operating at low power.

5. Turn the laboratory lights off. Move the LDV traverse through its entire range and confirm that there are no reflections coming toward where you or your colleagues are standing. **Do not look towards the measurement location until this is complete. Look at the wall where any reflections would hit.**
6. If you are not ready to take data, then switch the laser back to **Standby**. Generally, keep the laser in **Standby** mode unless you are taking data.

Setting Up the Software

7. Open the **FlowSizer** program - any important messages will appear during the experiment in the text window in the bottom right of the screen (for example, if the **FSA Connection** box in the bottom corner contains a red **X**, it means the computer is unable to establish a connection with the FSA).
8. Using the tabs at the top of the screen, go to *File* → *Experiment Manager*. Click *New Experiment* and name the experiment/folder with the name of your lab group, e.g., A1. Then click once on *Run1* in the right hand side window and then click *Select* at the bottom of the window.
9. Go to *Run* → *Run Setup*.
10. In the *Run Settings* tab, you can choose the **Maximum Particle Measurement Attempts** (**MPMA** - how many data bursts you want to collect at a given point in the flow) and the **Time Out** length (how long you are willing to wait in attempting to acquire the MPMA). Be sure to hit **Apply** after you change the settings.
11. In the *Optics* tab, you will see several important parameters like wavelength, focal length, and fringe spacing. You should note down settings that you think are important. Again, be sure to hit *Apply* if you make any changes.
12. Move the Run Setup window so that you can see the *LDV Controls* on the main screen of the program. It is located on the right side of the screen.
13. Set the **Burst Threshold** to 30 mV.
14. Change the **Band Pass Filter** and **Downmix Freq.** settings in the *LDV Controls* tab to capture the range of velocities/frequencies from your preliminary calculations. When you hit *Apply*, notice the resulting changes in the *Optics* tab.

15. When you are satisfied with your settings, close the Run Setup window. Be sure you hit *Apply* so your settings are saved!

Taking Data

16. Turn on the tunnel and bring it to the required operating speed (same speed as in the hot-wire anemometer lab). Turn on the centrifugal blower (for jet) and bring it to the required operating setting (again, same setting as the hot-wire anemometer lab).
17. Ensure the LDV is aligned in the direction of flow you wish to measure. The LDV transceiver should be rotated such that the rule marks point to 90° and the yellow warning label should be on the upstream side (ask the TAs for help if necessary).
18. Make sure that the detector output of the FSA is connected to the oscilloscope.
19. Turn on the seeder for both test section and the jet. Move the LDV measuring volume to a location corresponding to the wind tunnel freestream and then switch the laser to **Run**.
20. Verify that there is a proper signal on the oscilloscope. Try to measure the fringe crossing frequency from the oscilloscope display. Verify that the frequency that you are seeing on the oscilloscope is indeed close to the value for the freestream that you calculated in step 2 of the Preliminary section. Write down your observations. **IF YOU DON'T DO THIS, YOU MAY END UP MEASURING NONSENSE.**
21. Obtain the jet profile data.
 - a. Manually move the traverse to the top position in the windtunnel.
 - b. Move the traverse to the first measurement position using the Labview VI Move Traverse utility on the computer (note: position will be controlled by relative motions from the current location, e.g., +1 inch means move down 1 inch from current position).
 - c. Press **F9** to capture data for a single run. Press **F10** to save the data.
 - d. Repeat steps a and b at enough points to obtain a well-resolved profile across the jet (at a minimum, make sure that you use at least the same measurement locations that you used in the hot wire lab).
 - e. **YOU WILL NEED TO MANUALLY RECORD** the vertical position in the windtunnel corresponding to each run number. The data saved by the LDV software does not include this information.

22. From the dropdown menu at the top, select a run you would like to look at. Press **F7** to playback the run for post-processing. Right-clicking on the graphs will allow you to change the axes. When you are done (before changing any Run settings or taking new data), select the **LAST** run in the dropdown menu (this is run that will be used for the next data acquisition).
23. Go back and repeat the measurements for at least **TWO** locations (the first point being in the free stream and second in the shear layer), but with different **Bandpass Filter/Downmix Frequency** setting (see Step 14).
24. Return the filter settings to their proper values, and change the **Burst Threshold** value to 150 mV and repeat the measurements in the shear layer (to see if the original threshold value was a reasonable choice).
25. Return the **Burst Threshold** to its original value, and repeat the shear layer measurement two more times. The first time, turn off (or nearly off) the free stream seeder. The second time turn the free stream seeder back on and turn off (or nearly off) the jet seeder.
26. **IF YOU ARE DONE** - turn the laser back to **Standby** mode; return the traverse to the top most position; turn off the seeders, then the jet and tunnel flows. If your lab group is the last one for the day, turn the laser **Discharge** switch to OFF and let the laser cool down before turning off the laser power supply (switch and key).
27. Export your data to an Excel file
 - a. Go to *File* → *Experiment Manager*.
 - b. Select all the runs for which you would like to save data.
 - c. Open the **Export File Dialog Box** by choosing *File* → *Export Data*.
 - d. From the **Available Data** pane, select any values you would like to save and click the “>” button to move them to the **Exported Data** pane.
 - e. Choose **Comma Separated Values** under *Export Format*.
 - f. Select **Export Headings (first row)**” and **Export to 1 file**; choose the **Export File** location, and click *Export*.

Data Reduction

1. Show your calculations for fringe spacing. Not only are they required on the pre-lab, but also in the laboratory report.

2. Show your calculations for the filter settings, i.e., what velocities correspond to your chosen filter settings

Results Needed For Report

1. Plots of your results in the same manner as described in the hot-wire lab, i.e., the normalized mean velocity profile in the jet, \bar{U}/U_∞ versus location, and normalized turbulence intensity profiles in the jet, *normalized two ways*: first, u_{rms}/U_∞ and second, u_{rms}/\bar{U} .
2. Histograms of the velocity values recorded at interesting points in the flow.
3. A comparison plot for the LDV and hot wire data. At a minimum, provide one plot (separate from those listed in item 1) showing \bar{U}/U_∞ from both experiments on the same graph, and a second graph for u_{rms}/U_∞ .
4. A comparison between the points taken with different filter, burst threshold and seeder settings.

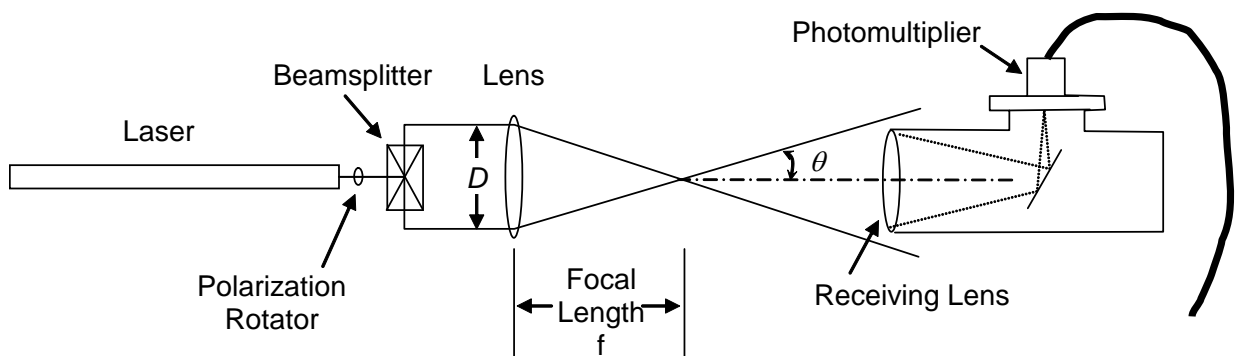


Figure 1. Schematic of a basic 1-component LDV system in forward-scattering mode (plan view).

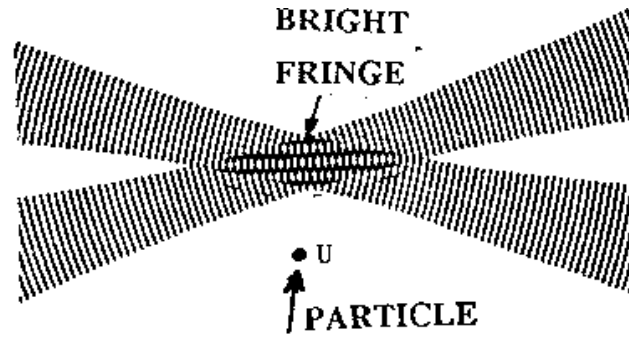


Figure 2. Plan view of fringes formed when two laser beams cross (particle motion across fringes will yield vertical velocity in plane of paper). Note that the region with fringes looks ellipsoidal in shape.

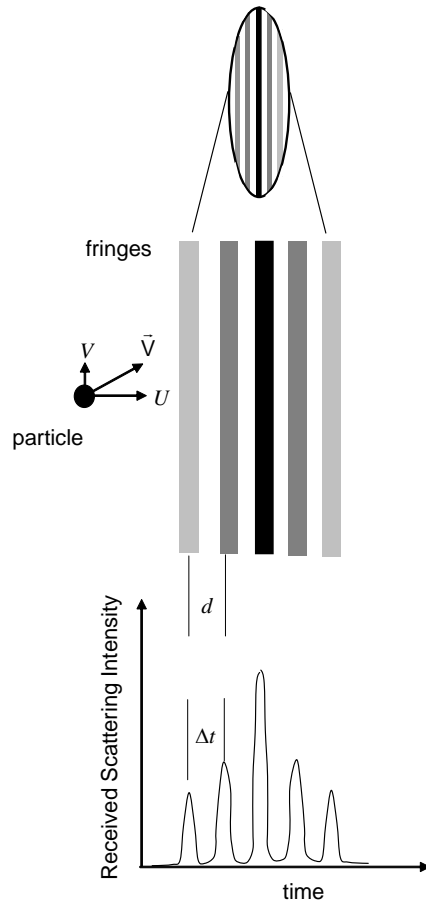


Figure 3. Sinusoidal variation in the intensity of scattered light, as a particle crosses the fringes (d =fringe spacing; U =velocity component perpendicular to the fringes; Δt =time between scattering peaks or $1/\Delta t =$ Doppler frequency).

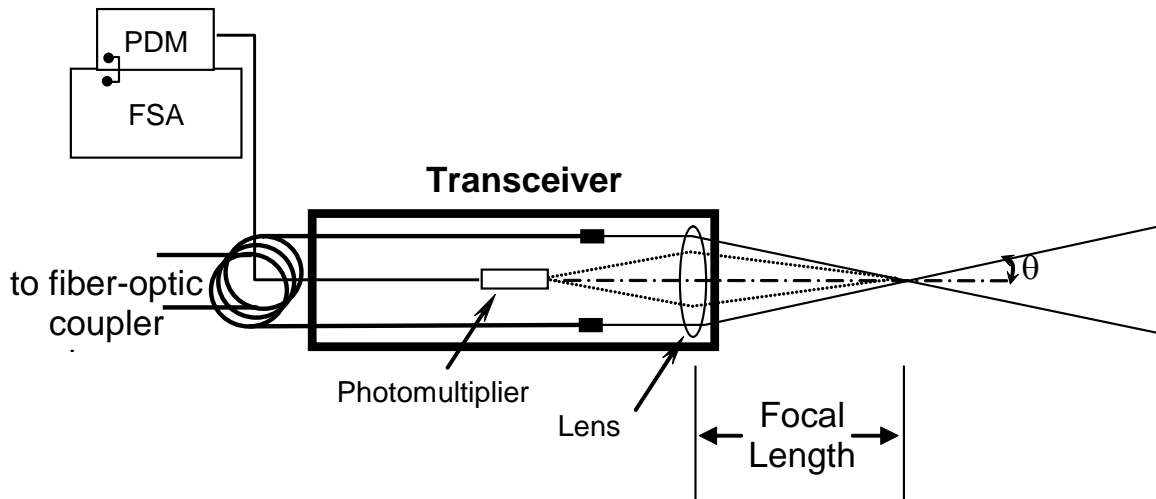


Figure 4. Schematic of lab LDV system with combined transmitter and receiver (transceiver) used in back-scattering mode.

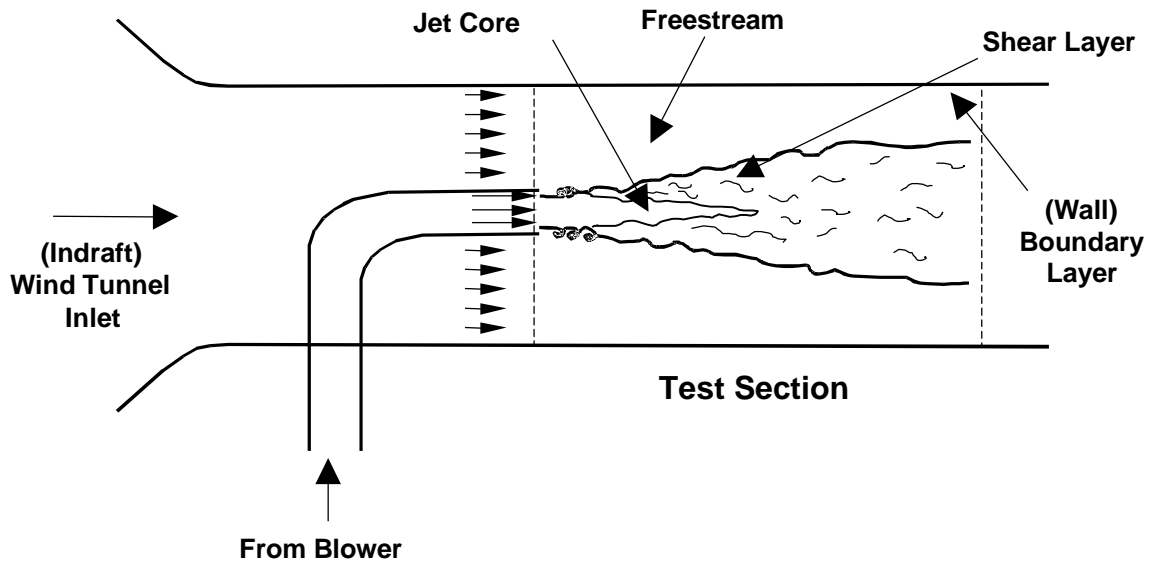


Figure 5. Schematic of jet flow in the wind tunnel