

Appendix A

LDV Measurement System Manual

A.1 Introduction

Laser Doppler Velocimetry (LDV) is a non-intrusive method for the measurement of velocity. This technique measures the frequency shift (Doppler shift) in the light scattered from particles moving through the intersection of two coherent laser beams. Single probe implementations can measure two of three velocity components simultaneously. Directional sensitivity of the velocity probe is obtained by frequency shifting one of the two intersecting beams. The result is a non-intrusive measurement technique well suited for highly turbulent separated flows. A complete introduction to LDV can be found in many textbooks on the subject, some of which are given in the bibliography. Commercial system manuals also contain a treasure of technical information and should be consulted if available.

A.2 Principles of Operation

LDV relies on the principle that the light scattered from a particle moving through a coherent laser beam will be frequency shifted in direct proportion to the particle's velocity in the direction of the beam. The difficulty of measuring a frequency shift of several megahertz out of the light frequency of several gigahertz is removed by mixing the shifted frequency light and original frequency light. The result of the mixture of these two coherent signals will contain a component at the Doppler shift frequency. In practice, the mixing of light signals can be achieved by intersecting and focusing two coherent laser beams causing the intersection area to exhibit a diffraction pattern. If both laser beams are of exactly the same frequency and are coherent, the diffraction pattern will be stationary. As a particle moves through the diffraction pattern the scattered light from the particle will exhibit frequency content proportional to the particle's velocity perpendicular to the diffraction pattern. The velocity component measured by such a beam intersection is the resultant of adding the two beam vectors as shown in Figure A.1. An example diffraction pattern is shown in Figure A.2 using the optical probe described here with only green light

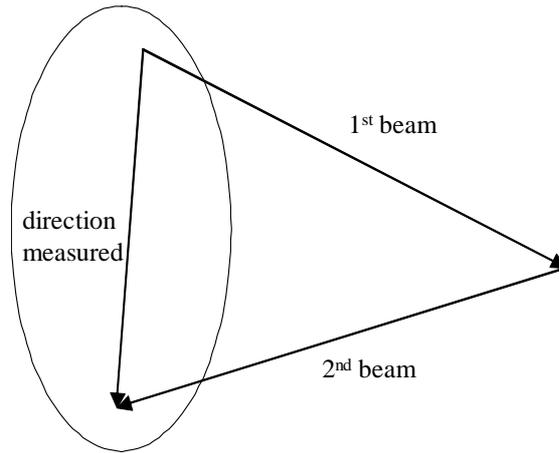


Figure A.1: Velocity vector measured by a given laser beam pair

(514nm) emanating from the probe.

In its raw form, as just described, the LDV will not be able to measure the direction of the velocity component perpendicular to the diffraction pattern. To obtain a direction sensitive signal, one of the two laser beams is frequency shifted causing the diffraction pattern to move at a constant velocity, directly related to

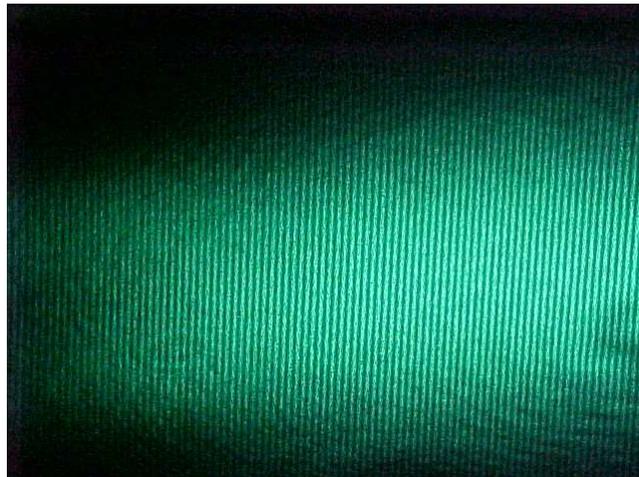


Figure A.2: Photograph of single 514 nm diffraction pattern

the frequency shift between the two beams. The frequency contained in the light scattered from the particle will now be centered about the shift frequency of the two beams and the velocity direction can be deduced from the frequency.

To measure two velocity components simultaneously, a second pair of beams is focused onto the same point, however, with the laser beam resultant orthogonal to the first laser beam pair resultant. In this manner, two independent velocity components will be measured by the two beam pairs. Similarly, if a third pair of beams were focused on the same point, the third velocity component could be measured. The problem with implementing a 3-D LDV system is that in order for the third component to be measured, the resultant of the two laser beam vectors can not lie in the same plane as the resultants of the first two laser beam pairs. In practice, this requires that the third pair of beams not be focused using the same focusing lens as the first two laser beam pairs as this would guarantee that the resultant of the third pair of laser beams lies in the same plane as the resultants of the first two pairs of laser beams. This also means that if the angular alignment of the focusing lens is changed without changing the measurement location, successive measurements at this same point allow the third component of mean velocity to be deduced. A close-up of the diffraction patterns generated by the green and blue beams pairs without frequency shifting of one of the beams is shown in Figure A.3.

A further distinction in LDV systems is made based on the manner in which the scattered light is collected. If the light is collected on the opposite side of the laser beam focusing lens, the system is called a forward scatter system because the light collected is scattered in the direction of the laser beams. If the light is collected on the same side as the laser beam focusing lens, usually even using the same lens, the system is called a back-scatter system. The advantage of forward-scatter systems is that the amount of light scattered in that direction is greatest. The back-scatter system has the advantages of requiring less optical access and being more spatially compact with the penalty that the amount of light scattered back towards the focusing lens is much smaller than the light scattered away from the focusing lens.

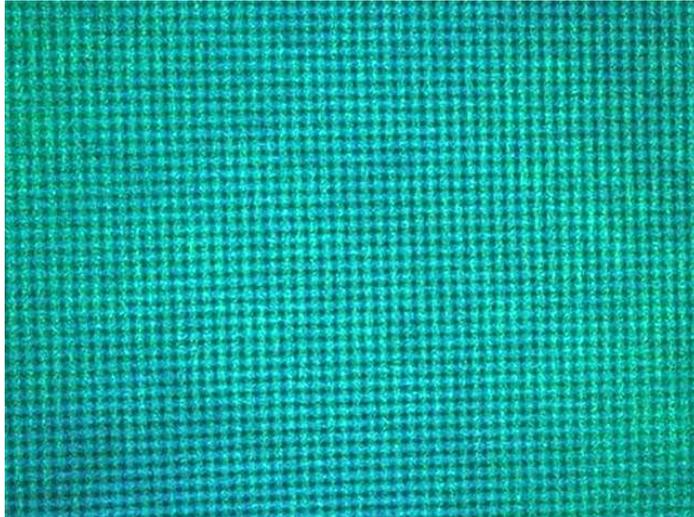


Figure A.3: Photograph of the 2-D diffraction pattern

A.3 Laser Operation Alignment and Maintenance

LDV performance is strongly influenced by the characteristics of the focused laser beams. Proper laser alignment and good maintenance practices are key to maintaining the performance of the LDV system as a whole.

A.3.1 Laser requirements

The LDV requires that the laser beams focused produce a sharp diffraction pattern with bright fringes and good contrast between the bright fringes. To obtain such a diffraction pattern, the beams must be coherent, of equal intensity and exhibit the same polarization. Beyond these requirements, detection of the scattered light signal requires that the focused laser beams have the highest intensity possible, to generate more scattered light. This is especially important in a back-scatter LDV as was implemented here. Furthermore, the laser must be operated in multi-band mode so that at least two high intensity laser beams of different wavelengths are generated.

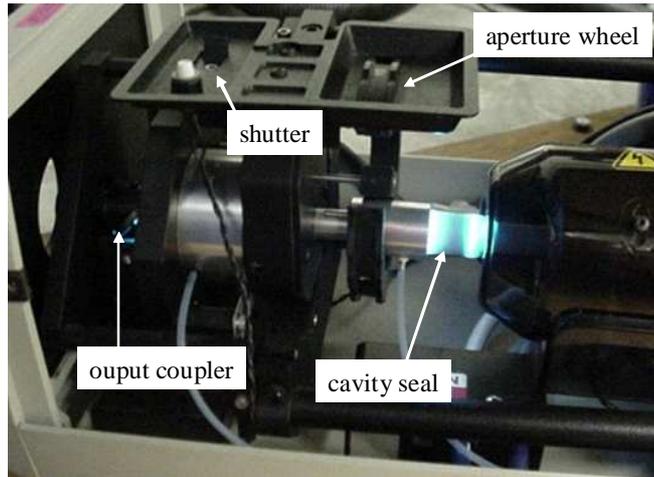


Figure A.4: Front of the laser head assembly

A.3.2 Basic laser alignment and maintenance

To maintain and align the laser, the instructions contained in the Spectraphysics 2020-05 manual (Spectraphysics, 1984) should be followed closely. The alignment instructions have been verified with their use all the way through starting with the relatively simple procedure for walking the mirrors to the more complicated procedure for aligning the plasma tube and centering the beam on the aperture. However, some additional information is helpful for the clarification of several of the instructions. It has also been necessary to develop a "from scratch" plasma tube alignment procedure.

For the case where all lasing is lost, the Spectraphysics 2020-05 manual, does not give a re-alignment procedure. However, such a circumstance had to however be handled and the following is the procedure used to re-align the laser plasma tube, output coupler and high reflector. The start of the procedure assumes that the laser head is open with all power disconnected and cavity seals retracted. The procedure also assumes familiarity with the laser head components and their location. The front of the laser head is the end containing the output coupler (Figure A.4) whereas the rear of the laser head is the end containing the high reflector (Figure A.5).

To obtain approximate alignment between the front of the plasma tube and the

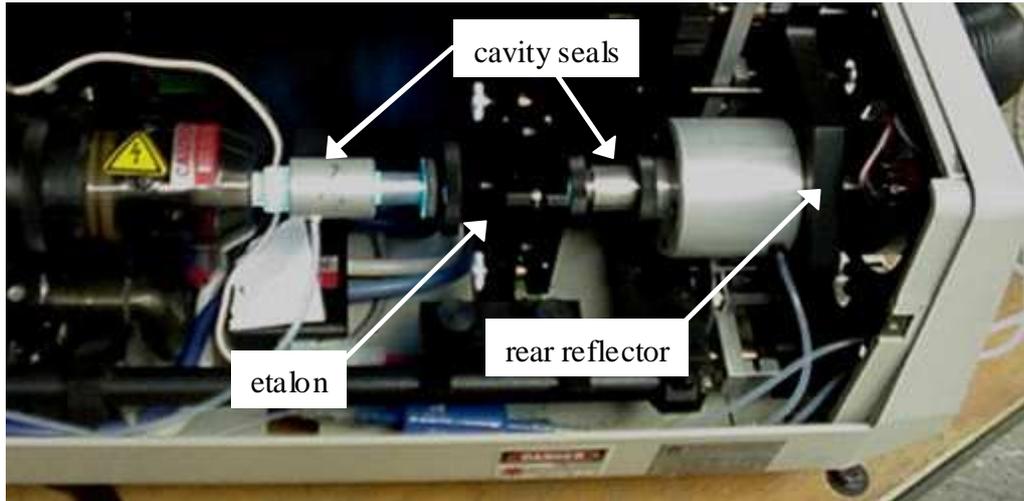


Figure A.5: Rear of the laser head assembly

aperture, hold a flashlight at the rear of the laser with the high reflector removed shining the light forward towards the output coupler. Also with the output coupler removed, observe the light coming out of the plasma tube core and move the plasma tube front end so that the light is centered on the aperture. Next shine the flashlight into the front of the laser and center the light coming out of the rear of the plasma tube with respect to the high-reflector enclosure. The alignment of the plasma tube here will not be as accurate because it is harder to visually center the light from the plasma tube with high-reflector enclosure.

At this point, lasing should usually be possible but may require a large amount of mirror walking in order to optimize laser power output. A further helpful procedure in laser alignment uses an outside laser source such as a HeNe laser to align the output coupler and rear reflector. First, with both the output coupler and rear-reflector removed, align the laser beam so that it travels through the entire laser head, through the center of the plasma tube from the rear to the front. Install a mirror at the front of the laser head and align it so that the beam doubles back on itself. A reflection from the front plasma tube window should now be visible on the ceiling. The output coupler should now be installed. After the output coupler is

installed a second reflected beam will be visible along with the first reflection just mentioned. Adjust the output coupler controls to align the second beam with the first using the front laser head output coupler alignment controls. The output coupler is now aligned very close to its optimal position.

Next, the laser source should be moved to the front of the laser head and be aimed back through the laser. To align the beam, use the reflection from the output coupler back towards the source. Now, the high reflector should be installed. To align the high reflector, align the laser beam that travels back through the plasma tube with the laser beam origin. The further the distance between the output coupler and the laser source, the more accurate the alignment of the high reflector. When this procedure is finished the laser can be started in the usual way and if lasing is not immediately obtained, the beam search procedure described in the Spectraphysics 2020-05 manual (Spectraphysics, 1984) will allow lasing to occur. Be sure to reinstall all cavity seals, especially in the front of the laser as the reflection from the front plasma tube window can be very powerful and is easy to look into accidentally.

A.3.3 Etalon installation and alignment

The following describes the etalon installation. In the current setup, the etalon is not required because the path length of each of the focused laser beams is kept constant so that the path difference is well below the coherence length of the laser without etalon (4 cm). However, a lot of time was invested in determining the proper use of the etalon and other application will require it. Therefore, these instructions have been included here. Note that it is extremely difficult to operate the etalon in single frequency mode and also obtain two reasonably strong and equal intensity beams of different wavelength. The etalon is best used with a prism installed, in single wavelength mode when efficiencies of 50% are attainable.

Once laser alignment has been optimized, both in terms of maximum output and centering with respect to the aperture, the etalon installation can proceed. The following are the alignment steps recommended based on a trial and error record of experience with the installation and alignment of the etalon. The etalon is used

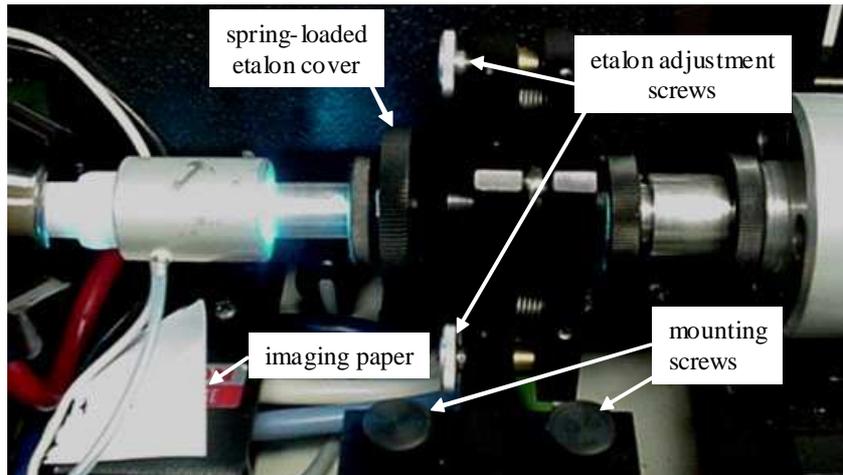


Figure A.6: Rear of the laser head assembly

to select a single frequency of operation of the laser in order to improve the laser's coherence length. The laser's coherence length is the maximum beam distance over which the phase relationship remains constant. Without an etalon a typical Argon ion laser has a coherence length of 4 cm. With an etalon installed the coherence length can be increased to 20 m. In a fiber optic LDV system implementation, a long coherence length for the laser beam is an absolute necessity as the distance effectively traveled by the beam inside the fiber varies not only from fiber to fiber but also for each of the polarization modes of the fiber. (See Section A.4.2)

In the installation of the etalon, refer to Figure A.6 for part identification and orientation. Before installing the etalon in the laser, remove it from its enclosure by twisting the large knurled plastic cover. After removing the spring that presses the etalon into place gently tap out the etalon. Use a cotton swab to push the etalon out if tapping is unsuccessful. Once removed from its enclosure, inspect the etalon carefully for any dust and dirt. Clean the etalon using the usual procedure for delicate optics, making sure that no residue is left when the etalon is put back in its enclosure. Once back in the enclosure, insert the spring and then the cover but only start the cover into its threads. Do not tighten down the cover.

Before installing the etalon in the laser head, turn the laser on and allow ample time for warm-up. Make a note of the output power. The laser should be started and allowed to warm up in the same configuration in which it will be used for measurements. That is, the power-level and aperture should be set at their anticipated final operating points. Currently, the laser is operated at full open aperture and a current of 34 A. The etalon can be installed with the laser running but with the shutter closed. If the installation is performed with the laser running, extreme caution should be used as lethal combinations of voltage and current are present near the installation location. It is highly recommended that the unfamiliar user shut down the laser and disconnect power to install the etalon. After the etalon is slid into place, make sure that the rear plasma tube cavity seal is completely retracted so that the plasma tube window is visible and that the rear cavity seal in no way impedes the glibal movement of the etalon enclosure.

The first step in the etalon alignment is to obtain what is called "flash". The "flash" condition is obtained when the etalon surfaces are exactly perpendicular to the laser beam direction and do not cause any beam displacement. Consequently the laser power observed should be near 100% of the value observed before etalon installation. In order to obtain "flash" very accurate and small adjustments of the etalon angular position are required. In the case where no lasing is observed, a beam search technique similar to that used for the high reflector alignment can be used. Obtaining some amount of lasing should not be difficult, especially at higher current driving levels. Once some lasing has been obtained, place a piece of paper under the rear plasma tube window. Observe the dots on the paper as the glibal controls on the etalon enclosure are manipulated. To obtain "flash", all the dots have to be completely lined up. Note again that "flash" is obtained for one particular alignment of the etalon and a large amount of patience is helpful in finding it. Any "flash" level below 90% of the original power should not be considered flash. It is also important to realize that the output has several maxima throughout the glibal adjustment range and that a given maximum not near 100% of the original power is not necessarily an indication of a dirty etalon.

Once "flash" is obtained, align the table optics for transmission of the non frequency shifted beams into the fiber optic cables, as described below in Section A.4.2. Place the 40X microscope objective at the laser beam intersection. Project the image onto a surface at least 10 ft away. Observe the image projected onto the surface. A sharp diffraction pattern for both the green and blue beam pairs indicates single frequency operation. At "flash" the laser is not in single frequency operation and the diffraction pattern will not be sharp. If the laser were operated in single line mode, it would be possible to achieve 50-60% of original beam power in single frequency operation. Further performance decreases must be taken to achieve balanced 488 nm and 514 nm laser output with single frequency operation for both.

From "flash" adjust the vertical gimbal control to lean the etalon, turning the control to the right. Stop when both green and blue diffraction patterns are sharp. At this point, the laser is single frequency operation but the operating frequency is probably not located near the maxima of the laser gain curves for each of the laser lines. By turning the knurled etalon enclosure cover, the pressure exerted by the spring on the etalon increases and changes its length slightly. With the length change, the resonant frequency of the etalon changes and can be adjusted to be closer to the gain curve maxima. During the spring pressure adjustment, the output power should be monitored either at the laser head exit or for one of the two laser lines of interest. The key is to achieve balance between the 488 nm line and the 514 nm line without losing single frequency operation and while maximizing beam intensity to increase the amount of light scattered for measurement. There is no set procedure for finding the optimal point and trial and error is an essential ingredient in this procedure.

Once the etalon is aligned, the laser beams should remain non frequency shifted for several days so that the repeatability of the operating condition can be checked.

A.4 Laser Doppler Velocimeter Optics

The following sections describe the optical components used in the LDV along with their purpose and any operating and usage guidelines. The description follows the path of the laser beams from the laser head all the way to the measurement volume and back through the receiving optics until finally the light flux is converted to an electronic signal using a Photo Multiplier Tube (PMT).

A.4.1 Overview

The following paragraph is a basic description of the entire optical system from a functional perspective, omitting any alignment procedures or other detailed operational information. The multi-band beam from the laser head is redirected by a set of three mirrors to the top of the table. There the beam is re-collimated to be slightly converging using a Galilean telescope. The individual laser wavelengths contained in the multi-band beam are then separated by two successively placed dispersing prisms. The diverging beams are reflected on the far side of the table by a 1 inch mirror. The desired laser beams of wavelength 514 nm and 488 nm are picked off successively and processed further, each beam undergoing the same conditioning on its way to being coupled into the fiber in two parts, one frequency shifted half and one non frequency half.

The laser beam is first rotated from its vertical position using a polarization rotator. Then the beam is split in two by a polarization beam splitter which reflects the horizontally polarized portion of the beam and transmits the vertically polarized portion. The horizontally polarized portion is reflected by a second polarization beam splitter and then coupled into the fiber. The vertically polarized portion is reflected off of a half inch mirror and then frequency shifted by a Bragg cell. The frequency shifted beam is reflected off of a second half inch mirror, rejoining the horizontally polarized portion at the second polarization beam splitter. Both beams travel along the same fiber.

The frequency shifted and non-frequency shifted beams travel along the same

fiber independently because the fiber used is polarization maintaining fiber and the two beams are perpendicularly polarized. The present LDV implementation thus requires only two light delivery fibers. One fiber is used for the green beams (514 nm) and one fiber is used for the blue beams (488 nm). The fiber connect to the LDV probe. At the probe, the fibers connect to a pair of laser collimators which form approximately 3 mm diameter beams. Inside the probe, the two laser beams are separated from each other by a polarization beam splitter. The reflected beam hits a mirror and is redirected to travel in the same direction as the transmitted beam. Once reflected, the beam passes through a polarization rotator in order to match the reflected beam's polarization to the transmitted beam's polarization. The beam separation occurs identically for the green and blue laser beam pairs.

At this point four laser beams are traveling parallel to each other toward the large achromatic focusing lens. The lens focuses all four beams to the same spot, which is called the measurement volume. As particles pass through the measurement volume, the scatter light. Some fraction of this light is reflected back towards the focusing lens. The focusing lens collimates the coherent light from the measurement volume. The collimated light is then focused onto the end of a $50\mu m$ multimode fiber. The fiber transports the light back to the optics table from the probe. At the end of the multimode fiber, the scattered light is collimated. The light contains both green and blue scattered light. A dichroic mirror is used to separate the two colors. The green light is transmitted whereas the blue light is reflected. The transmitted green light and reflected blue light are further filtered by narrow band-pass filters. The scattered light flux of each laser color is then converted to electrical current by the PMT as described in Section A.5.

A.4.2 Table optics

To accommodate the entire LDV system on a single optical table, able to be moved from experiment to experiment, the laser head is located on the bottom of an optical table. Three mirrors are used to redirect the beam vertically to the top of the table and provide it level travel along the long edge of the optical bread board.

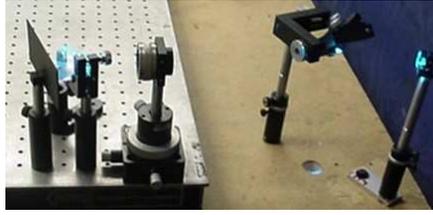


Figure A.7: Top beam steering, beam collimator and dispersion prisms

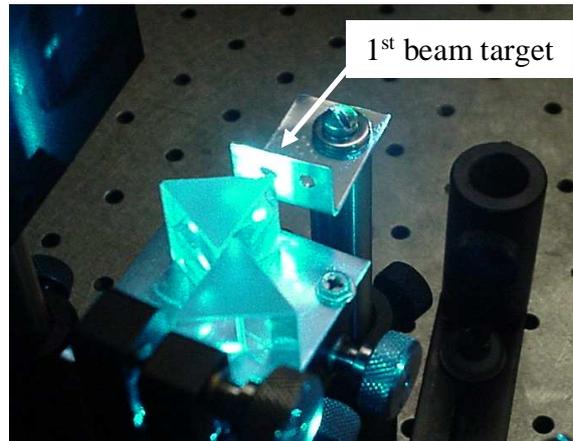


Figure A.8: First beam target located near dispersion prisms

Figure A.7 shows the three mirrors and follows the laser beam from the laser head through the steering mirrors. The two end mirrors, the first and third mirrors are used in the initial adjustment of the beam location when fiber alignment is begun. The first mirror is used to center the beam on the first beam target hole located immediately after the two color separating prisms(see Figure A.8). The third mirror is then used to center the beam on the second beam target hole near the blue polarization rotator (see Figure A.9). Finally, the beam alignment can be given an initial fine tuning by visually optimizing the light coupling into the fibers.

The collimator is used to convert the slightly diverging beam emanating from the laser to a slightly converging beam. The collimator design is based on a Galilean

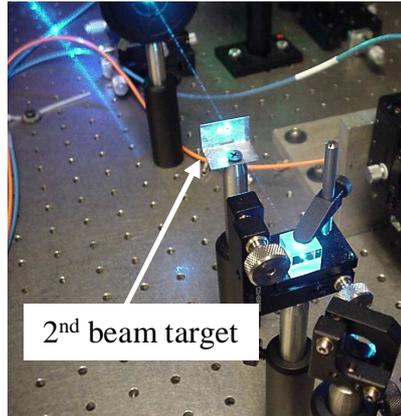


Figure A.9: Second beam target located near first blue polarization beam splitter

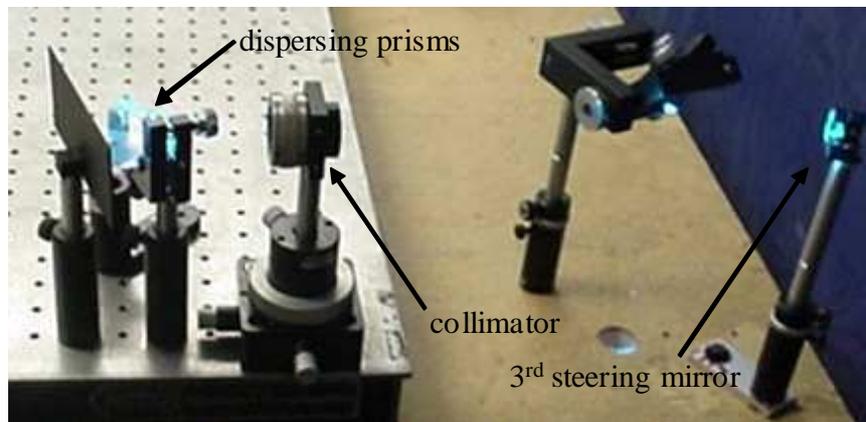


Figure A.10: Top beam steering, beam collimator and dispersion prism assembly

telescope design using a concave and convex lens. The collimator is shown in between the dispersing prism assembly and the last steering mirror in Figure A.10. The collimator can either expand the beam or contract the beam. In its present alignment, the collimator contracts the beam. By adjusting the knurled control on the collimator the focusing distance can be changed from far positive (slightly converging) to far negative (slightly diverging). In the present setup, the collimator is set up to focus the beam at some large positive distance much greater than the total optical path length of the system (laser head to fiber coupler).

The next component is the color separator which consists of two back to back

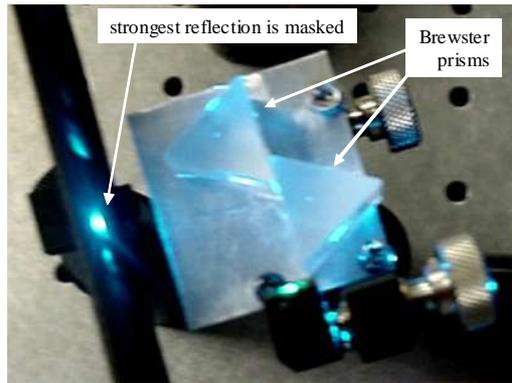


Figure A.11: Top view of Brewster prism assembly

dispersing (Brewster) prisms, shown in Figure A.10 and in a top view in Figure A.11. The prisms separate the different laser lines by diffraction at the glass surfaces. Two prisms are used to increase the divergence angle of the laser lines and allow for easier optical line separation. The optimal orientation of the two prisms is tip to tip as shown in Figure A.11. In order for the color separator to work most efficiently, the incident angle of laser beam must be close to the Bragg angle which will minimize internal reflection losses at the glass–air interface. To set the angle, the platform the prisms are mounted on is rotated. As the platform is rotated, the laser beams formed by the different laser lines will move and change separation when observed on a target. With rotation the beams will move to and away from the collimator end of the table. As the beams move not only the separation will change but also the shape of the beams, from circular to elliptical. The optimal separation of the laser lines is obtained by fixing the rotational position of the prism platform so that the beams are at their turn-around point, furthest away from the collimator end of the table. At this point the beams are still circular and the beam separation is acceptable. Further beam separation will only be achieved at the cost of non-circular beams and increased reflective losses. Some reflective losses will be incurred regardless and the strongest of these reflections should be masked to prevent injury.

In order to adequately separate the two laser lines of interest (488 nm and



Figure A.12: Redirect mirror giving necessary path length for separation

514 nm), a certain path length has to be covered. The beams are therefore reflected from the far end of the table using a 1 in. broad-band mirror, shown in Figure A.12. Once reflected the laser beams of interest are picked off using two small half inch mirrors as shown in Figure A.13. The optics downstream of these mirrors for each of the laser beams of interest are the same, and the components will be described only once with the understanding that analogous components are used for the 514 nm and 488 nm laser beams.

All of the optics of the two analogous optical paths are shown in Figures A.14 and A.15. Of the optical components used, several are specific to the laser line wavelength, that is to say, these components are functionally identical but can not be substituted for each other. For example, the polarization rotator used for the 488 nm laser line is designed specifically for that wavelength and should not be used for the 514 nm wavelength. The polarization rotators are marked with their wavelength, whereas the polarization beam splitters are not. Therefore, care and labeling are necessary if the optical system is ever disassembled.

The separated laser beam's polarization is vertical as it has not been modified from its state at the exit of the laser head. To enable separation of the beam into equal intensity parts, a polarization rotator is used to change the polarization angle of the laser beam to near forty-five degrees. Both green and blue polarization rotators

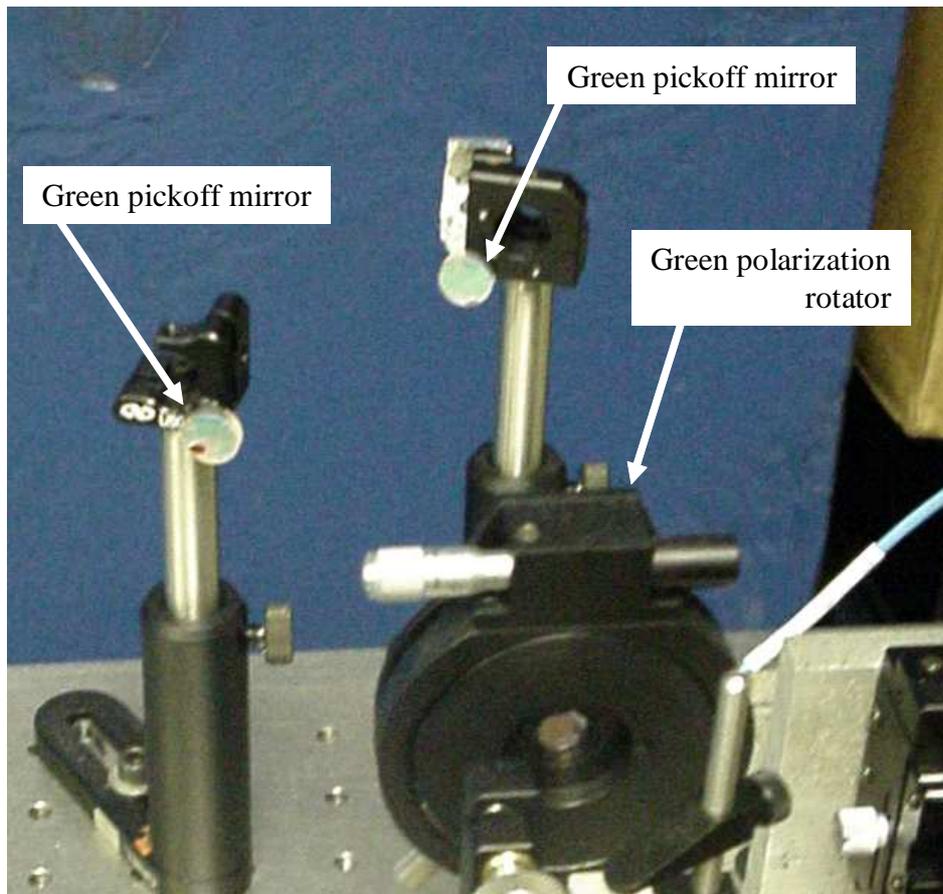


Figure A.13: Laser beam pick-off mirrors

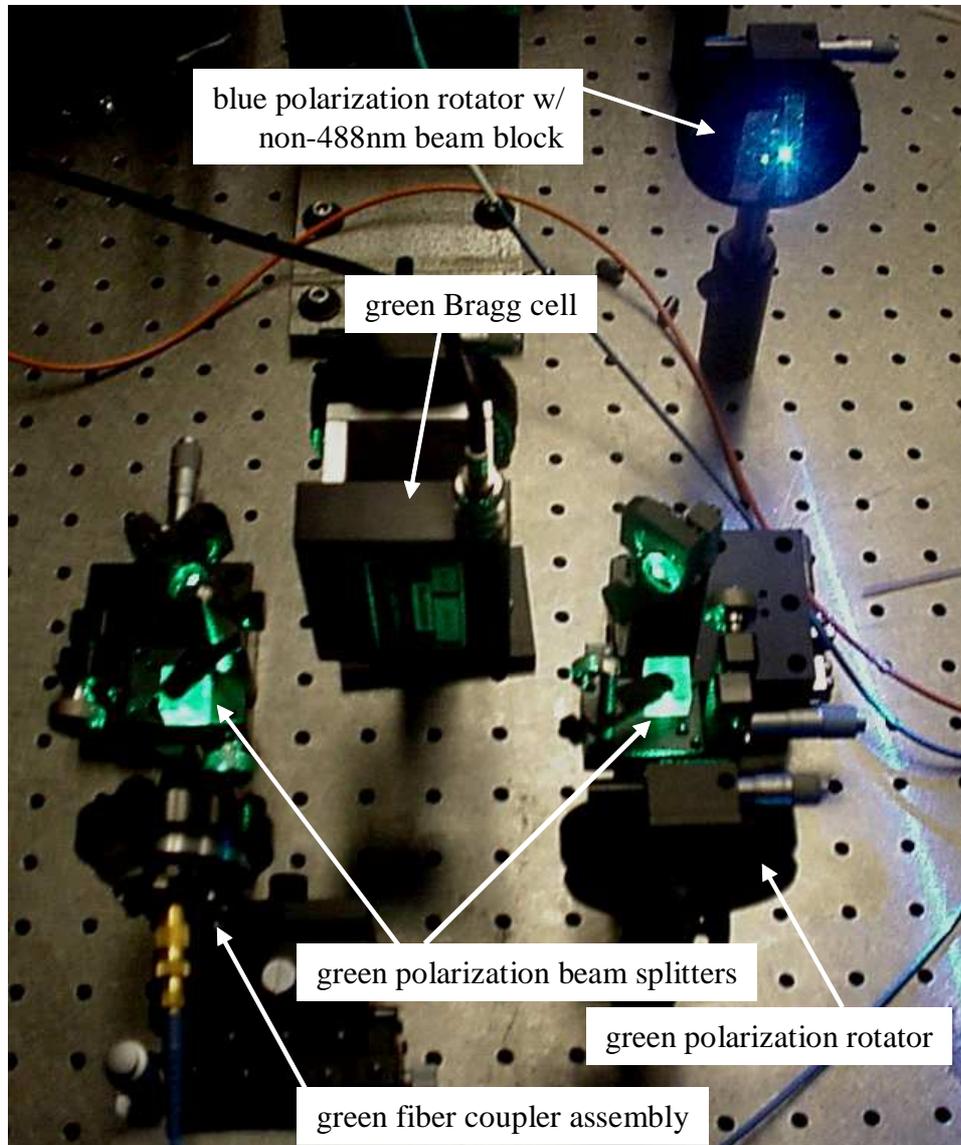


Figure A.14: Green beam conditioning components

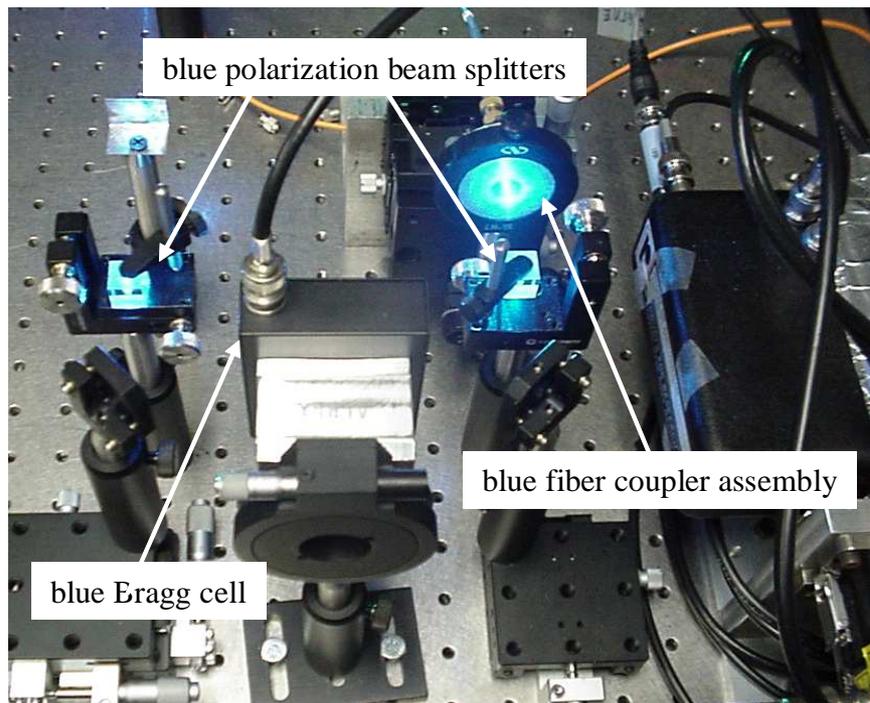


Figure A.15: Blue beam conditioning components

are shown in Figure A.14, where part of the blue polarization rotator is masked to block the beam components at wavelengths other than 488 nm. The beam is separated into two equal intensity parts by a polarization beam splitter. The beam splitter transmits the vertically polarized part of the incoming beam and reflects the horizontally polarized portion at ninety degrees. The transmitted portion of the beam is reflected by a half inch mirror and then frequency shifted by a Bragg cell, as described below. The reflected portion travels towards the second polarization beam splitter.

The LDV system Bragg cells are used to shift the frequency of one of the coherent beams forming the diffraction pattern by 40 MHz, resulting in a moving diffraction pattern as discussed above. Depending on the Bragg cell alignment, the Bragg cell can also be used as a beam splitter. Both the angle of incidence of the laser beam and the power supplied to the Bragg cell change the behavior of the Bragg cell. For the LDV application, in the present setup, the goal is to maximize the intensity in the first order of the Bragg cell diffracted beams.

To align the Bragg cell, first align the laser beam so that it is centered on the Bragg cell inlet and outlet windows. Once the beam is centered on the Bragg cell windows, measure the intensity of the beam with the Bragg cell power supply off. Next, turn on the Bragg cell power supply and set to near full power. The Bragg cell power supplies are shown in Figure A.16.

When the power is turned on, the original single beam is separated into several diffraction orders. The zero frequency shift beam can be identified by turning the power down to zero and noting which of the beams remains. The first order beam is located right next to the zero frequency shift beam. It is this beam's intensity that must be maximized by changing the angular alignment of the Bragg cell and the Bragg cell power level. Using these controls it should be possible to obtain greater than 95 % of the originally measured power in the first order diffraction. Experience has shown that the optimal power level (dial setting) for the 514 nm laser line is about nine whereas the optimal power level for the 488 nm laser line is closer to 7.5. To finish the optimization, it is possible to measure the intensity of the zero shift beam



Figure A.16: Bragg cell drivers

and use the controls to minimize this intensity. This step should be the last step in the alignment of the Bragg cells because minimization of the zero order beam only succeeds in maximizing the first order diffraction beam if the alignment is already close to the maximum. Using the zero order intensity merely allows a more sensitive detection of the optimal alignment. The Bragg cells are not laser line specific and could be interchanged if necessary. The polarization angle of the beam is not altered in the frequency shifting process. Note that a first order beam can be produced on either side of the zero shift beam. Depending on the orientation of the Bragg cell, the first order beam is either upshifted or downshifted in frequency. It is important to make the frequency shift compatible with the measurement setup. The frequency shift should be such that both measured components are predominantly on the same side of the shift frequency. This will allow a better selection of the mixing frequency as described below in Section A.5.1.

The frequency shifted beam and non frequency shifted beam are collocated using a second polarization beam splitter. The originally vertically polarized frequency shifted beam is again transmitted while the non frequency shifted beam is once again reflected. The polarization beam splitter is oriented so that the reflected beam prop-

agates in the same direction as the transmitted frequency shifted beam. In order to facilitate the alignment of the fiber coupler, the two beams are collocated visually as close as possible before attempting fiber coupler alignment. With the fiber coupler still removed from its alignment housing, the two beams are collocated using the following procedure.

In the current setup, the frequency shifted beam is designed to travel a longer distance on the optical table so that the overall path length traveled by each beam will be equal by the time the beams are focused to the measurement volume. The non-frequency shifted beam travels a longer distance inside the probe equal to 3 in. Both the 514 nm and 488 nm beam pairs are setup in this fashion. Due to this setup, the non-frequency shifted beam position and angle cannot be changed without changing the alignment of the polarization beam splitters which after initial alignment should be avoided.

To align the polarization beam splitters, use the following procedure, involving only the non-frequency shifted beam. Mount the first polarization beam splitter such that the weak reflection off of its face travels back along the original beam. The reflection can be seen either on the polarization rotator or on the pick-off mirror. Once perpendicular alignment is achieved, add the second polarization beam splitter and repeat the procedure to ensure that the non-frequency shifted beam also hits the second polarization beam splitter at normal incidence. The non-frequency shifted beam should now have been reversed from its original direction of travel. Locate the fiber coupler assembly so that the non-frequency shifted beam is as close to the center of the assembly as possible given the constraints of the optical breadboard. The coupling assembly should also be located as close as possible and practical to the last polarization beam splitter.

Each of the mirrors that reflect the vertically polarized beam (the beam marked for frequency shifting) have to be located so as to provide an additional 3" of travel compared to the non-frequency shifted beam. Thus, the distance from the center of the first polarization beam splitter to the first mirror must be equal to 1.5". The same is true for the distance between the second mirror and second polarization beam

splitter. The Bragg cell is mounted between the two mirrors. Before beginning the beam collocation, ensure that the Bragg cell optimally frequency shifts the laser beam using the procedure above.

To move the frequency shifted beam horizontally, a translation stage is used to move the second mirror. To change the beam angle horizontally or vertically, the second mirror gimbal controls should be used. Vertical movement is more difficult and involves walking the two mirrors used by the vertically polarized beam, ensuring after each adjustment of the first mirror, that the Bragg Cell is still aligned optimally. The resulting process is iterative but since only small adjustments in height are required, the procedure is not too cumbersome.

The actual collocation of the frequency shifted and non-frequency shifted beam is accomplished as follows. Observe both beams on a screen a far distance away from the fiber coupler (> 5 m). Move the frequency shifted beam image on top of the non-frequency shifted beam image using the gimbal controls of the second mirror. Now observe the beams as they come out of the second polarization beam splitter. If they are not collocated at this point move the frequency shifted beam using the horizontal and vertical displacement procedures as discussed above. Repeat this procedure until the beams appear collocated both at the polarization beam splitter and the screen.

The two collocated beams are finally coupled into the fiber. The type of fiber used in LDV and other coherent light applications is polarization maintaining fiber. Polarization maintaining fiber is designed to allow the transmission of light without altering its polarization state if the polarization axis of the light is aligned with one of the two eigen-axes of the fiber. In the present implementation of the LDV, one fiber is used to transmit both the frequency shifted and the non-frequency shifted beam, each beam traveling along one of the fiber eigen-axes. Such a configuration makes the LDV less sensitive to vibration because both beams are always exposed to the same environmental conditions. Using polarization maintaining fiber thus requires rotational alignment of the optical fiber with the light beam polarization. Note that since the input light beams are polarized at ninety degrees with respect to each other, rotational alignment of the fiber for one beam guarantees rotational alignment of the

other. The rotational alignment requires repeated optimization of the fiber coupling because of the slight eccentricity of the alignment housing and fiber coupler mount. The fiber coupling procedure will be described first followed by a method to check the rotational alignment of the fiber input end.

To couple the collocated beams into the fiber, proceed as follows, assuming the two beams have already been visually collocated as described above. In order to assure that the correct beam is coupled into the fiber of the various diffraction orders generated by the Bragg cell, the non frequency shifted beam is coupled into the fiber first. Once the non frequency shifted beam has been coupled into the fiber, the frequency shifted beam is uncovered while the non frequency shifted beam is blocked. The frequency shifted beam will be coupled into the fiber to some degree due to the previously mentioned visual collocation procedure. The fiber coupler assembly consists of five parts as shown in Figure A.17: the assembly platform (L-shaped aluminum bracket), the coupler adjustment controls (combination of 2-D translational stage and a 2-axis tilt platform), the coupler alignment housing, the fiber coupler mount and the fiber coupler itself.

To couple a light beam into the fiber, proceed as described in this paragraph. Insert the fiber coupler mount into the alignment housing without the fiber attached. Use the translation controls of the alignment stages to visually center the beam on the fiber coupler focusing lens. Observe the light emanating from the fiber coupler on a screen no more than 12 in removed from the coupler. Center the beam in the opening visually. Maintain a smooth elliptical shape of the image using the gimbal alignment controls. Insert the fiber into the coupler, but do not insert it all the way. Remove the other end of the fiber from the probe and observe the light from the fiber on a screen. The light will be very faint. Insert the fiber further and further into its receptacle while continuously attempting to maintain some light coupling into the fiber. As the fiber is inserted further and further with the key aligned to the key-way (see Figure A.18), the maxima achieved by alignment will increase. Be sure to look for single mode coupling not multimode coupling. Single mode coupling is indicated by a smooth intensity distribution in the light beam coming from the

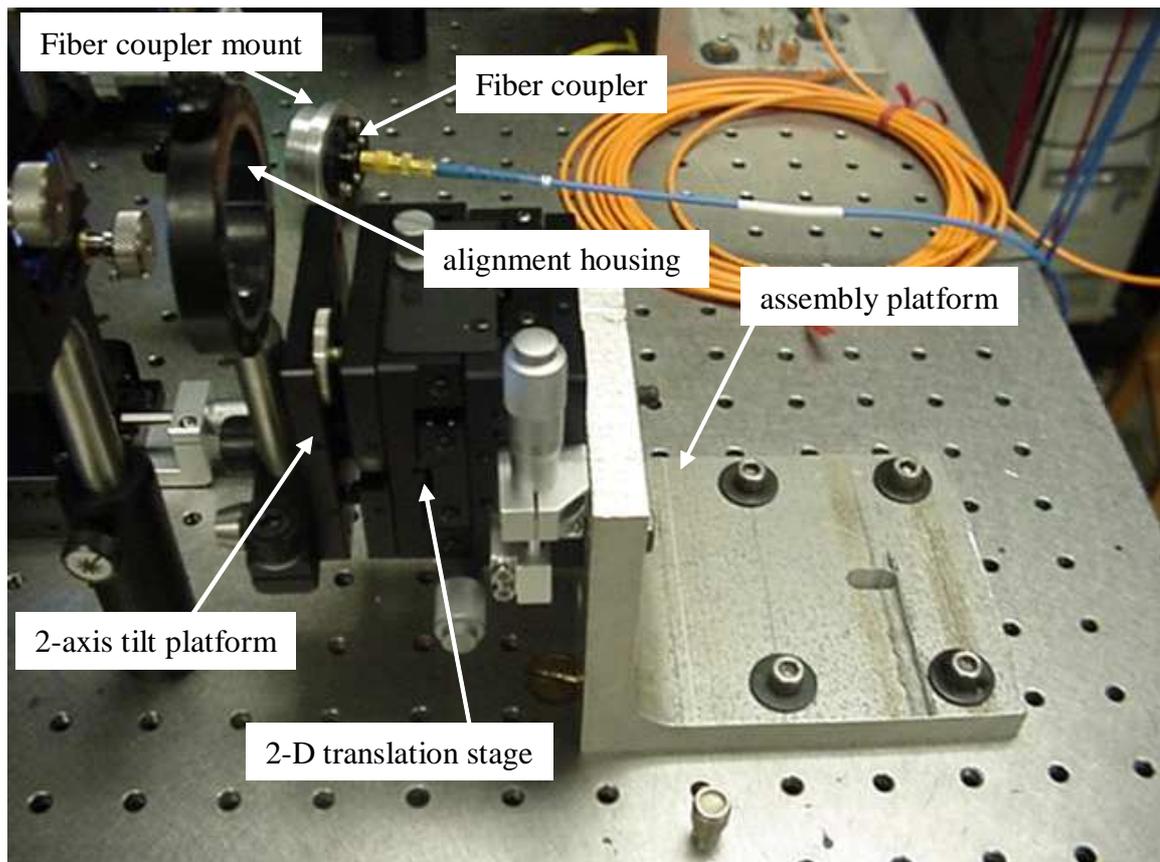


Figure A.17: Fiber coupler assembly

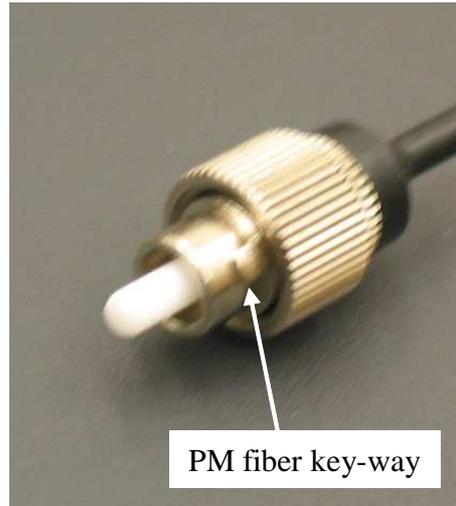


Figure A.18: Polarization maintaining fiber key-way

fiber. Multimode coupling is indicated by a speckled light output. If single mode coupling is not achieved prior to full fiber insertion, finding the operating point for single mode coupling is exceedingly difficult. Once the fiber is fully inserted and the fiber attachment screw is tightened down, the coupling is optimized using all the controls, repeating adjustment of all controls because the adjustments are not independent. The maximum coupling efficiency able to be achieved using the present setup is around 33 %.

Once coupling has been optimized for the non frequency shifted beam, block that beam and uncover the frequency shifted beam. Optimize the coupling for the frequency shifted beam using all of the fiber coupler alignment controls. Make a note of the controls which yield the highest increase in coupling efficiency. Once the coupling has been optimized, uncover the non frequency shifted beam and check its coupling. Very likely coupling will have deteriorated from its initial setting. Once again optimize the coupling efficiency of the non frequency shifted beam. Finally, optimize the coupling efficiency of the frequency shifted beam without using the fiber coupler alignment controls. Adjust the beam controls that will yield the most

improvement in coupling first. These should have been noted during the procedure just described. The procedure for translating the beam and changing its angular alignment was described above. The coupling efficiencies of each of the beams should be similar.

The rotational alignment of the fiber is achieved using the procedure outlined in this paragraph. The rotational alignment is achieved by maximizing the extinction ratio of the light coming out of the fiber. The extinction ratio must be measured without any polarization optics in place in the probe. The extinction ratio is defined as the ratio of the maximum to minimum light intensity observed as a linear polarizer is rotated. Place the polarizer at the exit of the fiber collimator and rotate to find the maximum intensity by measuring the light transmitted through the polarizer. Make a note of the intensity and repeat to find the minimum intensity. Once the minimum intensity is found, slightly shake and move the fiber and observe the output. Make a note of the maximum in the oscillations in intensity. Take the logarithm of the ratio of the maximum over the minimum measured power and multiply by 10. The ratio should be about 20 for good rotational alignment. The oscillations induced by shaking and moving the fiber should not cause the intensity to change by more than approximately 30 % when the fiber is correctly rotated. The rotational alignment of the fiber is facilitated by the knowledge that the fiber key is aligned with one of the polarization eigen-axes. As the fiber is rotated from its initial position, the coupling efficiency suffers and re-alignment will be necessary. Use small adjustments to ensure that the beam coupling is not lost completely.

At this point the input ends of the 488 nm and 514 nm laser line fibers are aligned for optimized coupling and are rotated to match the eigen-axes with the input light beam polarization. The following section describes the optical components of the LDV probe and the procedures to align its components for proper LDV operation.

A.4.3 Probe optics

Traditional LDV implementations, before fiber optics were readily available for the task, translated all of the optics including the laser to scan a range of locations.

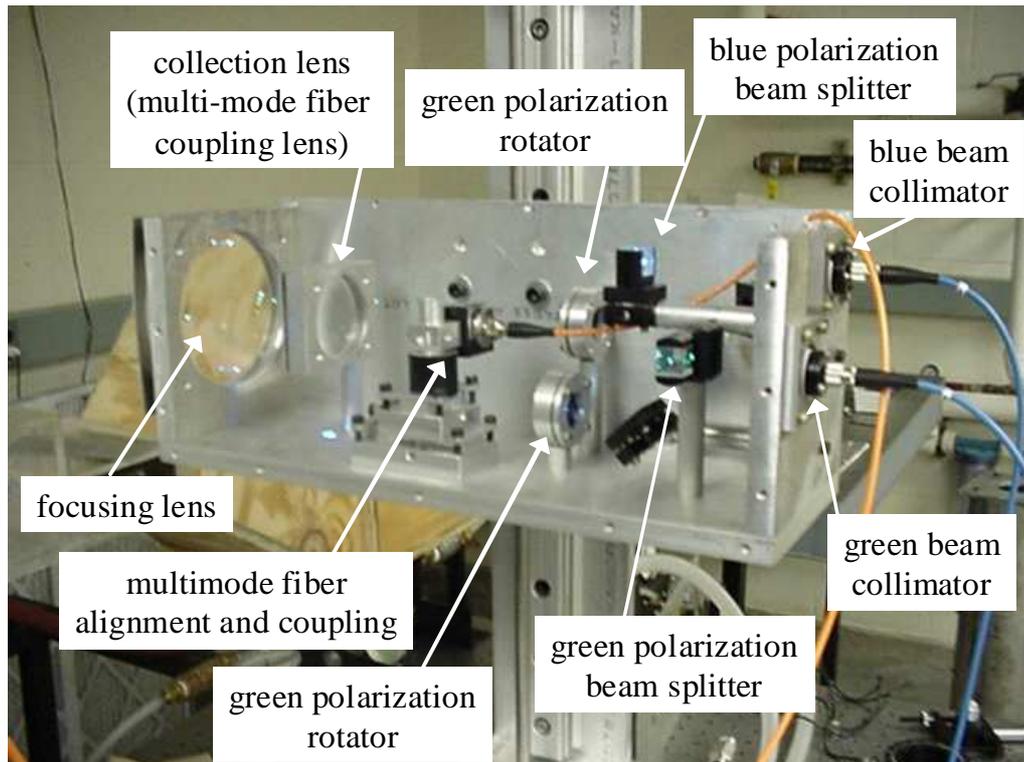


Figure A.19: LDV probe with components labeled

The advent of the use of fibers in LDV allows most of the optics including the laser head to remain stationary and a much smaller probe containing few optical components is translated to obtain measurements in the locations of interest. A labeled photograph of the LDV probe is shown in Figure A.19.

For the present implementation the probe contains fiber collimators to reform the laser beams as the light escapes the fiber. The probe also contains two polarization beam splitters which split the two beams that traveled along the same fiber into the frequency shifted and non frequency shifted beam. After the polarization beam splitters, one of which is used for the 488 nm line and the other for the 514 nm line, there are four beams inside the probe, two 488 nm beams and two 514 nm beams. The beams split off by the polarization beam splitters are redirected in the same direction as the frequency shifted beams using two mirrors. After being redirected by

the mirrors the beams pass through a polarization rotator whose role it is to make both 488 nm beams and both 514 nm beams have the same polarization. All four light beams are then focused using a large achromatic lens. The light scattered from the measurement volume is collected by the same focusing lens and then focused down onto a multimode fiber using a two inch achromatic lens. The multimode fiber serves as an aperture filter for the scattered light and ensures that the light measured on the other end of the multimode fiber originates from the measurement volume center.

Thus the optics for the green and blue beams are once again exactly analogous and the discussion about the beam alignment applies to both beam pairs, green and blue. In the discussion it is assumed that since the beams must be realigned, the probe is also disassembled. Disassembled here means that the polarization beam splitters are removed from their mounts and that the focusing lens is also removed from the mounting platform. The probe should be located on an optical table for the alignment procedure, locked in a position that will allow the straightness of beam travel to be checked, e.g. parallel to a row of mounting holes on an optical table. The longer the table, the more precise the initial alignment of the beams. The procedure assumes that all other alignment procedures have been completed and especially that the fiber correctly aligned rotationally at the input end.

The first alignment procedure to be accomplished is the correct rotational alignment of the fiber collimator. The vertical, horizontal and angular alignment of the fiber collimator follows the rotational alignment because rotation of the collimator requires the mounting/adjustment screws to be relatively loose. Approximate rotational alignment can once again be obtained by recognizing that the key of the fiber is aligned with one of the fiber eigen-axes. The key should be horizontal for the green collimator and vertical for the blue collimator for the current setup. A change of 90 degrees in the rotational alignment will switch which of the two beams traveling in the fiber will be transmitted by the first polarization beam splitter and which will be reflected. The orientation of the collimator must take into account the constant path length requirement and the direction of frequency shifting.

To align the collimator, block the frequency shifted beam before it enters the fiber.

With the fiber key approximately aligned, place a linear polarizer at the collimator exit. For correct rotational alignment and a vertically aligned linear polarizer axis, the green beam intensity should be a maximum and blue beam intensity should be a minimum. The ratio between max and min should be close to the measured extinction ratio of the fiber, as discussed above in Section A.4.2. Alignment should be performed when the polarizer alignment (vertical or horizontal) is close to an intensity minimum because the intensity minimum is more sensitive to adjustments than the intensity maximum. Thus the blue beam collimator should be aligned with the polarizer aligned vertically and the green beam collimator should be aligned with the polarizer aligned horizontally.

Once the collimators are rotationally aligned, the position and angular alignment of the collimator should be fixed. To accomplish this, check that the beam travels through the center of the hole in the collimator mounting platform. Knowing the dimensions of the collimator mounting platform and the fact the beams should lie on a circle of 3 inches diameter, the straightness of beam travel can be checked by measuring the beam vertical and horizontal position with respect to the table at several locations. Position adjustments are accomplished by pushing on the collimator which is held to the collimator mounting platform by a cover and separated from the platform by an O-ring. Angular adjustments are performed by tightening the four collimator cover mounting screws, shown in Figure A.20. At the end of alignment the collimator cover mounting screws should be relatively tight so that the collimator is securely held in place but yet not as tight as possible to allow future tweaking of the alignment.

In the same configuration, insert the polarization beam splitters into their mounts. The correct alignment of the polarization beam splitter is achieved when both the green and blue frequency shifted laser beams are transmitted (not reflected) and the non frequency shifted beams are reflected in the direction of their redirection mirrors. Ensure using methods described above in Section A.4.2 that the polarization beam splitter is aligned perpendicular to the laser beam. For initial alignment also check that the polarization beam splitters are mounted aligned with the vertical given by

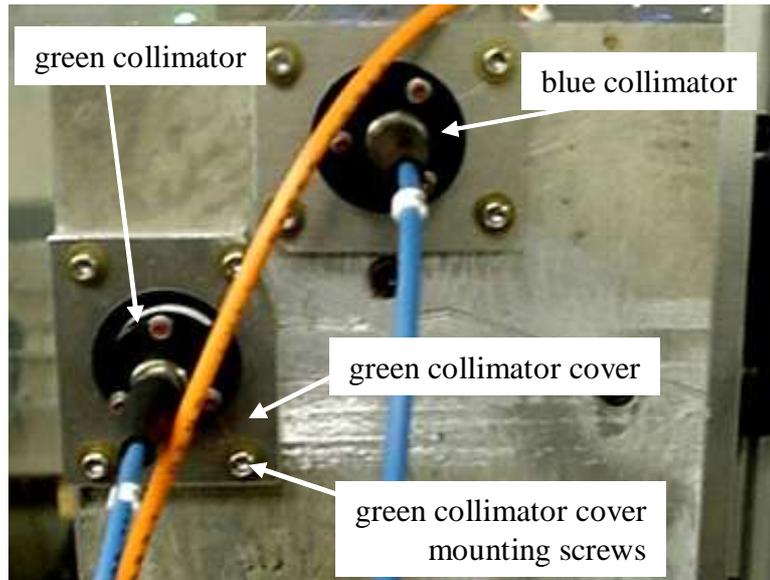


Figure A.20: Probe collimator mounting platform

the collimator mounting plate. Uncover the non-frequency shifted beams if that has not already been done. At this point, four beams should be traveling away from the collimator mounting platform. The distance between the two green beams should always be 3 inches and the same is true for the distance between the blue beams. Since the frequency shifted beam location has already been adjusted, the other beams must now be aligned. Angular movement is accomplished easily using the mirror gimbal controls. Displacement of the beams is more cumbersome and involves walking the mirror together with the corresponding polarization beam splitter.

Once all four beams are aligned to travel in parallel, the polarization of the non frequency shifted beams must be changed to match that of the frequency shifted beams. The adjustment is accomplished by the proper rotational alignment of the two polarization rotators mounted in the probe. First, place a linear polarizer in front of the frequency shifted beam and adjust the polarizer for minimum light transmission. Then, without changing the orientation of the polarizer, place it in front of the non frequency shifted beam. Remove the polarization rotator cover, shown

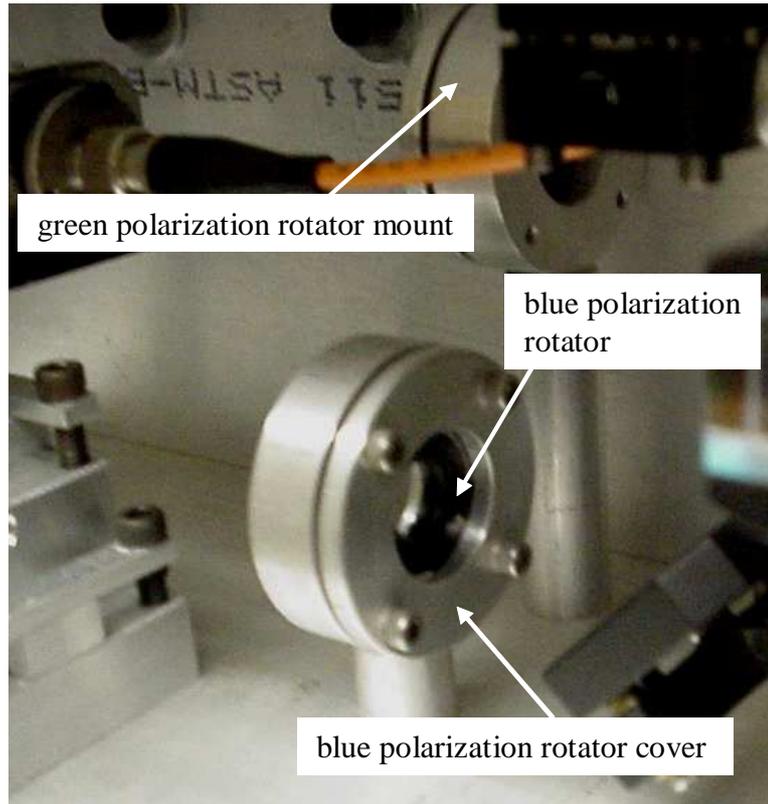


Figure A.21: Probe polarization rotator mounts

in Figure A.21, and adjust the angle of the polarization rotator until a minimum in intensity is achieved. At this point both green beams and both blue beams have the same polarization.

At this point, the focusing lens mounted on its platform is attached to the probe. To check that all four beams are focused to the same spot, a 40x microscope objective is required. The image of the microscope objective should be observed on a screen at least 12 inches away from the objective. It is not possible to check beam alignment at the exact focal point of the lens. Instead, current practice uses the green beam pair as the alignment standard. The only adjustment required for green beam crossing is vertical. Using the microscope objective, follow one of the green beams near the focal point until the second green beam comes into view. The two beams will likely

miss each other, but the working focal point of the lens in our current setup is defined to be the location at which the beams are only separated vertically. Adjust the non frequency shifted beam angular alignment inside the probe to make the green beams intersect here. The blue beams should also be in view at this point. Blocking the non frequency shifted blue beam, adjust the angular alignment of the blue beam collimator so that the frequency shifted beam intersects the green beams at their intersection point. Now, unblock the non frequency shifted beam and adjust its angular alignment using the mirror controls to also intersect at the same location. All four beams are now optimally aligned for data collection. If one of the beams in each of beam pairs were not frequency shifted, a diffraction grid could now be observed on the screen, if that screen is placed several meters from the microscope objective. Because the beams are frequency shifted however, the diffraction pattern is not stationary and cannot be made out in the image.

The last optical alignment for the probe is the alignment of the scattered light coupling optics. The 2 inch scattered light focusing lens located inside the probe cannot be aligned very precisely. Its location is fixed by an accurately located mounting hole and accurately machined lens holder and post. The only available adjustment is the angle of the lens with the plane of the focusing lens. The two should be aligned as parallel as possible. The light focused by the lens is collected by a fiber which is mounted to five degree of freedom compact translation stage. The stage assembly is shown in Figure A.22. To align the assembly, the blue fiber is disconnected at the input end and the output end of the multimode fiber is connected in its place. Since the optical system under investigation here only involves linear optics, focusing the light coming from the multimode fiber to the green beam crossing will ensure that the light from the four beam crossing is also focused into the multimode fiber. Some training is required to identify the focused beam image from a multimode fiber. Since the fiber employed is not a multimode fiber, the image will be somewhat speckled. Away from this axial location, the image either becomes blurred or much larger in size. Three pictures of the multimode fiber spot are shown in Figure A.23. The first picture is taken with the objective placed too close to the lens. The image shows the

speckled nature of the spot. The second image shows the spot in focus. The size of the speckled spot has decreased and the density of light is greater. The focus is at this maximum point of light density. The third image is taken with the objective too far from the lens. Some of light has begun to spiral away from the center. The goal of the alignment is to have the multimode fiber focused spot located at the same exact location as the green beam crossing. To obtain the desired alignment an iterative procedure is required. The iterative procedure is required because the translation stage adjustments are not entirely independent (poor design). Special care and patience is required for these adjustments especially because it is highly desirable to have a rigid mount at the end of alignment. The mount becomes rigid by tightening the lock-down screws and unfortunately the very tightening of these screws can cause alignment to be lost.

At the end of the alignment procedure, the multimode fiber should be disconnected from the blue fiber coupler and the blue fiber should be reconnected. Some realignment for optimal coupling will probably at this point also be required. Once coupling for the blue beams is optimized, with the microscope objective still in place, the scattered light from the green and blue beams can be observed coming out of the multimode fiber.

It should also be mentioned that a fiber alignment monitoring system was added to the probe. The system takes the form of a large photodiode that measures the intensity of one of the errant beam reflections off the focusing lens. The reflection is always in the same place and so represents an ideal opportunity for monitoring the light power in the fiber on a relative basis. The photodiode is shown in Figure A.24. The circuit used to bias the diode and obtain a voltage signal proportional to light flux is shown in Figure A.25. The circuit is related to the PMT amplifier circuit discussed below in Section A.5.1.

A.4.4 Receiver optics

The receiver optics process the scattered light collected at the probe and coupled into the multimode fiber. Figure A.26 shows the receiver optics. A collimator is used

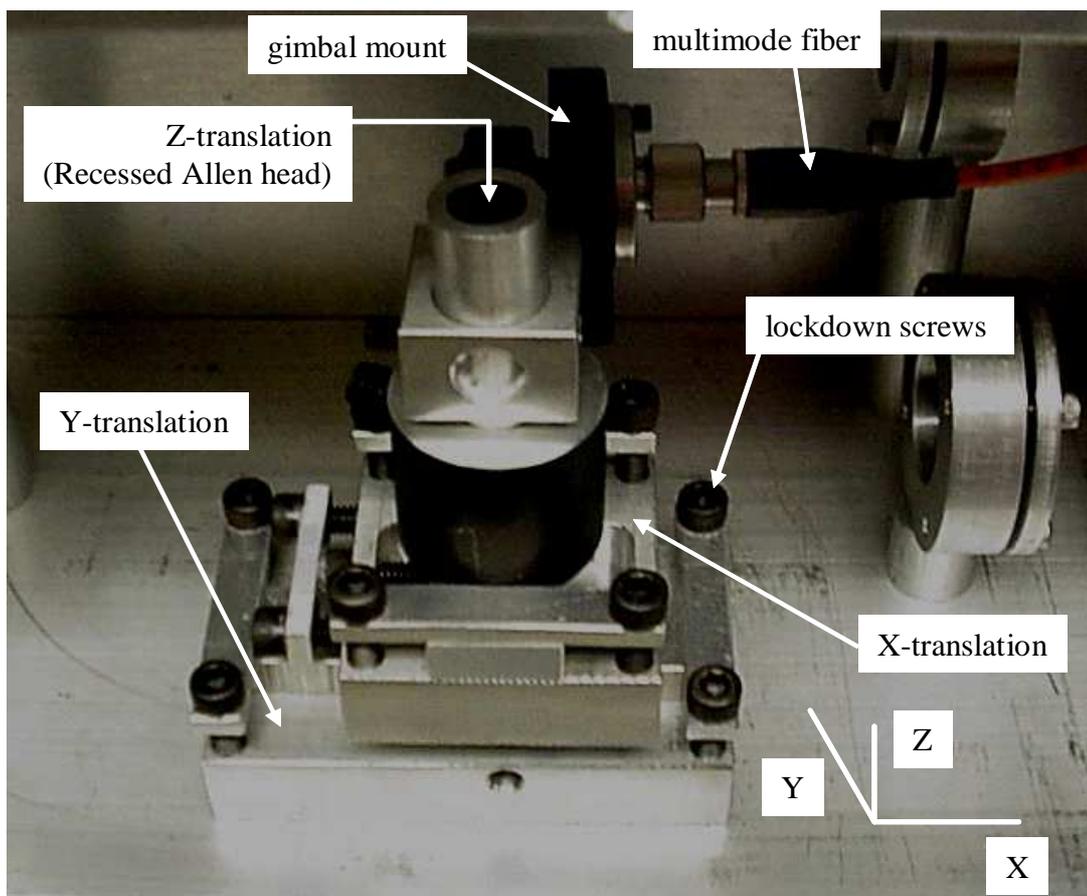


Figure A.22: Probe collection fiber translation stage

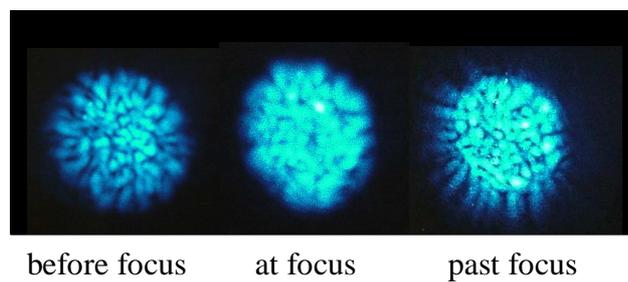


Figure A.23: Collection fiber image series

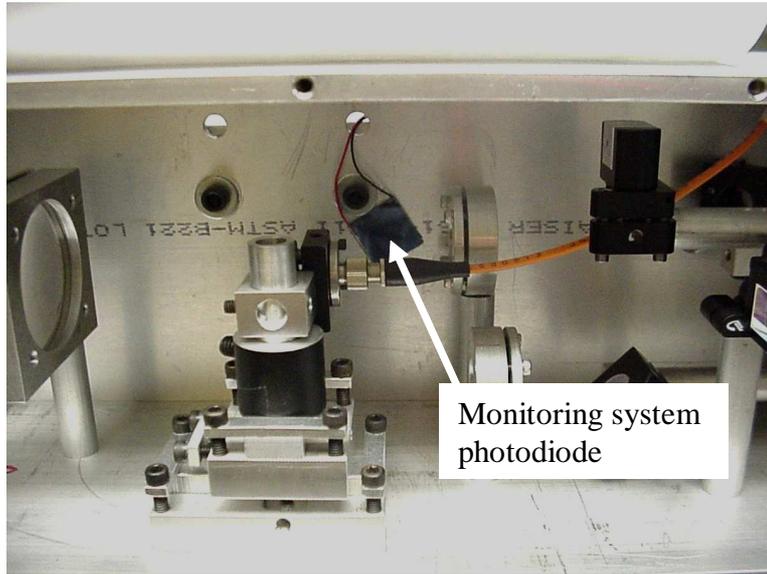


Figure A.24: Fiber alignment monitor photodiode

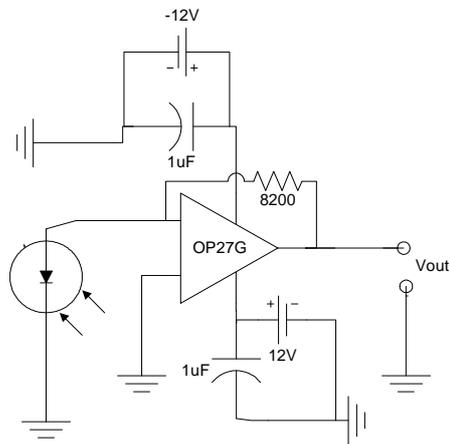


Figure A.25: Photodiode amplifier circuit

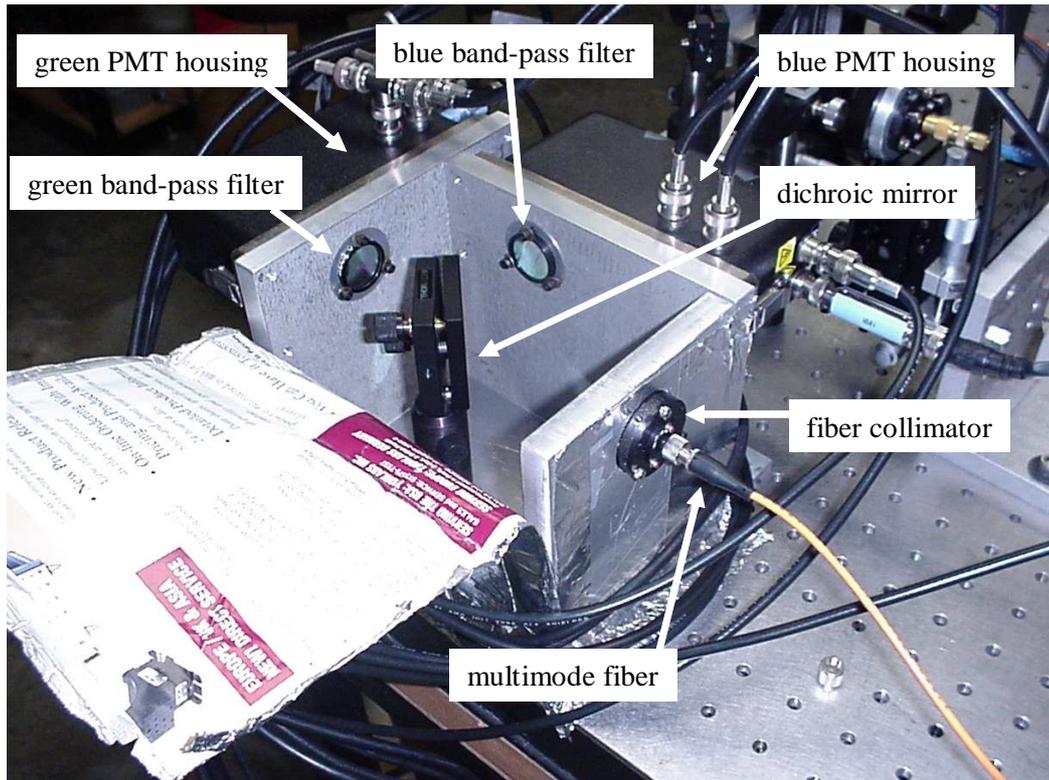


Figure A.26: LDV receiver optics

to form a beam from the scattered light which contains both green (514 nm) and blue (488 nm) light. The green and blue light is initially separated by a dichroic mirror which reflects most of the blue light (80%) and transmits most of the green light (80%). Both reflected and transmitted light is further decontaminated by a narrow band pass filter at 488 nm and 514 nm respectively. After the light is filtered, it is absorbed by a PMT which converts the light flux into electrical current. The PMT circuit is described in detail in Section A.5 which discusses the processing of the electronic signal.

A.5 Laser Doppler Velocimeter Electronics

The next sections deal with the electronics that process the scattered light collected by the optics. The PMT converts the light to electronic current. From there the current must be converted to voltage. The voltage is then filtered amplified and collected by rapid D/A conversion. The D/A conversion cannot be continuous and must be triggered by the presence of a Doppler burst. The detection circuitry will also be described here. The analysis of the digital signal collected will be discussed in Section A.6. Note that the signal path does not differ for the green or blue signals so that the discussion is left general without referring to each signal separately unless necessary.

A.5.1 Photomultiplier signal conditioning

The PMT converts the scattered light flux into electrical current. The current is produced by a photosensitive cathode which emits electrons in proportion to the incident light flux. The cathode emitted electrons impact ten successive dynode stages, each of which emits electrons in proportion to the incident electron flux. The result of this large amplification of the initially cathode emitted electrons is a measurable current.

The current is converted to voltage by a transimpedance amplifier. Ordinary applications would only require a load resistor but employing a transimpedance amplifier allows the current to voltage conversion process to be accomplished more efficiently (larger voltage for given current) and the output impedance of the amplifier can be designed to match the downstream device impedances, thereby avoiding signal loss and distortion. The transimpedance amplifier circuit diagram is shown in Figure A.27. Note that the construction of the circuit had to be done using extremely short leads to enable the circuit to perform well even at frequencies around 50 MHz. Impedance matching at these frequencies is especially important and therefore the transimpedance amplifier was designed with an industry standard 50Ω output impedance.

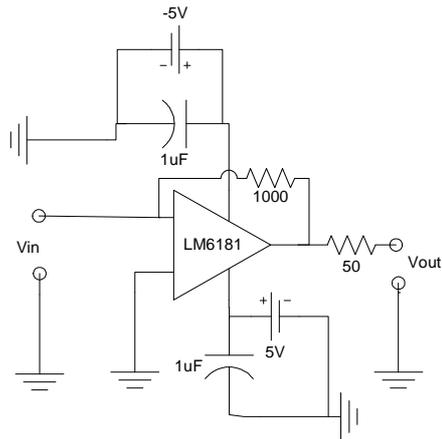


Figure A.27: Transimpedance Amplifier Circuit

The electronic signal leaving the PMT is filtered at the exit by a high-pass filter whose cut-on frequency is 25 MHz. The filter eliminates any low frequency noise that could not possibly carry a signal. One of the consequences of this is that the resulting signal no longer contains any time average information. After being high-pass filtered the signal is connected to the instrumentation box, shown in Figure A.28 inside of which it enters the mixer. The mixer is a circuit element that effectively multiplies two electronic signals. When two periodic signals of different frequency are multiplied, the resulting signal contains the sum and difference of the two original frequencies. The second signal into the mixer is an amplified and split RF generator signal.

The RF generator, shown in Figure A.29, is used to provide a constant frequency reference so that rather than having to measure frequencies around 40 MHz, the velocity information is extracted from a signal around 10 MHz which is much easier to acquire using an A/D conversion process. Furthermore, the accuracy of frequency identification increases dramatically if the same number of samples are used to identify a frequency of around 10 MHz compared to a frequency around 40 MHz. The mixing frequency choice requires some discussion. If 40 MHz were chosen as the mixing frequency then all of the advantages of frequency shifting would be lost. The mixing frequency should be chosen to be either higher than or lower than all anticipated



Figure A.28: Instrumentation box

doppler shifted burst frequencies. For the present setup, a typical mixing frequency is 38 MHz. The Bragg cells were aligned so that forward flow and clockwise rotation of the swirl velocity will cause a positive shift in the light frequency (i.e. shifting the frequency beyond 40 MHz). The 2 MHz difference between the shift frequency and the mixing frequency allows for 2 MHz worth of reverse flow (about 3.4 m/sec - see Section A.6).

The RF generator signal needs to be split between the mixer for the green and



Figure A.29: RF generator

blue signals. The signal is split using a power splitter device which allows the two signals to be split without distortion. Simply connecting the signal in parallel would cause an impedance miss-match and would result in signal distortion. Since the power provided by the RF generator is insufficient to drive both mixers, an amplifier is used to amplify the RF generator signal before it is split and connected to the mixers. The signal level leaving the RF generator must be chosen so as to not cause saturation in the amplifier and not exceed the input limits of the splitter and the mixer. For further information on these devices, please refer to the manufacturer website: www.minicircuits.com.

The output of the mixer is low-pass filtered with a cut-off frequency of 30 MHz, effectively isolating the frequency difference portion of the multiplied signals. The resulting signal is then sent to the trigger identification circuit, discussed in Section A.5.2.

A.5.2 Doppler identification and trigger circuits

The filtered signal from the mixer now contains the information desired at a practical frequency. The signal now enters a circuit designed to amplify the signal and determine whether or not it contains a Doppler burst worthy of data collection. The circuit is shown in Figure A.30 and the diagram for one of the trigger circuits (the green and blue circuits are identical) is given in Figure A.31. The trigger logic circuitry shown in Figure A.30 is described below and illustrated in Figure A.32.

The first portion of the circuit is a simple amplifier with gain of approximately 100. The output of the amplifier is connected to another stage of the circuit and to the back of the instrumentation box. From there the signal is connected to the data acquisition board. The second stage of the circuit essentially consists of a half-wave rectifier that also additionally amplifies the signal. The next element consisting of a resistor and capacitor combination, follows the peaks in the rectified signal in a delayed fashion. A single sharp peak will be filtered out by this R-C circuit. The time constant was designed so that the repeated peaks of a Doppler burst will allow the output of the R-C circuit to reach the Doppler burst signal peak.

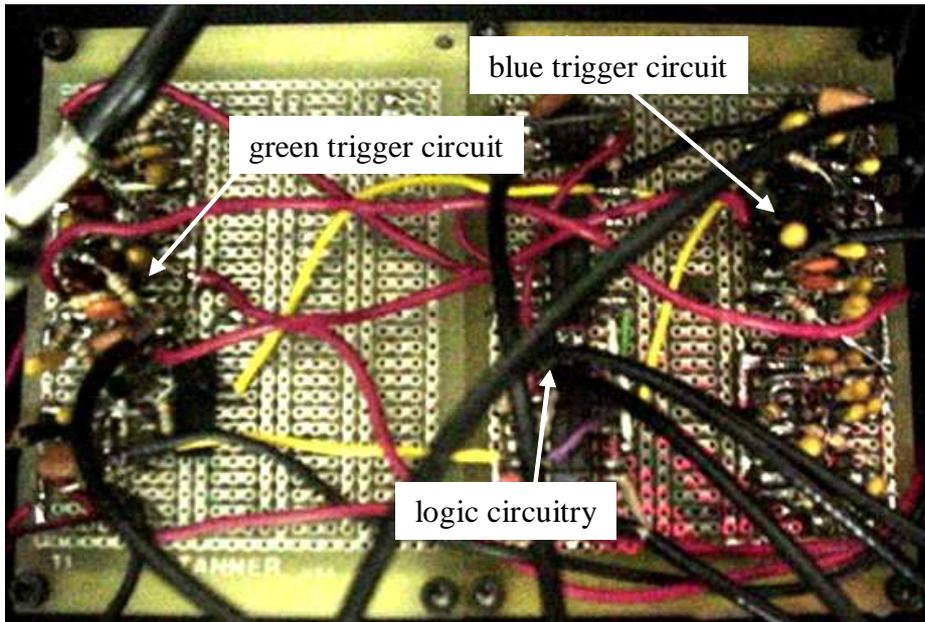


Figure A.30: Trigger circuit

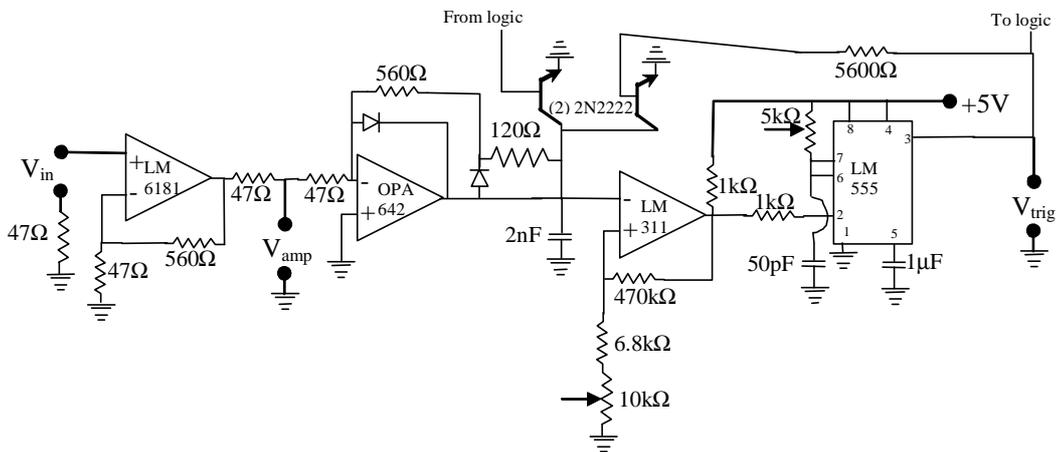


Figure A.31: Trigger circuit diagram

The next circuit element consists of a comparator whose output is logic high unless the R-C circuit level is above the current trigger level. The trigger level is set using a potentiometer, as shown in Figure A.31. The higher the resistance, the higher the trigger level. As soon as the output from the comparator drops below two thirds of its steady state value, a counter-timer circuit is activated that sends out a digital trigger pulse. The width of the pulse determined by another potentiometer setting. The higher the potentiometer setting, the longer the pulse width. The trigger pulse width is important in forming the coincidence window, as discussed below. The pulse is interpreted by the logic circuitry and, independent of the logic circuitry, the digital trigger pulse activates the transistor causing the R-C voltage to be held to ground for the duration of the pulse. The voltage of the R-C circuit is thus reset, although the voltage does not quite go to zero because there is a finite voltage drop across the transistor of about 0.1 V. A second transistor is shown in Figure A.31. This transistor is connected to the output trigger of the logic circuitry so that whether or not a Doppler burst occurred in the circuit under consideration, if a data acquisition trigger is produced by the logic circuitry, this pulse also resets the R-C circuit voltage.

The logic circuit that is used to control under what conditions the data acquisition is triggered is illustrated in Figure A.32. Note that all AND ports are located on the same IC chip. The 555 circuit indicated is similar to those shown in Figure A.31 and a potentiometer again allows the trigger pulse width to be determined. The pulse width for the data acquisition trigger essentially works as an absolute limit on the repeat frequency of triggers. The longer the pulse width the longer the minimum time between recorded Doppler bursts. The circuitry supports three trigger types: green, blue and coincidence. The trigger types are controlled by the output from the digital port of the National Instruments data acquisition board (PCI-6034E). The digital port also controls the trigger enable function of the circuit. In order to synchronize both the rapid A/D and pulse timing operation, both of these operations are armed before the trigger enable and trigger type bits are set on the digital port. Only if the trigger enable bit is high, will trigger pulses actually pass through to the data acquisition system. Note that, if neither the green trigger or blue trigger bits are

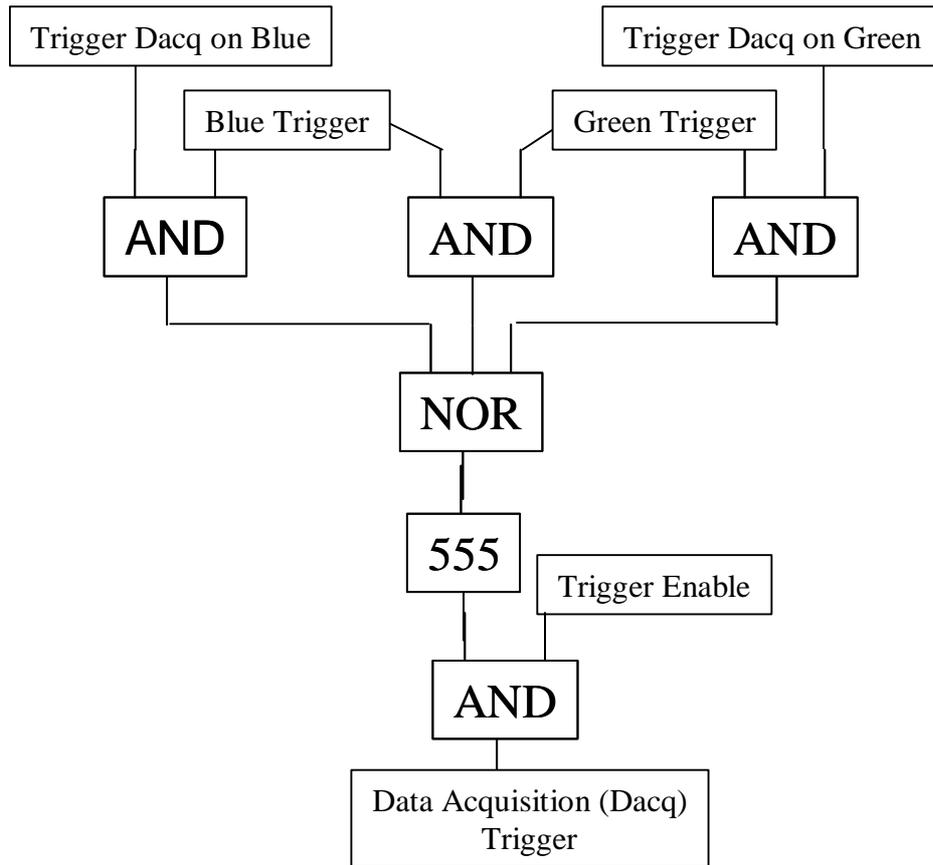


Figure A.32: Trigger logic circuit diagram

set to high, the system outlined in Figure A.32, will turn into a coincidence trigger automatically (i.e. only 2 digital bits are necessary to control the three trigger types).

A.5.3 Doppler data acquisition

In order to complete the picture of the electronics involved with the LDV, the data acquisition trigger issued by the Burst trigger circuitry must be followed to the actual collection of data. There are two elements to the data acquisition. The first is high speed analog to digital (A/D) conversion of the Doppler burst. The second is the recording of the time of collection of the Doppler bursts so that a time resolved picture of the flow field can be obtained.

High speed A/D conversion is accomplished using a Gage model CompuScope 2125. The board is configured with 4 Ms (mega samples) of on-board memory. The board is set up to run in what is called multiple record mode which allows the board to support extremely high trigger repeat frequencies. The board fills up the on-board memory with blocks of data, the length of which is usually 256 samples. The data acquisition rate is 25 MHz for most cases. Collecting both components of velocity therefore allows for 8065 blocks of data, corresponding to a potential 8065 velocity data points. Based on the 4 Ms of on-board memory a number of 8192 blocks of data is expected. The reason for the discrepancy has to do with the Embedded Bits feature of the board which helps make the bounds of each data block more precise. See GaGe (1999) for more information. Each trigger thus causes the board to collect a block of data. If both green and blue velocity components are being measured, two blocks of data are collected simultaneously.

The same rising edge trigger that causes the A/D block to be collected, also activates the counter timer part of the PCI-6034E board. The PCI-6034E is set up to measure the period (in clock ticks) between adjacent rising edge triggers. Each trigger also resets the counter so that the period measurement can begin anew. The very first trigger received causes a nonsense value for the period to be recorded since there is no previous trigger to measure a period against. Subsequent triggers reset the clock and write the clock value prior to reset into memory. The clock speed chosen is 20 MHz so that the period measurement has a resolution of $0.05\mu s$. The individually measured periods can then be added together to form a time vector with the first Doppler burst located at time zero.

A.6 Laser Doppler Velocimeter Signal Processing

The interpretation of the collected blocks of data in terms of velocity requires detailed discussion. The method of information extraction and the proper determination of the quality of the information is critical to the accuracy and speed of the LDV. A proper method for calculating LDV velocity statistics will also be discussed.

Finally, an overview of the software designed to control the LDV is given followed by a description of the binary and LabVIEW data file formats.

A.6.1 Frequency identification and burst quality

Each of the data blocks collected is analyzed for its frequency content. Two different methods of frequency identification were considered. The first is the standard FFT (Fast Fourier Transform) (Press et al., 1992) and the second is a parametric autoregressive model (Marple, 1987). The FFT is further processed to obtain an estimate of the power spectral density. Regardless of the estimate for the power spectral density, an interpolation was performed on the peak to further refine the frequency estimate. For both algorithms the form of the interpolation is that described by Matovic and Tropea (1991), fitting a parabola to the logarithms of the values in the immediate vicinity of the frequency peak. The authors actually recommend an interpolation algorithm based on the \cos^2 curve but report that the algorithm is subject to instability. Thus the algorithm chosen has a small performance penalty but is overall more stable. The three values defining the parabola are the frequency peak itself and the power estimates immediately before and following the peak. The peak estimate is then obtained from the maximum in the parabola. Figure A.33 compares the two methods in a histogram of errors. Errors were calculated for random velocities distributed over the entire possible measurement range. The Doppler bursts were simulated by multiplying a gaussian exponential function by a sine function. The simulated Doppler bursts include the effects of 8-bit discretization to correctly simulate the GaGe CompuScope board. The simulated bursts also include added noise. For Figure A.33, the signal to noise ratio is about 0.5 corresponding to -6 dB. The figure shows that both estimates perform very similarly. The method implemented in the LDV system is however the autoregressive method because it offers advantages in accuracy over the FFT method when actual data is used. Figure A.34 shows a comparison of accuracy similar to Figure A.33, except that real Doppler data was used. The standard for the calculation is the autoregressive estimate (100% accuracy). Note that for this set of data the FFT method is clearly inferior, causing artificial scatter

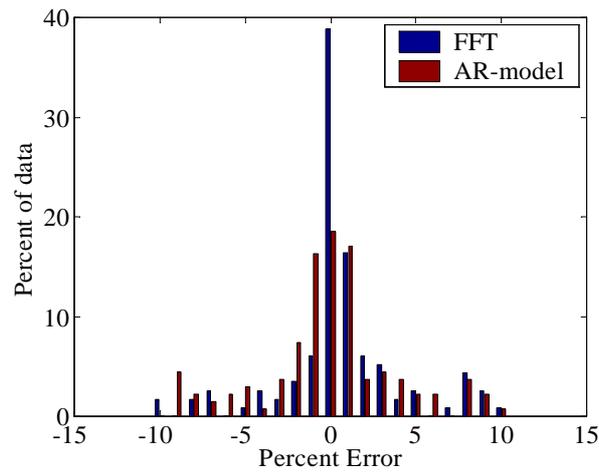


Figure A.33: Comparison between FFT and autoregressive frequency identification for simulated data

in the data. This was observed consistently, especially at lower signal to noise ratios.

Beyond obtaining an estimate of the Doppler frequency, the data must also be processed to obtain a measure of the significance of the peak. The signal to noise ratio (SNR) of the estimate will be used as indication of how significant the frequency peak

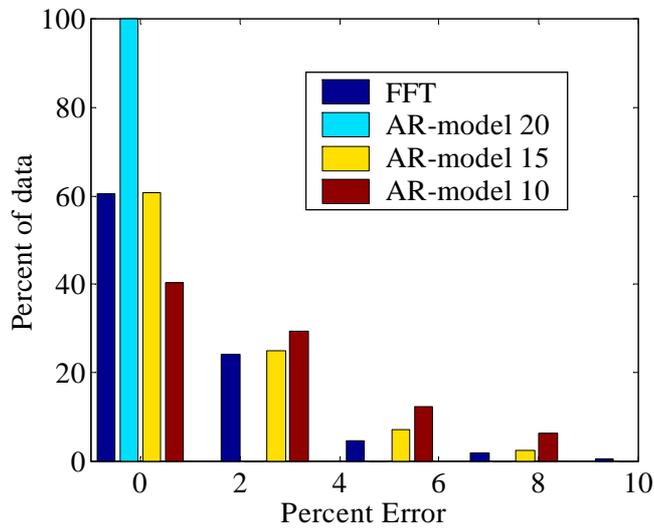


Figure A.34: Comparison between FFT and autoregressive frequency identification for actual data

in the collected data was. Very low signal to noise ratios may indicate that there is no Doppler frequency information at all. As the trigger level is lowered, this becomes a possibility where a burst of noise can cause the circuit to issue a trigger even though there is no significant Doppler information present. A lower signal to noise ratio may also cause significant error in the peak frequency estimation. After processing some data points, whose SNR is lower than some threshold value, will be discarded because of the likelihood that the frequency estimate contains large errors.

The SNR of the frequency estimate here is determined by the ratio between the frequency peak value and the the average power spectrum value. The logarithm of the ratio then forms the displayed value for SNR. The value thus calculated is different from that more commonly used. Strictly speaking, the SNR should be calculated as the ratio of the area under the peak of the power spectrum over the rest of the area under the entire power spectrum. The SNR estimate used here is related to the customary one but is computed more easily.

A.6.2 Conversion to velocity

In order to obtain a physical velocity from the measured doppler frequency estimate, both optical and electronic system parameters must be known. Equation A.1 shows how the fringe spacing is calculated for a given beam separation and focusing lens focal length. Table A.1 gives the values of the optical parameters in the current LDV configuration as well as the calculated fringe spacing for both 488 nm and 514 nm laser beams. The fringe spacing is then used in conjunction with Equation A.2 to determine the velocity, including directional sign. Equation A.2 clearly shows how the mixing frequency changes the velocity measurement range of the LDV for a given sampling rate. For a sample rate of 25 MHz, the maximum frequency that can be resolved is 12.5 MHz. The minimum frequency is of course close to 0. The range of measurement is thus the sampling frequency divided by two and by the fringe spacing. The measurement range can be shifted by changing the mixing frequency as clearly shown by Equation A.2. The selection of the mixing frequency must be matched with anticipated experimental conditions.

Table A.1: Optical parameters required for frequency to velocity conversion

Beam separation (mm)	76.2
Lens focal length (mm)	250
Beam diameter (mm)	2.2
Light wavelength (nm)	488 / 514
Fringe spacing (μm)	1.62 / 1.71

$$d_f = \frac{\lambda}{2 \sin \arctan \frac{d_b}{2f_l}} \quad (\text{A.1})$$

$$v_d = \frac{f_d + f_m - f_s}{d_f} \quad (\text{A.2})$$

A.6.3 LDV velocity statistics

Developing statistics of velocity from LDV measurements is not straightforward because the sampling intervals are uneven. Furthermore, a bias in the velocity statistics exists due to the fact that seed particles are uniformly distributed in a measurement medium. The bias is often explained using the conveyor belt analogy. The seed particles are evenly spaced on the conveyor belt but the belt moves at various speeds. The number of particles passing through a given location is thus not constant in time. At times of higher velocity, a higher rate of particles passes a given location than at times of lower velocity. A simple particle or data point weighted average thus results in a bias toward higher velocities.

The most efficient, straightforward way to combat this effect is to calculate true time averages, that is performing an integration such as that given in Equation A.3 and dividing by the measurement period. Similar expressions can be developed for RMS and even higher order statistics of the velocity field.

$$\bar{x} = \frac{1}{T} \int_0^T x dt \quad (\text{A.3})$$

The evaluation of the power spectrum of the unevenly sampled data also requires some discussion. However, this is treated in Section 3.2.4 of Chapter 3.

A.6.4 Software description

The present section is divided into three parts, successively becoming more and more low level in programming. The routines visible to the user are described first followed by LabVIEW subroutines. Finally, C-code that interfaces with LabVIEW is discussed.

A.6.4.1 LDVinstCTRL

The routines described here are all visible to the user and demand some form of user input or action. The main program that controls all other LDV processes is called LDVinstCTRL. The LDVinstCTRL front panel is shown in Figure A.35. The user can move the probe, set the PMT excitation voltage, check fiber alignment, set the LDV data acquisition parameters and call several different subprograms.

After loading the program by starting LabVIEW and opening the LDVinstCTRL VI, the actual program is initiated by pressing on the white arrow at the top left of the screen. A dialog window will come up asking the user to power up the stepper motors. At this point the program has sent an inhibit signal to the stepper motor controller to allow for the power to the motors to be turned on without inadvertent stepping. After the motors have been powered up, the OK button on the dialog should be clicked. The inhibit signal is reset and normal operation of the control program can begin.

The top left and middle of the front panel show the controls to move the probe along all three axes. This part of the front panel also allows the swirl angle to be changed. To move the probe or change the swirl angle, select the desired axis of movement (X,Y,Z or swirl) to the left of the front panel under "Axis". Enter the change in position including sign into the "Distance to move" box. The program will calculate whether or not the movement can be accomplished exactly. The minimum round

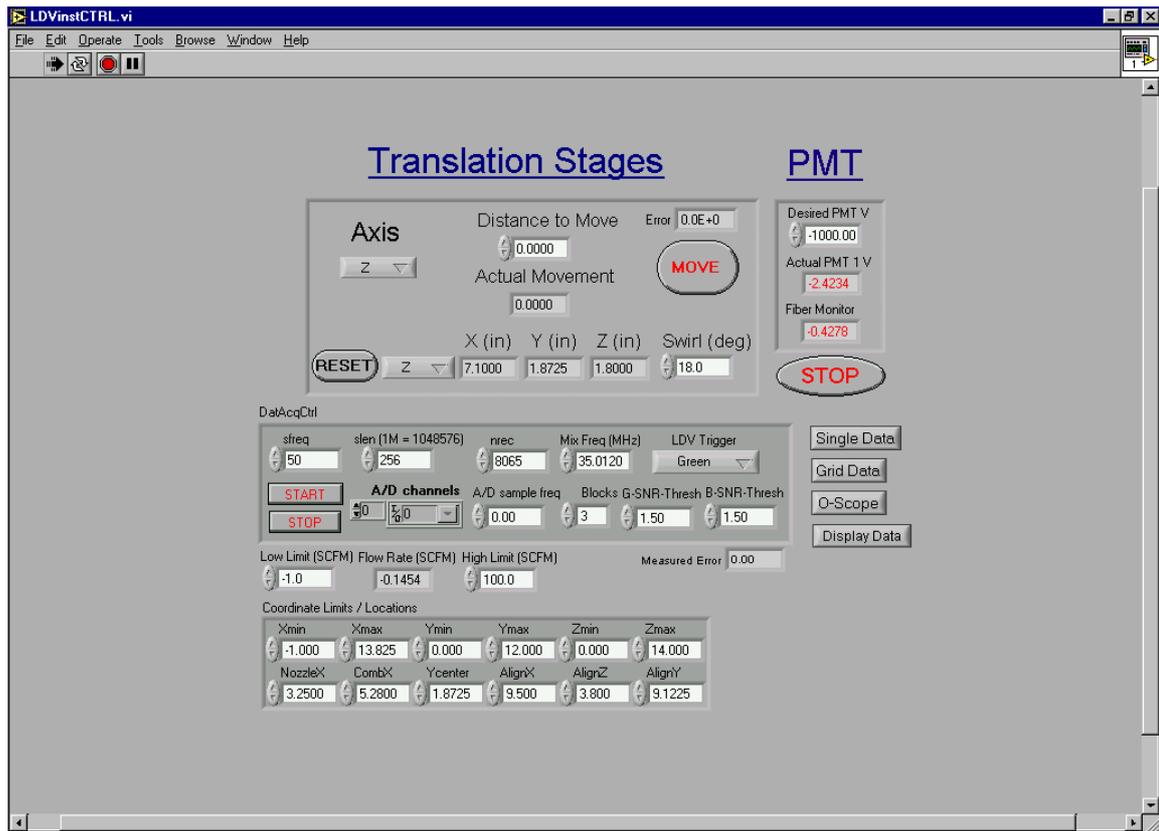


Figure A.35: LDVinstCTRL front panel

number of inches that can be resolved is 0.0025 inches. The minimum rotational step is 1.8 degrees. If the movement cannot be accomplished exactly, the actual movement box font will change to red and the box marked Error will contain the percent error between the desired and actual movement. Sometimes roundoff error is sufficient to make the font for the actual movement to turn red. The error in this case is seen to be very low however and it is OK to proceed with the distance entered. To initiate motor movement, the "Move" button is pressed (clicked). Control of the program will pass to the subroutine StepDir.vi described below in Section A.6.4.8. During the movement, the screen will be non-responsive to user actions. When movement is done, control returns to the front panel and the new probe location is saved to "Coordinates.dat". In this way, even if the system halts or the program is otherwise aborted, the probe location is recorded on disk and the axes will not have to be re-zeroed. The current axis positions are indicated below the "Actual Movement" box. Selecting an axis and pressing the "Reset" button will cause the current location to become the origin of the selected axis.

To the right of the front panel, at the top, the PMT desired and actual voltage is displayed. The control voltage is sent through a D/A channel to the PMT power supply. The monitor output from the PMT is connected to the PMT-M1 monitor input on the instrumentation box. The input is measured using an A/D channel. The measured value is reported in "Actual PMT 1 V". Below the "Actual PMT 1 V" indicator is the indicator that allows monitoring of the fiber alignment as discussed above in Section A.4.3.

Some LDV data acquisition characteristics can be controlled from the LDVin-stCTRL front panel. These include the Doppler sample rate, the length of the burst collected and the number of bursts collected. Note that due to hardware restrictions, only combinations of burst length and number of bursts that will fill up the entire on board memory (4Ms) are allowed. The most common configuration is for 8065 bursts of length 256. Other LDV parameters controlled from the panel include the trigger mode (whether triggering on green bursts, blue bursts or only under coincidence), the mixing frequency which is approximately the same from day to day but should always

be changed to the number exactly measured with the frequency counter, the number of data blocks (blocks of 8065 bursts) to be collected and the SNR threshold for green and blue Doppler bursts above which the velocity data points must lie. Further, it is possible to "Start" or "Stop" the burst collection automatically depending on the setting of these buttons on the front panel. When the "Start" button is depressed, the burst collection will begin immediately upon entering the measurement subroutine (Unsteady-Velocity). When the "Stop" button is depressed the subroutine will exit immediately following completion of data interpretation. The LDVinstCTRL front panel also allows A/D channels and an A/D sample frequency to be specified. In Unsteady-Velocity, the A/D channels will be collected at the same time as the Doppler bursts at the specified frequency. If the sampling frequency is specified to be zero, then no A/D data collection will be performed.

Below the LDV data acquisition characteristics, a current flow rate indicator is located between user specified flow limit controls. The indicator displays the flow rate currently measured on the A/D channel, scaled to have units of SCFM. To the left and right of the indicator are the low and high limits between which the flow rate is desired to be held during data collection. If the measured flow rate falls outside these limits, data collection in Unsteady-Velocity will be prevented.

To the right of the LDV data acquisition characteristics, four different subprograms can be called up. Pressing the "Single Data" button will cause the program to call Unsteady-Velocity (see Section A.6.4.2) to collect the specified data at the current location only. Pressing the "Grid Data" button will bring up the MeasGrid program to setup a 2D scan of spatial locations (see Section A.6.4.3). Pressing the "O-Scope" button will bring up a window that allows the raw voltage collected from the high speed data acquisition card to be viewed directly (see Section A.6.4.4). The program is used in troubleshooting the system, making sure light is hitting each PMT. The PMT voltage can be monitored directly by disconnecting the corresponding BNC connectors on the front panel and connecting the cable to the BNC cables leaving the rear of the instrumentation box connected to the high speed data acquisition board. Pressing the fourth button "Display Data" will call up the program used to review

mean and RMS velocity results (see Section A.6.4.5).

Below the flow rate indicators, lies a cluster of important probe locations. These values are specific to the translation stage setup and experimental setup (see Appendix C). Alignment locations refer to a location where the beam alignment can be checked using the microscope objective. The axis limits depend on the coordinate system used. The most practical (for experiments) reference for these coordinates are the limits of the translation stages. The program will not allow movement past these coordinates.

A.6.4.2 Unsteady-Velocity

The program Unsteady-Velocity is called from both the main LDVinstCTRL program as well as MeasGrid. The front panel for Unsteady-Velocity is shown in Figure A.36. The program performs the actual velocity data collection and if desired pressure data collection. In an automated collection process, the data collection can be set to begin immediately and the program can also be set to exit automatically. If Unsteady-Velocity is called with both "Start" and "Stop" buttons pressed in, the program will start and exit automatically. Manual operation will allow the user to control the data acquisition parameters displayed on the Unsteady-Velocity front panel before acquisition begins. The acquisition process is started by pressing the "Start" button. The controls available for the LDV data acquisition on the Unsteady-Velocity front panel mirror those available in LDVinstCTRL. There are however additional controls. The shift frequency as well as the fringe spacings can be separately controlled from the Unsteady-Velocity front panel. Unless optical elements are changed, these values should not be changed.

The program panel contains two charts. The top chart displays the calculated and validated velocity data whereas the bottom chart shows the distribution of signal to noise ratio in time. For the signals displayed in the top chart. The top chart can display either velocity component or both at the same time depending on the setting of the data selector located to the left of the "Save Data" button. The data selector defaults to "Both" meaning that both measured velocity components will be

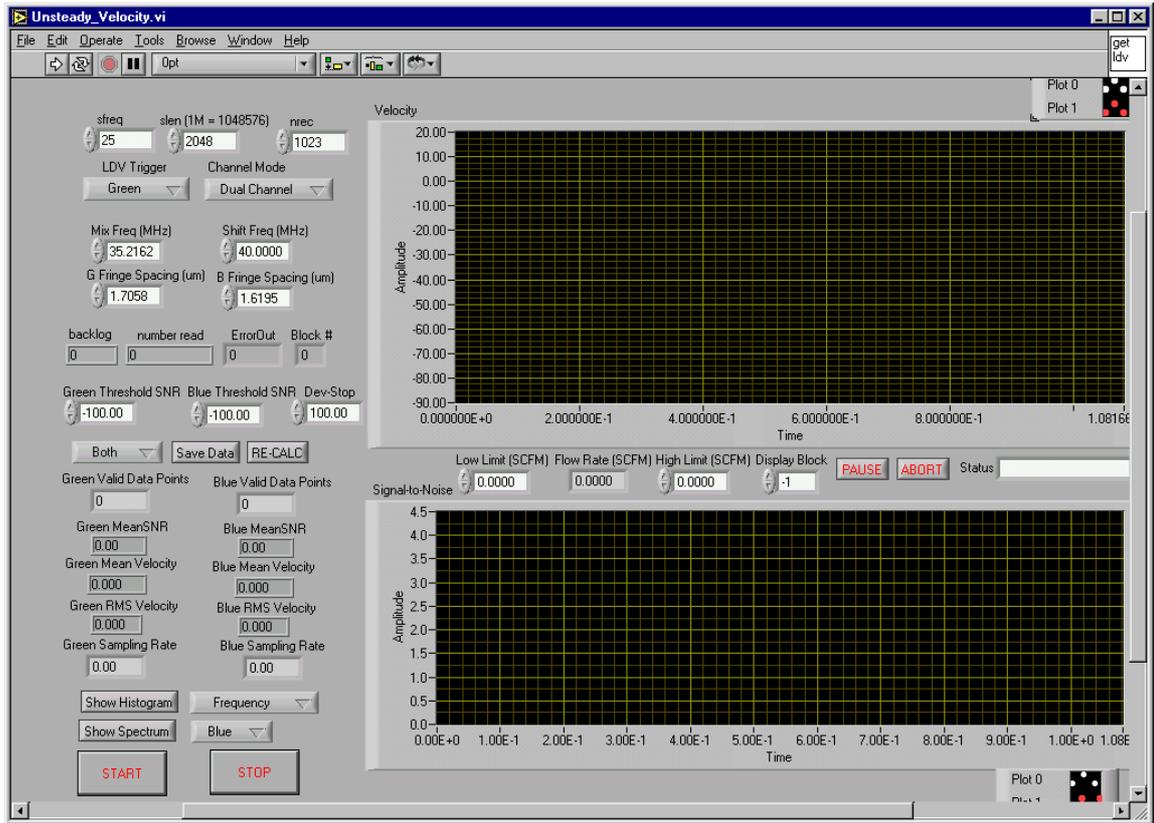


Figure A.36: Unsteady-Velocity front panel

shown. Pressing the "Save Data" button allows the user to save either the green or blue velocity component to a text file containing both time and velocity columns. To the right of the "Save Data" button is the "Re-Calc" button which causes the program to run the data validation and statistics calculations again. Data validation can be changed in two ways. The first is by lowering the signal to noise threshold for validated data. The second way is to change the "Dev-Stop" value. The "Dev-Stop" value is used to eliminate all data points located outside a certain number of standard deviations from the mean. These controls are located in above the data selector, "Save Data" and "Re-Calc" buttons.

A row of indicators is shown above the data validation parameters. The "backlog" indicator shows how many Doppler burst periods the counter buffer contains beyond the last number of burst periods read. The "number read" indicates the number of burst periods that have been read. The counter increases continually as Doppler bursts are collected. The "ErrorOut" indicator reports any errors associated with the high speed data acquisition. If there are no errors, its value is zero. If the number of bursts requested exceeds the number of bursts the board is able to collect at a time, "ErrorOut" shows the number of bursts actually collected. The "Block #" indicator represents the data block that is currently being collected. The counter will increase towards the total number of data blocks requested.

Two columns of velocity component specific data statistics are displayed below the data selector row. Each column contains for each velocity component, the number of valid data points, the mean signal to noise ratio, the mean velocity, the RMS velocity and the mean sampling rate. For coincident trigger data collection, the two columns will show the same mean sampling rate and number of valid data points.

The velocity data can be examined in more detail using the programs called up by the buttons located below the component statistics. Pressing the "Show Histogram" button will bring up a window that will display a histogram of the quantity selected to the right of the "Show Histogram" button. "Frequency" will show a histogram of velocity. If the data selector is set to "Both", the histogram will contain both component data sets. Selecting "Time intervals" will show a histogram of the time

intervals between Doppler bursts. Selecting "SNR" will show a histogram of the signal noise ratio calculated for the current data set.

Below the "Show Histogram" button, the "Show Spectrum" button allows the user to bring up a window that displays calculated power spectra and cross spectra. The selector to the right of the button determines the data set on which the spectra are calculated. If either "Blue" or "Green" is selected only the power spectrum will be calculated. If "Both" is selected, each components power spectrum is calculated along with the cross-spectrum and transfer function between the two components. Further information on the spectrum window can be found in Section A.6.4.6.

The flow rate measured before the current data block is indicated between the two charts. To the left and right of the flow rate indicator are the limits between which the flow rate must fall for data collection to proceed. To the right of the high flow rate limit is a control that allows scrolling through each data block collected. The default setting of "Display Block" is -1 which shows all collected data blocks superimposed on each other. To the right of the "Display Block" control are two switches that allow the user to pause data collection between two data blocks and to abort the current data block collection respectively. The status window indicates the task currently being performed by the program.

Pressing the "Stop" button will cause Unsteady-velocity to return control to its calling program which is either LDVinstCTRL or the MeasGrid program described in the next section. If the program is called with the "Stop" button pressed in, the program exits as soon as all processing is completed.

A.6.4.3 MeasGrid

The MeasGrid program is called from the main LDV control program LDVinstCTRL (Section A.6.4.1) and is used to perform spatial scans of the measurement domain. The front panel of MeasGrid is shown in Figure A.37. The program is set up to perform two dimensional traverses in measurement space. Correspondingly the program requires inputs for the two axes along which the traverse will take place. "1st Direction" is the outer translation direction, the direction along which the probe

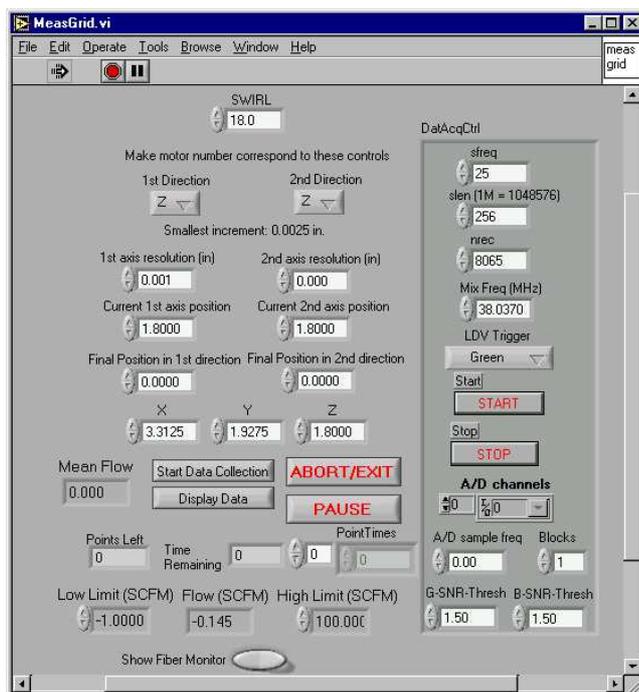


Figure A.37: MeasGrid front panel

will translate after completing a scan of the "2nd Direction". Although the nomenclature seems reversed, the labels refer to the fact that programmatically, the "1st Direction" is the first or outer loop and the "2nd Direction" is the second or inner loop in the iteration over the total number of points to be collected. Once an axis (direction) is selected the current position is indicated under "Current 1st/2nd Axis Position". The spatial increment along that axis and its maximum extent are entered under "Axis Resolution" and "Final Position" respectively. To perform a single axis scan set the first axis final position to be the axis current position and ensure that the increment for the axis is a positive number. The probe will only execute the scan along the second axis.

The front panel of MeasGrid also once again shows the LDV data acquisition parameters. The parameters may be changed and will be passed to Unsteady-Velocity each time MeasGrid calls for another data point. Additionally, the currently measured

flow rate and the flow rate limits are displayed and will also be passed to Unsteady-Velocity. "Mean Flow" reports the mean flow rate measured for all the data blocks collected at the previous point. The "Show Fiber Monitor" button brings up a large indicator that shows the currently measured voltage for the fiber monitor. The indicator is oversized so that alignment checks and adjustments can be performed during a test without moving the probe from its current location or having to attach the light power meter. The indicator is sized to be visible from the first beam steering mirror at the exit of the laser.

Just collected data (at the end of a scan) or any previously collected data set can be displayed by pressing the "Display Data" button. The DisplayData window will be called up and the mean statistics of the measured flow field can be reviewed (see Section A.6.4.5). Pressing the "Pause" button will interrupt data collection and allow for realignment of the fiber optics in the middle of a test for example. Pressing the "Abort/Exit" button during a data sequence will completely stop all program execution and should only be used in emergencies. Pressing the "Abort" button or the red stop button in the LabVIEW tool bar has the same effect and in order to continue, LabVIEW must be exited completely and restarted. The "Abort/Exit" button can be pressed safely before data collection is initiated or at the end of data collection and processing. At these times, the window will close and control will return to LDVinstCTRL.

The button "Start Data Collection" is used to begin the data collection sequence. Before Unsteady-Velocity is called for the first time, a file dialog window prompts the user for the data file name to be used. The filename entered will be used to hold the LabVIEW type data file. The filename, appended with "TIM" is used to save the binary data file. Both data files are saved after each point is taken so that aborting a test part way through will not result in significant data loss. The file types and formats are described below in Section A.6.5.

Progress of the programmed scan can be monitored by checking the "Points Left" indicator. The program also measures how long each data point takes and based on an average for all the collected data points forecasts the time to complete the scan

in minutes. The value is reported in the "Time left" indicator. Additionally, the completion times for previous data points can be reviewed by scrolling through the "Point Times" list.

A.6.4.4 Oscilloscope

The oscilloscope program has many of the same controls as a traditional digital oscilloscope. The oscilloscope program front panel is shown in Figure A.38. Trigger levels and sources can be specified. Data from one of the channels or both channels can be collected and displayed. The input impedance and range can be selected. The length of each data record can also be set using a front panel input. The oscilloscope is started by pressing the "ReStart" button. If parameters are changed, pressing the "ReStart" button will incorporate the new parameters in the collection process. If the trigger level selected is too high and data collection does not start, the "Abort" button can be used to abandon the current data collection process and begin anew using the "ReStart" button. Pressing the "Exit" button will cause the program to return control to LDVinstCTRL.

A.6.4.5 DisplayData

The DisplayData program window allows the review of previously or just collected data. The DisplayData front panel is shown in Figure A.39. The program has access to mean and RMS velocities of both components. The mean sampling rate for the trigger component at each data point. The overall mean and RMS flow rate for a test can be examined. The "Choose variable for graph" and "Choose 2nd variable for graph" selectors allow two different quantities to be plotted at the same time on the chart. The chart includes a legend whose entries reflect the selected quantities for plotting.

Pressing the "LoadData" button will bring up a file dialog window for the selection of the data file. If DisplayData is called at the end of a 2-D scan, the collected data is automatically displayed without explicitly loading the data file.

The selector located under the second graph variable selector changes the spatial

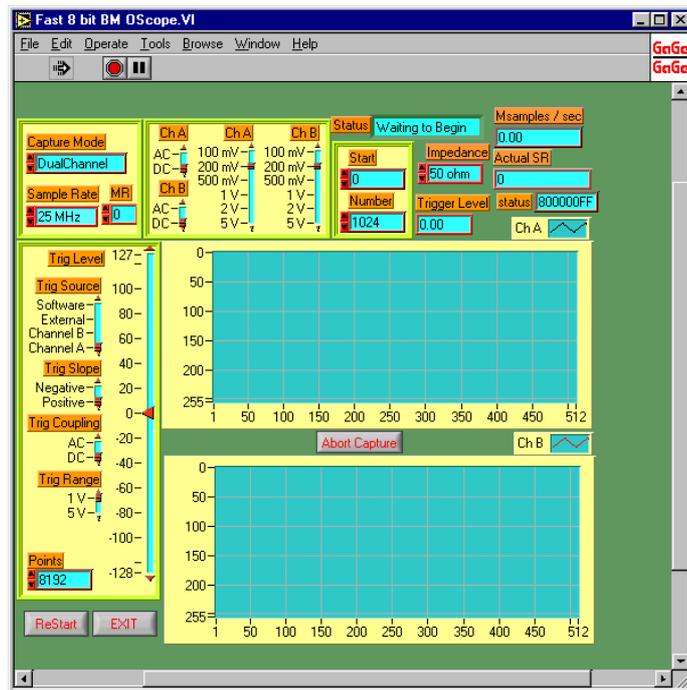


Figure A.38: Oscilloscope front panel

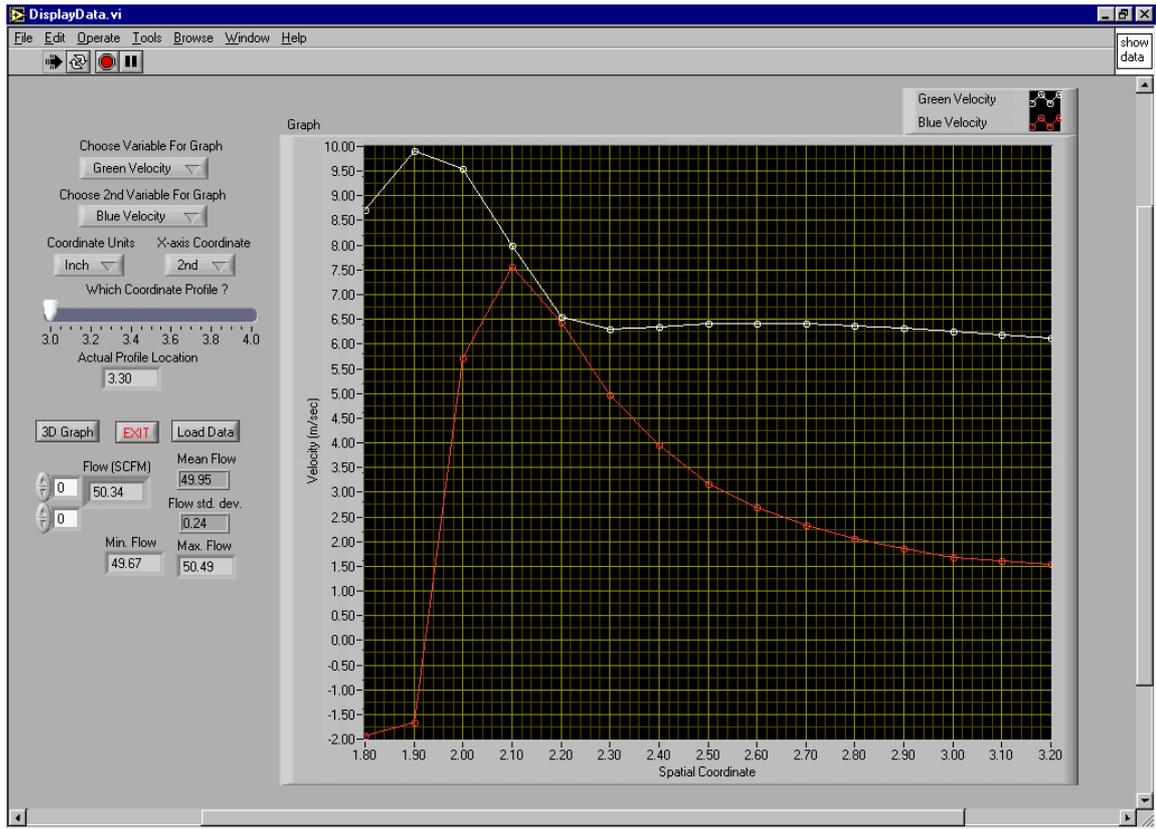


Figure A.39: DisplayData front panel

coordinate units from "inch" to "mm" or vice-versa. The selector to the right of the unit selector is used to determine which of the two axes scanned will be used as the x-axis of the chart. For a scan that was collected with the streamwise direction selected as the first axis and the radial direction as the second axis, setting the axis selector to "2nd" will show radial profiles of velocity at different axial (streamwise) locations. The streamwise location of the radial profile is determined by the slide control below the x-axis selector. To change the streamwise location, drag the slide by pressing and leaving pressed the left mouse button. As the slide is moved, different profiles will be shown on the chart corresponding to that streamwise location. The exact location of the profile is displayed below the slide control.

Pressing the "3D Graph" button will bring up a window with a 3-D graph. The z-axis of the graph will contain the first chart variable selected. The other two axes are the two coordinate directions of the 2-D scan. Pressing the "Exit" button will cause the program to exit and if called from another program return control to that program.

A.6.4.6 PSDavg - Spectrum window

The spectrum window shows the results of the calculation of velocity power spectra, cross spectrum and transfer function. The front panel of the program is shown in Figure A.40. A measure of coherence can also be calculated. Cross spectrum, transfer function and coherence are only calculated if the data selector in Unsteady-Velocity is set to "Both". Additionally, it is only possible to get reasonable data for these functions if the data was collected in coincident mode. The program has inputs for starting and ending frequency as well as frequency resolution and block length. Once these inputs are set, the calculation of the quantities is initiated by pressing the "Calculate" button. The calculation proceeds according to the procedure described in Section 3.2.4 of Chapter 3. The results are displayed in the four charts. The results can also be reviewed by scrolling through the arrays below the charts. Results and velocity inputs can be viewed element by element. Pressing the "Exit" button will cause control to return back to Unsteady-Velocity.

A.6.4.7 Histogram display

The histogram display, Figure A.41, shows the histogram of the data displayed in the top chart of Unsteady-Velocity window if the histogram data selector in Unsteady-Velocity is set to "Frequency". The histogram window can also display histograms of time between data points and signal to noise ratio. The only input available is the number of bins to use in the histogram calculation. The chart does not separate the blue and green components if both components are displayed in Unsteady-Velocity. See Section A.6.4.2 for more information. Pressing the "Stop" button will cause control to return back to Unsteady-Velocity.

A.6.4.8 LabVIEW subroutines

The following is a list of subroutines that are used in the programs described above. Only custom written subroutines are described, i.e. the subroutines not supplied with LabVIEW. The underlined names followed by the file extension ".vi"

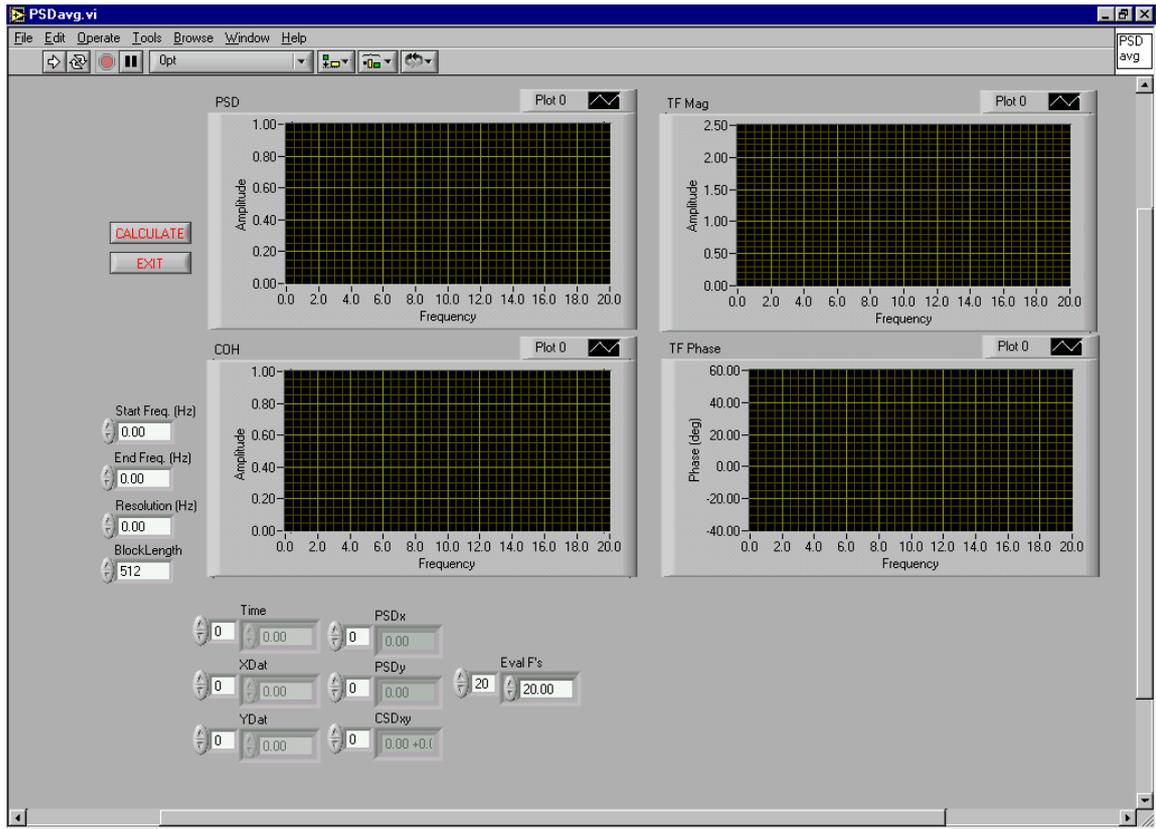


Figure A.40: Spectrum display front panel

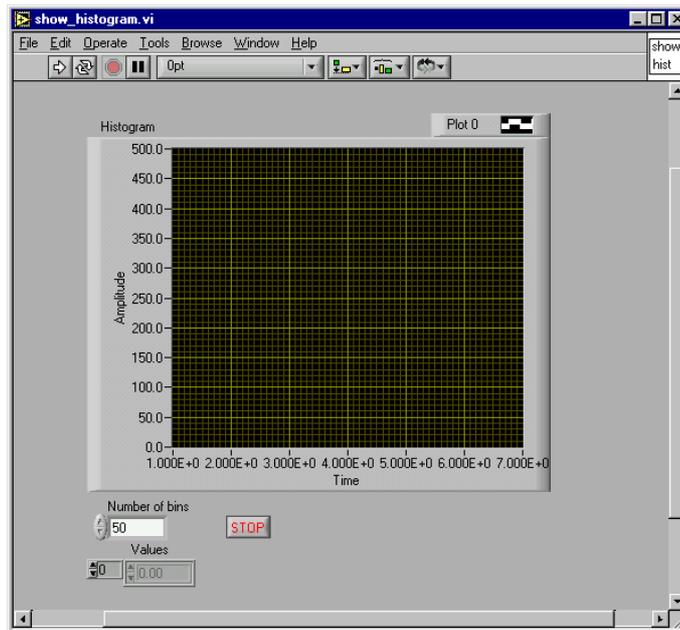


Figure A.41: Histogram display front panel

are the files where these programs can be found. Some of the files listed are not subroutines but are supplementary stand-alone programs that accomplish a specific task not able to be handled by LDVinstCTRL. These programs are indicated by using bold lettering.

- **BlockCfft** calculates an average Fourier transform by using Cfft repeatedly, each time using a certain length of data points. Each set can be chosen to overlap with the previous set. All the sets are averaged at the end to give one smoothed version of the FFT.
- **Cfft** calculates the Fourier transform of the input signals at the desired frequency. using a C subroutine (Cfft).
- **DisplayData3DSurface** is a subroutine to DisplayData and is used to show a 3D plot of the 2D scan data collected.
- **DivideArrays** is used to separate the results of each of the velocity components

from the single long arrays obtained from `lview_cs_board`.

- FilterandProcess enforces the signal to noise ratio minimum on each data point and then calls `SigCalc` to eliminate all points outside the "dev-stop" limits.
- Integerize is used in `OrganizeGridData` to determine whether or not two coordinates are identical. Simple comparison may give erroneous results due to numerical roundoff. This routine represents the coordinate by an integer that is 10000 times the original number. This means that unless the round off error is in the fourth decimal point two coordinates that are equal will be correctly identified.
- LDVstats is used to calculate the time mean and rms values of a velocity time record.
- lview_cs_board is the front panel for the C subroutine `gage_com_board` which controls the high speed data acquisition process. The same routine is used for all tasks, including configuration, arming, collection and interpretation. Different options are passed to the subroutine to distinguish the tasks.
- MicDataOnly collects a specified amount of binary A/D data to file from the specified channels, at the specified rate. The routine was used to collect raw microphone data. The routine works with the NI 6034E board.
- OrganizeGridData is the routine that uses the raw LabVIEW data file as input and organizes it so that results from a 2D scan are arranged in order in a 2D array, rather than one sequential record.
- PMT FLOW VI is used to collect the voltages from the Data Translation A/D card, representing the PMT monitor voltage, the fiber monitor voltage and the flow meter voltage. The routine also converts the quantities to the proper scale if known. Both PMT voltage and flow rate are converted to actual PMT volts and SCFM respectively.

- SigCalc is the front panel for the C subroutines in Filter_sig that calculates the mean and rms of a data set and eliminates all values outside the dev-stop limits.
- StepTester is used to cycle the stepper motor over many iterations to ensure that no steps are being missed by the motor. Missed steps would cause a slow drift in the start of the cycle position.
- std_dev_elim is the LabVIEW code version of SigCalc. It was replaced to speed up processing of data.
- StepDir executes all stepper motor movements. Inputs are the motor to move, the direction and the number of steps. The program coordinates the digital outputs of the Data Translation and National Instruments boards so that accurate motor movement is assured. (See Appendix C)
- TotalTime calculates the total amount of time elapsed while data was being taken. The total time is used to determine the mean sampling rate for a given set of data blocks.
- Trig_Contrl_Digital is used to control the trigger type and to enable the data collection. The routine is called once both the burst time operation and the actual burst collection operation have been armed so that the first trigger read by each card is the same.
- WriteMatlabDataFile is the front panel for the C subroutine WriteData that writes the binary "TIM" file as described in Section A.6.5.
- WriteMicsDataFile is the front panel for the C subroutine WriteMicsData that writes the binary microphone output data to file.

A.6.4.9 C codes

The following is a list of C files and the functions these files contain. Each listed function also contains a basic description of its purpose. The functions are listed in

the order in which they occur in the file. Some of the functions are not called in the process of analyzing the collected Doppler bursts. These functions are remnants of other explored methods of analysis.

- Cfft calculates the DFT of the given input time records, at the given frequencies. The routine removes the mean of the data before calculating the DFT.
- Filter_Sig
 - *SigCalc* get mean and rms from MeanCalc and GetSig and then conditionally eliminates all data beyond a certain number of standard deviations from the mean (dev-stop).
 - *MeanCalc* calculates the time integration based mean of the data time record.
 - *GetSig* calculates the time integration based rms of the data time record.
- WriteData writes the binary "TIM" data file for processing by other programs such as MATLAB.
- WriteMicsData writes binary 16-bit data to file. The use here was mostly to write out microphone data but the routine can be used for any binary A/D data writing.
- gagea2d_indiv_func
- board_config
 - *gage_com_board* main function determining the desired task and calling the appropriate function.
 - *distrib_data* organizes the collected data so that the two arrays returned to the calling LabVIEW routine represent the raw voltages of the two channels. If only one channel was collected, the second array is filled with the number 1.2.

- *interp_data* calls the Doppler frequency identification functions. For latest iteration, only *get_fest* is called because the auto-regressive estimate for the PSD is used to determine the Doppler frequency. For the FFT implementation, the FFT calculation functions are also declared for use in *interp_data*.

- Estimators

- *maxloc* returns the index of the input array's maximum value.
- *meancalc* returns the mean of the input array.
- *stdcalc* returns the standard deviation of the input array given the array's mean value.
- *parainter* based on the index of the maximum *estloc* in the array *psd*, the function returns a parabolic estimate for the actual peak location. The interpolation is performed on the logarithm of the *psd* values.
- *resample* resamples the array by reordering the elements from 1 2 3 4 to 1 3 2 4. The sample rate has thereby effectively been halved and the data record length effectively doubled.
- *fftest* returns an estimate of the fractional index at which the frequency peak occurred. The number has to be scaled by the sampling rate in order to obtain the actual frequency.
- *remmean* removes the mean from the input data array.
- *autocorr* frequency estimator based on a one bit autocorrelation. The estimator was eliminated because processing time was excessive. Could possibly compete with autoregressive speed.
- *get_fest* get Doppler frequency estimate using the already calculated FFT based power spectrum or get the frequency using an autoregressive estimate. The autoregressive analysis is the currently recommended method.

- PSDfunction

- *get_window* calculates a Hanning window of the specified length for use in FFT analysis.
- *four_1* calculates the Fourier transform or inverse Fourier transform. The routine is taken from Press et al. (1992).
- *twofft* calculates the Fourier transform of two real input vectors simultaneously. The routine is the most computationally efficient way to obtain the FFT of a series of data sets. The routine is taken from Press et al. (1992). The only change is that two arrays are filled with the power spectra of the two real input signals.
- *realft* calculates the Fourier transform of a single real input vector in the most efficient manner possible. The routine is taken from Press et al. (1992) with the exception that it has been rewritten to return the power spectrum of the input vector.
- *truefft* calculates the Fourier transform of a single real input vector. The routine is unmodified from Press et al. (1992).
- *pkloc* finds the peak in the input array and is designed to keep track of the sum under the peak found. The routine currently simply finds the maximum and then performs an interpolation similar to *parainter* to find the fractional index of the estimated peak location. The output still has to be scaled by the sampling frequency to obtain an actual frequency. The routine also calculates the signal to noise ratio based on the ratio of the peak value of the power spectrum and the mean value of the power spectrum.
- *arpsd* calculates the power spectrum at the given number of evenly spaced points, using the already calculated autoregressive coefficients. Code follows Marple (1987).
- *modcovar* calculates the coefficients of an autoregressive representation of the spectrum. Code follows Marple (1987).

A.6.5 Data file formats

There are several ways to save data from the LDV. For single data points, blue and green velocity data can be exported to text files as described in Section A.6.4. The files in this case consist of the velocity and time data for the selected velocity component in two columns. For data points collected using the MeasGrid subroutine, two data files are saved. The first data file has LabVIEW format and contains all of the results including flow rates, mean sampling rates, mean and RMS velocities etc., except the time resolved velocity data points. The format is designed for use with the DisplayData subroutine and stand alone program. If a data set was aborted, the file format of the LabVIEW file is not compatible with DisplayData. If the binary "Tim" data file is not available, the data file can be read using custom code similar to that in OrganizeData, discussed in Section A.6.4.8. The DisplayData program is a subroutine of MeasGrid and LDVinstCTRL but can also be used on its own, loading the data explicitly as discussed in Section A.6.4.

The LabVIEW data file is not designed to be exported to any other software platform. The other data file generated has the same name as the LabVIEW data file, except that "TIM" has been appended to the file name. The "TIM" file is a binary data file that contains the same information as the LabVIEW data file but also contains all of the validated velocity data points and their time tags. Table A.2 illustrates how the data from the "TIM" file should be read in. The table describes the data written for one point. Successive points in a spatial scan are appended in the file.

Table A.2: Structure of the "TIM" binary data file

Description	Format
1st coordinate in 2-D scan	Double
2nd coordinate in 2-D scan	Double
average flow rate for data point	Single
average velocity measured for green component	Double
average velocity measured in blue component	Double
RMS velocity measured in green component	Double
RMS velocity measured in blue direction	Double
average signal to noise ratio for green component	Double
average signal to noise ratio for blue component	Double
length of date string to be read (len)	32-bit Int
date string representing time and date the data was taken	(len)Char
length of green component time data vector (lentg)	32-bit Int
green component time vector	(lentg) Double
green component velocities	(lentg) Double
length of blue component time data vector (lentb)	32-bit Int
blue component time vector	(lentb) Double
blue component velocities	(lentb) Double
number of points collected	32-bit Int
green component signal to noise ratio threshold used	Double
blue component signal to noise ratio threshold used	Double
burst collection frequency in MHz	32-bit Int
burst sample length	32-bit Int
trigger type used (0=CI,1=G,2=B)	32-bit Int

A.7 Day to day operating instructions

The following should serve as a working copy of the operating instruction used in the startup and operation of the LDV. The instructions include the startup of the laser.

A.7.1 Laser startup and instrument startup

1. Remove any dust covers from LDV optics
2. Start the air purge system
3. Start the cooling water, setting the pressure to between 30 and 50 psi.
4. Turn on the power to the laser at the fuse panel or line power switch. (Do not press the "ON" switch though !!)
5. Place beam guards so that both the green beam and blue beam are blocked from reaching the fiber coupler.
6. Turn the key on the laser to the "ON" position and press the "ON" button.
7. Wait for the laser to lase and make sure beam guards are properly placed.
8. Record the date and time the laser was started and its operating condition in Amps (Read from front panel gauge).
9. Wait for the laser to warm up. This time is determined by checking the power on the laser. For the typical operating condition of 33 A, the power should reach 1.0 W before any alignment procedures are started. The time for warmup under these conditions is generally around 2 hrs.
10. Start the Bragg cell drivers and the RF generator to allow these instruments to warm up as well.

11. Start the program LDVinstCTRL, and turn on instrument box and stepper motor power supplies to move the probe to a location where convenient access for alignment is possible.

A.7.2 Fiber optic coupling

1. Place the blue beam guard behind the second beam target. Use the mirror closest to the laser head to move the blue beam onto the center of the target.
2. Observe the beam on the first beam target and make sure the beam is close to centered on it. If it is not, use the first mirror controls to center it and then the third mirror's controls to center the beam on the second beam target.
3. Set up the probe for fiber alignment using the left cover and the attached power meter mounting arm. Insert the power meter probe with optical post into the post holder on the power meter mounting arm. Leave the power probe below the focusing lens.
4. Move the blue beam guard such that only the non-frequency shifted beam is allowed to hit the fiber coupler.
5. Observe the beam exiting the probe and use the first mirror's controls to visually optimize the light coupling.
6. Move the power meter probe to measure the intensity of the blue beam exiting the focusing lens. Locate the power meter probe by maximizing the output on the display of the power meter.
7. Use the first mirror controls to maximize the output measured by the power meter
8. Use the first and third mirror controls to check if walking the beam improves coupling. The target value of intensity for the standard operating condition of 33 A is 60 mW for the blue beams.

9. After optimizing the output at the laser head, move to the fiber coupler controls and use these to further increase the output from the fiber, if possible.
10. Move the beam guard such that the non-frequency shifted beam is blocked from reaching the fiber coupler.
11. Move the power meter probe to measure the frequency shifted beam power.
12. Use the mirror controls for the frequency shifted beam and the translation stage to optimize the power output.
13. Slightly perturb the alignment of the Bragg cell to see if a gain in intensity can be gained through these adjustments.
14. If a gain was obtained in the previous step, repeat the alignment process.
15. At this point, both blue beams should contain close to the same power. If the frequency shifted beam has more than 5% lower power than the non-frequency shifted beam, walk the frequency shifted beam mirrors to translate the beam up or down, while ensuring the Bragg cell alignment remains optimized.
16. Place the blue beam guard to prevent all blue light from hitting the fiber coupler.
17. Place the green beam guard to let the non-frequency shifted beam hit the fiber coupler, while still blocking the frequency shifted beam.
18. Align the power meter probe to measure the power of the green beam coming from the focusing lens.
19. Use the fiber coupler alignment controls to optimize the fiber power for the non-frequency shifted beam.
20. Follow the same procedure as for the blue frequency shifted beam to align the green frequency shifted beam.
21. Remove probe side cover.

A.7.3 Probe alignment

1. Move the probe to a location that makes the measurement volume accessible for the microscope objective.
2. With the beam guard still blocking the entire blue laser beam, place the microscope objective at the intersection of the green beams.
3. At the intersection, the images of the two green beams should overlap completely. If they do not, adjust the alignment of the non-frequency shifted beam inside the probe by adjusting the mirror that redirects the beam.
4. Leaving microscope objective in place, block the entire green beam using the beam guard. Remove the beam guard blocking the blue laser beam.
5. Observe the blue images of the blue laser beams. Since the objective has not been moved, the blue beam images should also overlap completely. Use the redirect mirror of the non-frequency shifted beam to get the images to overlap.
6. Remove the beam guard from the green laser beam and observe all four beam images. If all of the images overlap, probe alignment is complete.
7. Use the blue collimator cover mounting screws to adjust the position of the blue beam images in case all four beams do not overlap. After adjusting the collimator cover, recheck that the blue beam images overlap.

A.7.4 Measurement setup

1. Start LDVinstCTRL if it is not already running.
2. Switch on the +/- 12V power supply to turn on the fiber alignment monitor and the PMT's.
3. Observe the value of the fiber alignment monitor, so that a reference for good alignment is known.

4. Disconnect the mixing frequency BNC connector from the RF driver and connect instead the BNC connected to the frequency counter.
5. Wait for the reading on the frequency counter to stabilize and then enter the value in the mixing frequency entry on the front panel of LDVinstCTRL.
6. Move the probe to one of the measurement locations of interest.
7. Set the number of blocks to collect to 1 and select "Single Data".
8. Run "Single Data" as often as necessary to establish an appropriate trigger level.

A.7.5 Measurements

Further details on the measurement procedure used in the experiments can be found in Chapter 3. Throughout the measurements a SNR cut-off of 1.50 and a standard deviation cut-off of 3.50 was used and these settings should not have to be changed. In general, the lower the trigger level, the higher the data rate but also the lower the total number of good points per record.

A.8 Improvements in the LDV design

The following items describe improvements to the LDV system and their associated cost, effort and reward.

- Doppler trigger circuit overhaul: The factor most responsible for limiting LDV performance are the trigger circuits. The concepts contained in these circuits work well but leave a lot to be desired in terms of speed. The result is that a velocity ceiling exists at around 20 m/sec. The high speed current feedback op-amp should be used in the first two stages of both circuits. These stages should be designed with lower gain so as to not limit the bandwidth of the op-amp excessively. The lost signal strength should be made up by installing amplifiers

immediately downstream of the transimpedance amplifier. No redesign should be necessary and the time associated with this change is equal to the time required to replace the op-amps and some of the gain-determining resistors. Cost is very low since the op-amps can be obtained by sample order. The minimum useful signal level at the input to the Schmidt trigger circuit is the voltage drop of the transistors which is 0.1 V. Design should be performed for a Schmidt trigger input signal level of 1 V (i.e. from current conditions, input can fall by 50%). The reward for this effort would be a tripling of the available velocity range.

- The transimpedance amplifiers installed inside the PMT's work well but have relatively low gain. Performance improvements can be achieved by replacing these transimpedance amplifiers with commercially available amplifiers. Cost for this is relatively high (several hundred dollars) but the increase in performance in future LDV applications may make the investment worthwhile.
- Additional amplifiers could be added prior to the mixer to improve mixer performance and increase the signal level into the Doppler trigger circuit. Care should be taken not to exceed the input levels of the mixer however. An RF amplifier from Minicircuits costs approximately 100 dollars.
- A second RF generator is recommended for greater versatility in the relative measurement ranges of the two velocity components. Currently both components are mixed with the same frequency which is not always practical. An RF generator costs approximately 150 dollars (MCM Electronics).
- A big handicap for the LDV system is that the maximum number of doppler bursts collected in succession is limited by the on-board memory of the GaGe board. Two alternative exist here. The first is to have the board serviced and add memory to it. The second is to replace the board all together with a new PCI bus board. On the PCI bus, the data transfer to memory is rapid enough to keep pace with most Doppler collection processes so that very long continuous

Table A.3: Specialized vendors and products: Electronics

Minicircuits	Ph: 718-934-4500	Web: Minicircuits.com
	RF amplifiers, RF mixers, RF filters	
Jameco	Ph: 1-800-831-4242	Web: Jameco.com
	IC chips, RG174 connectors, rack mount boxes	
Marlin P. Jones	Ph: 1-800-652-6733	Web: mpja.com
	power supplies, circuit boards, BNC connectors	
MCM Electronics	Ph: 1-800-543-4330	Web: mcm.com
	RF generators	
Analog Devices	Ph: 1-800-262-5643	Web: analog.com
	fast op-amps (get free samples)	
National Semiconductor	Ph: 1-800-272-9959	Web: national.com
	fast op-amps (get free samples)	
Newark Electronics	Ph: 1-800-463-9275	Web: newark.com
	high voltage connectors	

data sets could theoretically be collected. Any dynamic measurements require such data sets and circumventing the ISA bus will save a lot of testing time (approximately 30% reduction). Cost here is high probably exceeding 1000 dollars even for the memory expansion.

A.9 List of specialized vendors

The tables in this section list vendors that have been useful in obtaining components for the LDV system. As always, it pays to check several sources for lowest cost. At least one component of the LDV system was purchased from these vendors. The tables are divided by category: electronics (A.3), optics (A.4), optoelectronics (A.5), data acquisition (A.6), hardware (A.7).

Table A.4: Specialized vendors and products: Optics

Optosigma	Ph: 949-851-5881	Web: optosigma.com
	translation tables, tilt platforms, polarization beam splitters	
Newport	Ph: 1-800-222-6440	Web: newport.com
	lenses, mirrors	
JML Optical	Ph: 585-342-9482	Web: jmloptical.com
	lenses	
Thorlabs	Ph: 973-579-7227	Web: thorlabs.com
	rotary stages, mirror mounts, half wave plates	
Coherent (Ealing)	Ph: 1-800-295-3220	Web: ealingcatalog.com
	optical posts, post holders, prism mounts, beam splitters, prisms	
Edmund Optics	Ph: 1-800-363-1992	Web: edmundoptics.com
	microscope objectives, lenses, optical windows	
Omega Optical	Ph: 1-866-488-1064	Web: omegafilters.com
	optical filters, dichroic mirrors	
Oz-Optics	Ph: 613-831-0981	Web: ozoptics.com
	fiber optics: cables, couplers, collimators	
Evergreen Laser	Ph: 860-349-1797	Web: evergreenlaser.com
	laser maintenance	

Table A.5: Specialized vendors and products: Optoelectronics

Hamamatsu	Ph: 1-800-524-0504	Web: hamamatsu.com
	photo-multiplier tubes (PMTs)	
IntraAction	Ph: 708-547-6644	Web: IntraAction.com
	Bragg cell driver and modulators	

Table A.6: Specialized vendors and products: Data acquisition

National Instruments	Ph: 1-800-258-7019	Web: ni.com
	multi-function data acquisition	
Gage-Applied	Ph: 1-800-567-4243	Web: gage-applied.com
	high speed data acquisition cards	
Cyber Research	Ph: 1-800-341-2525	Web: cyberresearch.com
	terminal boards	

Table A.7: Specialized vendors and products: Hardware

C and H supply	Ph: 301-663-1812	Web: CandHsupplyco.com
	stepper motors, power supplies	
Servo systems	Ph: 1-800-922-1103	Web: servosystems.com
	stepper motor drivers	
TechnoIsel	Ph: 516-328-3970	Web: Techno-Isel.com
	stage components	
Pilot fasteners	Ph: 540-382-2365	Web: none
	all kinds of screws, nuts, bolts, washers	