Chapter 2 : Hardware

2.1 DGV Hardware

Figure 1.1 also shows some of the basic hardware used in Doppler Global Velocimeters. A laser is used to illuminate the area in which data are to be taken. The laser is fired into a lens or set of lenses to convert the laser beam into a sheet of laser light. Seed particles must be introduced into the flow. These particles must be large and abundant enough to make the portion of the laser sheet where data is to be taken visible and yet small and sparse enough not to influence the flow. The camera(s) used to acquire DGV data is housed in a camera module. A pair of images of the particles passing through the laser sheet are captured by a digital camera or a pair of digital cameras. As mentioned previously, one of these images is used as a reference and the other image passes through an iodine cell which acts as an optical frequency filter, thus capturing the magnitude of the Doppler shift of the laser light bouncing off of the moving particles, in the $(\hat{a} - \hat{l})$ direction. This chapter discusses in greater detail how this equipment is used in the Virginia Tech DGV system as well as discussing the other hardware used in this research.

Some of the new hardware used in this research included a new digital camera purchased to replace one of the original digital cameras in the system, a new calibration wheel system that was designed and built in house, new high damage tolerant laser optics, and a new smoke machine that acted as a particle seeder. While the iodine cells used in this research were not new they were modified during this research by having the cold fingers on the cells removed. The laser optics setup

was also changed during this research compared to setup used in previous tests performed with the VT DGV system.

2.2 Nd:YAG Laser and Optics

2.2.1 Laser

The laser used for Doppler Global Velocimetry can either be a constant wave laser or a pulsed laser, which emits a laser beam in the green portion of the visible spectrum. The use of constant wave lasers such as Argon-Ion lasers has been limited to time averaged data acquisition since the mechanical shutter on digital cameras open and close at a finite rate of speed usually on the order of milliseconds at best. The finite shutter speed causes the data acquired to be time averaged since digital cameras integrate the light collected while the camera shutter is open. In other words, as long as the data collection area is illuminated while the camera shutters are open the cameras collect and average data. Pulsed lasers such as the Nd:YAG laser equipped with a harmonic generator are capable of near instantaneous data acquisition since the time over which a single pulse of laser light is emitted is very brief.[34] A computer controlled shutter used in conjunction with the Nd:YAG laser allows a single high energy pulse of laser light to illuminate the data collection area during data acquisition (i.e. while the camera shutters are open).[35]

A Spectra-Physics GCR-170-10 Nd:YAG pulsed laser was used in this research to illuminate the data area. This laser emitted a pulse of laser light every 100 ms. The laser contained a harmonic generator which allowed the laser to produce two beams of laser light. One beam was an infrared beam (1064 nm wavelength) and the other beam was a green beam (532 nm wavelength). Only the green beam is used in the Virginia Tech DGV system.

The Nd:YAG laser had two operating modes. The long pulse mode was a low power mode, which was useful when aligning optics. The Q-Switch mode was a high power mode. The Q-switch mode was used during acquisition of DGV data. This mode used a device called a Q-switch to cause a large population of excited neodymium ions to build up in the YAG rod before each pulse was fired. The Q-switch also allowed the build up of ions to be quickly released causing a short burst of high intensity laser light to be emitted. When the laser operated in this mode the pulses of light emitted by the laser lasted approximately 9 ns and contained about 380 mj of energy per pulse (roughly 42.2 MW of power per pulse).[36]

The Nd:YAG laser was equipped with a seed laser. The seed laser helped the Nd:YAG laser to emit pulses of laser light over a very narrow band of optical frequencies. The seed laser was a monolithic single frequency Nd:YVO4 laser. The wavelength of the laser beam output by this laser was 1064 nm, which is the same as the output of the Nd:YAG host laser before being frequency doubled by the harmonic generator. The temperature of the seed laser and the laser diode used to pump this laser were controlled using thermoelectric coolers. The output wavelength of the seed laser could be adjusted by changing the temperature of the Nd:YVO4 seed laser. The control panel for the seed laser contained switches to change the operating configuration of the seed laser as well as outputs to monitor when the laser reset, the Q-switch build up time, the Piezoelectric voltage, and an input to change the frequency offset of the seed laser. The three outputs were used to monitor the performance of the laser. The laser reset output would send an analog signal when the laser reset. A laser reset occurred when the laser performance was not within a specified tolerance or when the Piezoelectric voltage approached the maximum allowable value. The Q-switch build up time was a voltage proportional to the time required by the Q-switch in the Nd:YAG laser to build up sufficient power to fire a pulse. The laser performance generally improved as the Q-switch build up time decreased   The Piezoelectric voltage was observed using a chart recorder and it provided an additional source of information regarding the performance of the laser. This voltage would oscillate near a specific value. If the voltage about which these oscillations occurred remained fairly constant or gradually changed in a constant direction the laser was performing well. If large changes occurred in this voltage or if the general direction the voltages were proceeding in changed then this indicated that the laser performance was being degraded in some way. Large changes in the Piezoelectric voltage usually indicated that the laser had reset. The frequency offset input was used to adjust the optical frequency of the laser.[37] For more information regarding the physical principles through which Nd:YAG lasers operate and other uses for these types of lasers see reference 38.

2.2.2 Laser Optics

A JML Optical model SES16500/900 shutter was used to allow only one pulse into the data area while the digital cameras were exposed. This shutter had a 25mm aperture. Trigger delays and exposure times down to 1 millisecond could be set using the driver/timer unit purchased with the shutter. Digital signals from the control computer and a synchronizing trigger from the laser were used to open the shutter when the laser emitted a pulse.[39]

Due to the amount of energy contained in each pulse of laser light emitted by the Nd:YAG laser in Q-switch mode special high damage tolerant optics were needed to steer the laser pulses to

the location where DGV data was taken. The main laser steering mirrors and lenses all had damage tolerances substantially higher than the required 380 mJ/cm^2 for the Nd:YAG laser used in this research. The high damage tolerant optics included 8 Melles Griot 1" high damage tolerant mirrors (part # 16MFB153), a CVI Laser Corporation spherical concave lens (part # BICC-25.0-26.1-C), a CV spherical convex lens (part # BICX-25.4-34.9-C) and a CV cylindrical concave lens (part # BICX-25.4-34.9-C). The optical system used to capture a portion of the laser beam to track pulse to pulse changes in the optical frequency has been made more efficient compared to the system used in the previous version of the Virginia Tech DGV system. The previous version of the Virginia Tech DGV system used neutral density filters to split off a small portion of the laser beam. This portion of the beam passed through several more neutral density filters before being projected onto a laser reference tab within the field of view of one of the three DGV camera modules.[40] Most of the split off portion of the beam was essentially wasted. This new set of optics captured the portion of the laser light that passed through one of the main laser steering mirrors. Tests were conducted to verify that enough laser light bled through the steering mirror to be used for monitoring the variations in laser optical frequency. This was in fact found to be the case. The bleed through light was directed to a piece of opaque white Plexiglas which acted as the laser reference tab. This laser reference tab was placed so that the portion of the tab where the bleed through light was projected was in the field of view of one of the camera modules. When this camera module acquired an image of the flow field it also captured an image of the bleed through light projected on to this target. Since the target was motionless the portion of the laser beam projected on the target could be used to track the variations in optical frequency of each laser pulse. There should, in fact, be enough bleed through light that the light could be passed through an optical arrangement that would expand the beam and allow it to be used to track spatial variations within each pulse. Such an arrangement would require a fourth camera module to be added to the DGV system. This fourth camera module would be dedicated to tracking spatial and temporal changes in the laser optical frequency. Reference 41 has more information on how to incorporate this extra camera module into the DGV system.

During the tests performed in the Virginia Tech Stability Wind Tunnel, the Nd:YAG laser and laser shutter were set up on an optical table directly below the test section. The laser pulses were fired into the control room through a hole in the control room floor. Figure 2.1 shows the laser optics setup below the test section. In the control room, the optics used to fire the laser into the test section were mounted on an optical table. An assembly resembling a periscope was used to turn the laser beam so it ran horizontally above the optical table. This "periscope" was also where the bleed through light used to monitor pulse to pulse variations in the optical frequency of the laser was

captured. Figure 2.2 is a photograph of the periscope assembly. There were two distinct optical setups used in the control room. The first optical setup produced a cone of laser light used to illuminate the data plane with laser light. This setup was used during acquisition of iodine cell calibrations and velocity data from the calibration wheel. Figure 2.3 shows the laser optics setup used during iodine cell calibrations and acquisition of velocity data from the calibration wheel. The other optical setup used in the control room produced a sheet of laser light. This sheet of light was used in acquiring velocity data in the wake of the 6:1 prolate spheroid model. Figure 2.4 shows the laser optics setup used during acquisition of velocity data in the wake of the 6:1 prolate spheroid model. Figure 2.5 is a photograph of the two sets of laser optics setup in the control room of the Virginia Tech Stability Wind Tunnel.
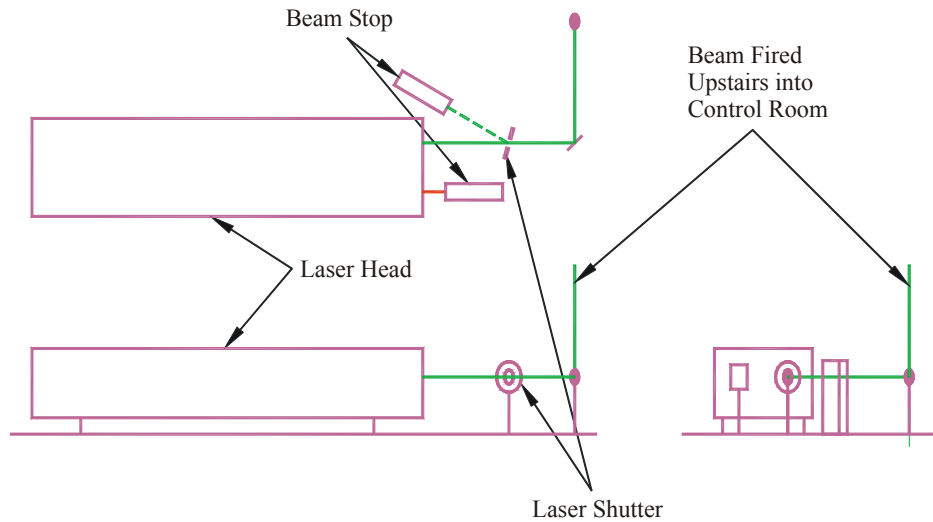

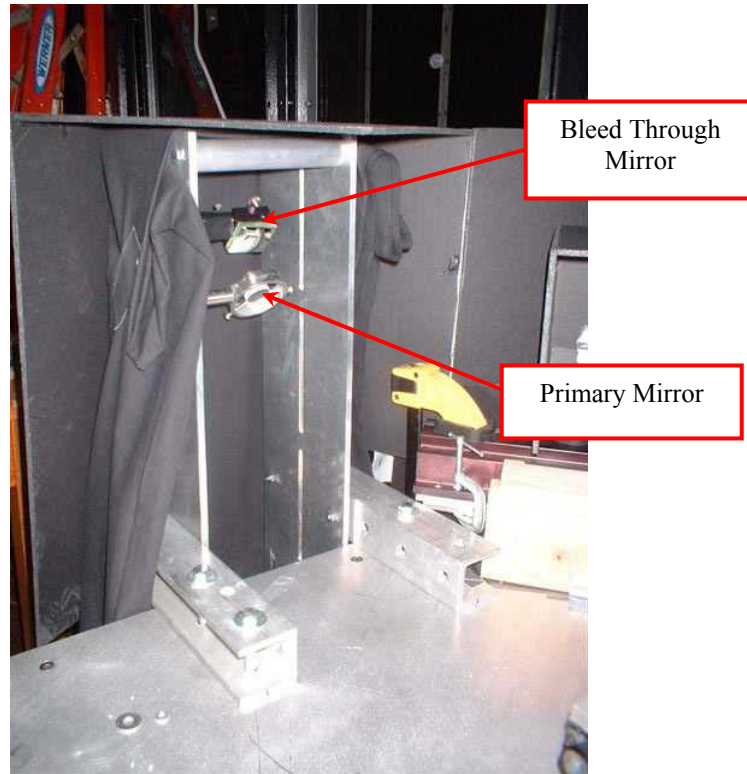*Figure 2.1: Laser optics setup below test section.*

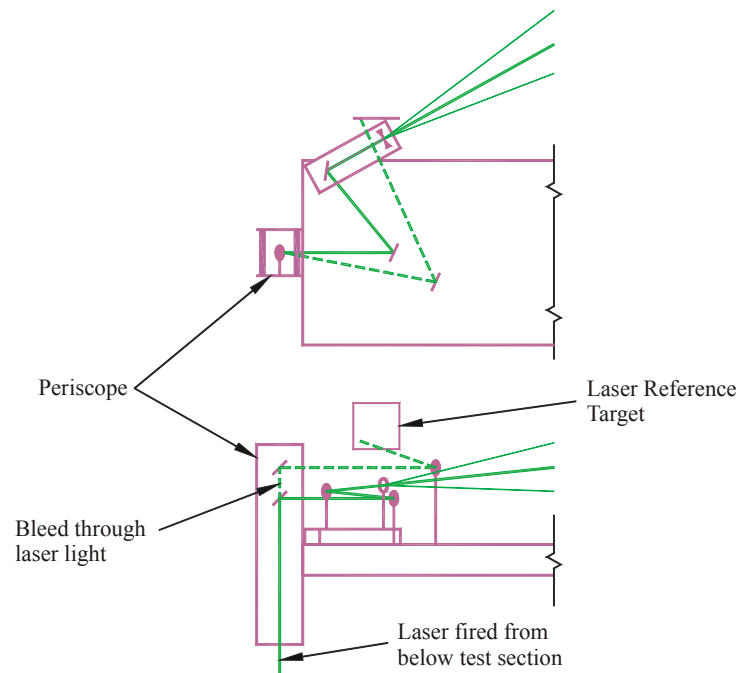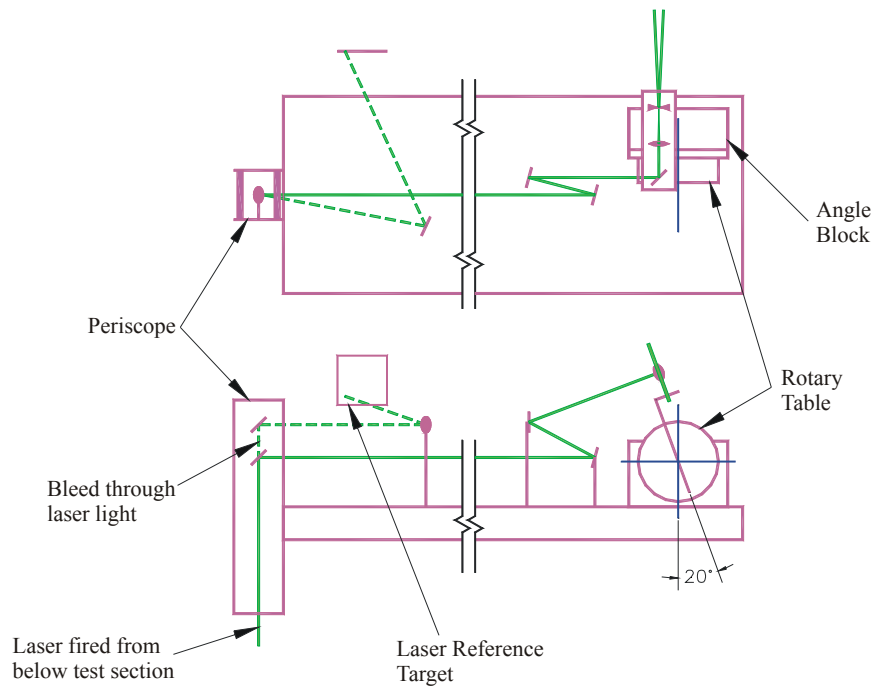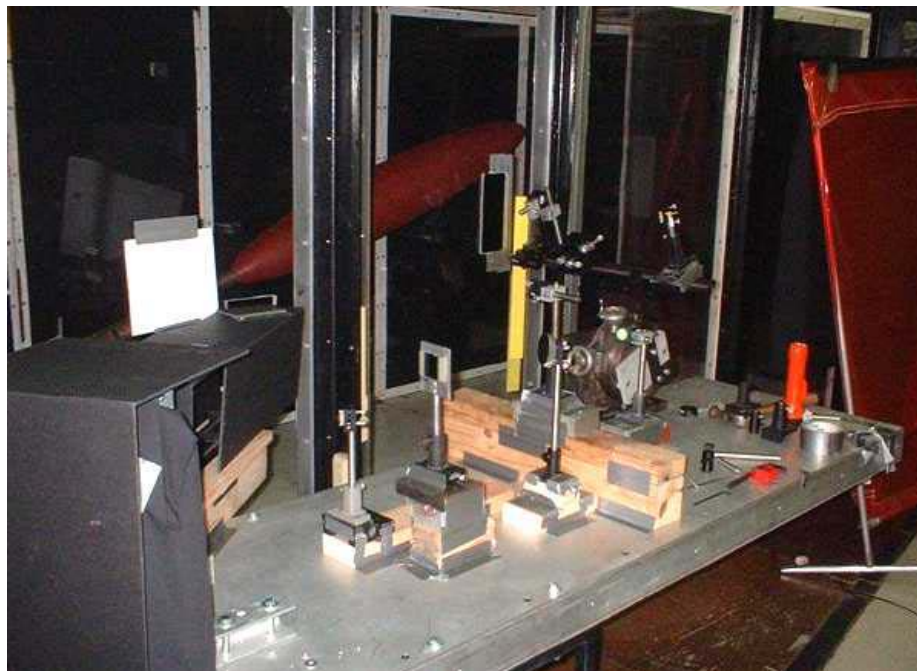*Figure 2.2: Photograph of periscope assembly.*

Figure 2.3: Laser optics setup for iodine cell calibrations and acquisition of velocity data from the calibration wheel.

Figure 2.4: Laser optics setup for acquisition of velocity data in the wake of the 6:1 prolate spheroid model.

Figure 2.5: Photograph of laser optics setup in the control room of the Virginia Tech Stability Wind Tunnel.

2.3 Flow Seeding

Smoke machines and theatrical fog machines are the most common devices used to inject seed particles into large low speed (Mach number 0 – 0.3) wind tunnels for Doppler Global Velocimetry data acquisition.[42, 43, 44, 45, 46] Some important features for a smoke machine used in collecting DGV data are high volumetric flow rate, small particle sizes and the capability to produce smoke constantly. Generally it is most desirable to keep the mean particle size of the particle seeder between 0.5 to 5 μm.[47] While high volumetric flow rate is important, Meyers *et al* caution that while more seed particles will increase signal strength they also increase secondary scatter which will add uncertainty to the velocity measurement.[48] So the amount of seed/smoke used is a trade off between sufficient signal strength and secondary scatter.

A Vicount 5000 smoke machine manufactured by Corona Integrated Technologies Inc. was used to inject seed particles into the wind tunnel. This smoke machine was recommended by James Meyers of the NASA Langley Research Center.[49] The machine heated mineral oil to produce smoke and used compressed nitrogen at a pressure of 0.482600 MPa (70 psi) as a propellant.[50] The machine and rig to inject smoke into the flow were placed in the settling chamber of the Virginia Tech Stability Wind Tunnel. The nitrogen cylinder was placed in the control room of the tunnel and a hose was fed into the tunnel and to the machine. Figure 2.6 shows the machine and injection rig. The smoke volume could be adjusted using a knob inside the smoke machine or by adjusting the propellant gas pressure.[51]
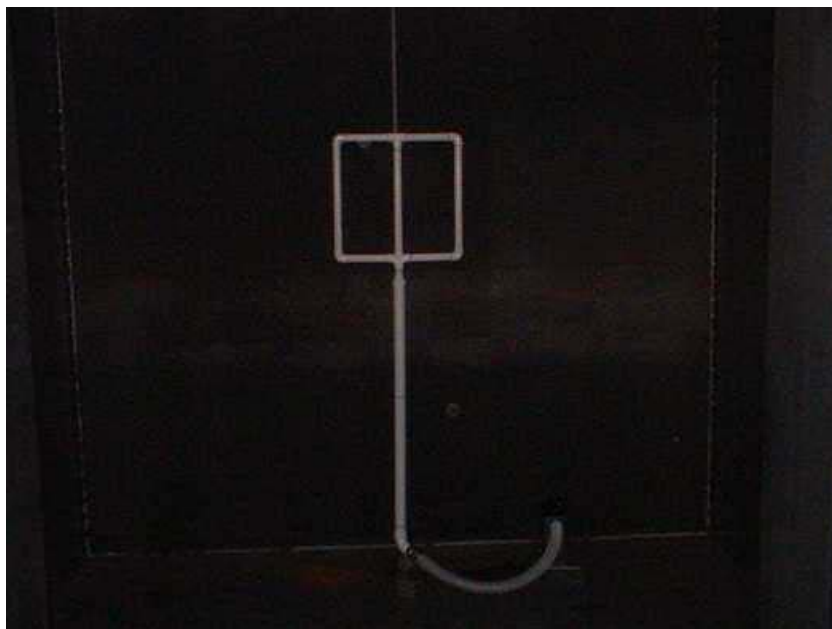

Figure 2.6: Smoke machine and injection rig

The rig used to inject smoke into the wind tunnel was constructed of PVC pipe. A 76.2 mm (3 inch) diameter hose connected the injection rig to the smoke machine. The injection rig consisted of a 76.2 mm (3 inch) diameter PVC pipe which was connected to a box shaped head made of 50.8 mm (2 inch) diameter PVC pipe. The head was 90.2 cm (35 ½ inches) wide from centerline to centerline and 88.9 cm (35 inches) high from centerline to centerline. Holes spaced 38.1 mm (1.5 inches) apart were drilled into the 50.8 mm (2 inch) diameter PVC pipe to provide outlets to inject smoke into the wind tunnel. The injection rig was attached to a 38.1 mm (1.5 inch) diameter galvanized pipe which was placed vertically along the centerline of the settling chamber of the wind tunnel. The injection rig was placed so that the stream tube of smoke ran roughly through the center axis of the test section.

2.4 Camera Modules

A camera module was used to hold each of the digital cameras and the optics needed to split the image viewed by each of the cameras into a reference image and a filtered image. Figure 2.7 shows the layout of the camera module. Figure 2.8 is a dimensioned drawing of the optical arrangement inside a camera module. The image acquired by the camera is reflected off of two mirrors before encountering a beam splitter, which allows half of the image intensity to pass through, and reflects the other half of the image intensity into the iodine cell. Each of these images is reflected off of two more mirrors before the images are captured by the digital camera. Special care was taken to make sure the image paths for the reference and filtered images were the same length. The digital camera and the optics are mounted between a 9.53 mm (3/8 inch) thick aluminum plate and a 12.7 mm (1/2 inch) thick Plexiglas plate. Spacers were placed between the plates to give the module additional strength.
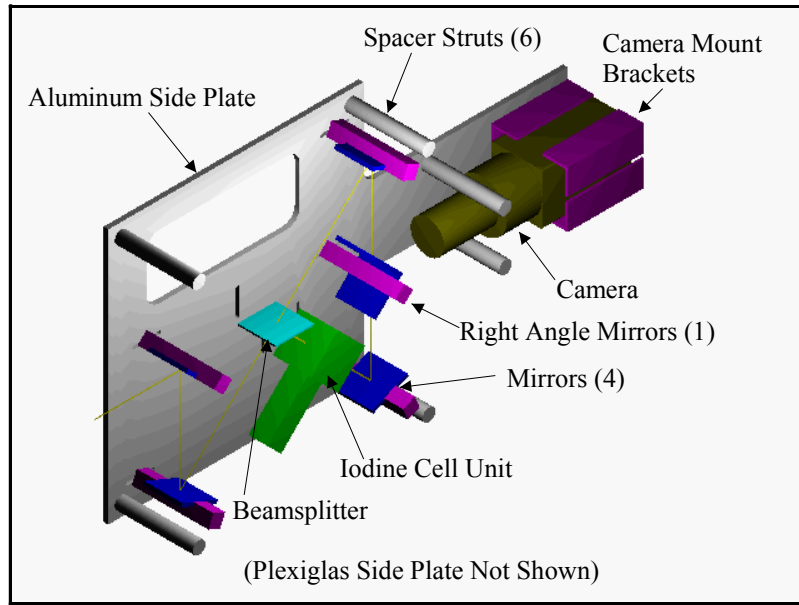
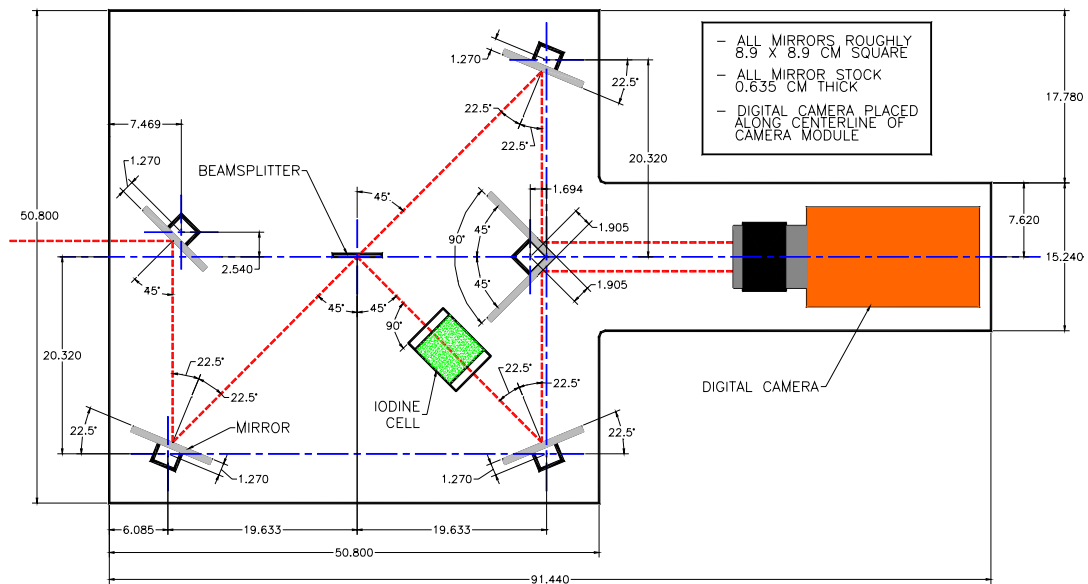*Figure 2.7: Layout of camera module (from Jones 2000)[52]*

Figure 2.8: Dimensioned drawing of the optical arrangement inside a camera module

2.4.1 Digital Camera

The first DGV systems assembled used analog video cameras in conjunction with frame grabbers to acquire data.[53] While some researchers have stayed with 8-bit or 10-bit surveillance cameras others recommend using 16-bit digital astronomy cameras.[54, 55] It appears the choice between these is primarily one of cost versus signal to noise ratio. The systems using 16-bit cameras generally have a higher signal to noise ratio but they can cost 10 to 28 times as much as a system

using 8-bit surveillance cameras.[56, 57, 58] Figure 2.9 shows a comparison of signal to noise ratios for various digital cameras.
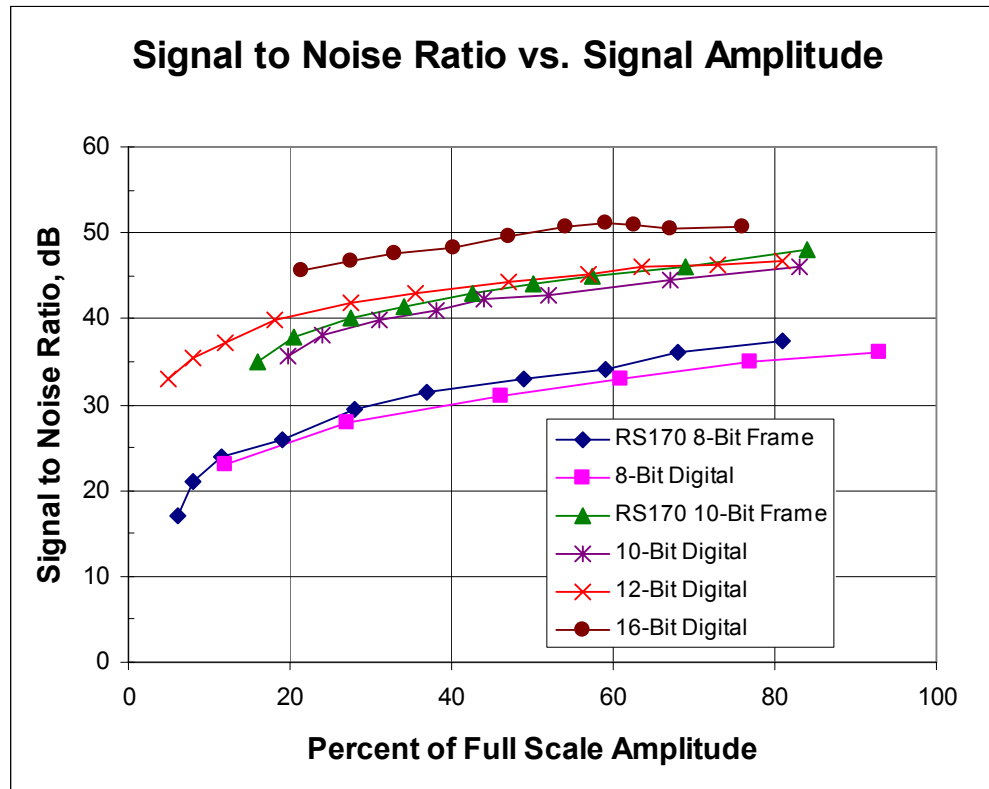

Figure 2.9: Signal to noise ratios for some digital cameras.[59]

The original Virginia Tech DGV system used three 16-bit digital cameras manufactured by Spectra-Source (1 – MCD 1000S and 2 – Orbis 16). The operation and performance of these cameras was virtually identical. One of the Orbis 16 cameras began to malfunction during the first set of DGV tests in the Virginia Tech Stability Wind Tunnel. During the research discussed in this volume the malfunctioning camera was replaced with a VersArray 16-bit camera manufactured by Roper Scientific. While the operation of this camera was somewhat different from the Spectra-Source cameras the performance was similar to the older cameras. The VT DGV control program was updated so that the new camera could be used by the VT DGV system. All of the functionality of the previous camera, before it began to malfunction, has been retained in the new camera system.

It should also be noted that the remaining Spectra-Source cameras also started to develop problems. Ice crystals began to form on the CCD array (the imaging surface) of the remaining Orbis 16 camera after it was on for roughly an hour. The camera was still usable, for the first hour that it

was on, but as section 5.3.3 will explain in greater detail, this problem led to a less than ideal solution to a problem with the images acquired by the camera modules shifting over time. During the final set of tests performed during the research discussed in this volume the MCD-1000S camera did not lock on the set point temperature required by the camera cooling system. While this did not appear to affect the performance of the camera during data acquisition the long term effects of this problem are unknown.

2.4.2 Iodine Cell

An iodine cell is essentially a hollow glass cylinder, with optical quality windows attached to the ends, and filled with iodine gas. As previously mentioned, iodine gas has some useful absorption properties for light in the green portion of the visible spectrum. Figure 2.10 shows a theoretical light absorption profile for an iodine cell over a small range of optical frequencies in the green portion of the visible spectrum. The variation in optical frequency is given in terms of the wave number. The wave number is calculated using the formula below:

$$WaveNumber = \frac{1}{\lambda} = \frac{\nu}{c} \tag{2}$$

where λ is the wavelength of the light, ν is the optical frequency of the light, and c is the speed of light.

A variety of different gas combinations have been used to tailor the iodine cell absorption transitions for specific uses. Researchers performing experiments in high speed flows often use cells containing a mixture of iodine and nitrogen to increase the range of optical frequencies over which a transition from full transmission to full absorption occurs.[60] Researchers performing experiments in low speed flows (Mach Numbers from 0 to 0.3) generally use iodine cells filled with pure iodine since this type of cell will have the sharpest transition between full transmission and full absorption, thus providing the best sensitivity to small variations in optical frequency.
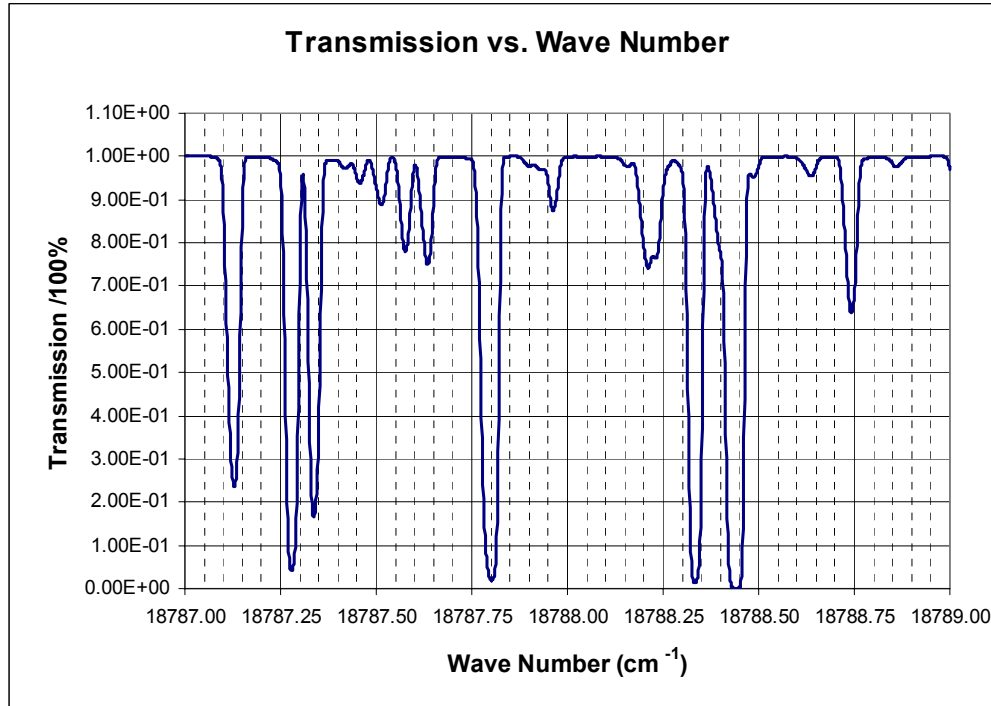
Figure 2.10: Transmission versus wave number for an iodine cell, containing pure iodine gas, at a cold finger temperature of 40˚C.

Previous researchers using the DGV technique to perform flow velocity measurements have used iodine cells with an attachment called a cold finger. The cold finger acted as a reservoir because it contained solid crystals of iodine. As the cold finger was heated the crystals melted providing iodine gas for the body of the cell. The cold finger temperature was controlled independently from the temperature of the body of the cell. Generally the body temperature was kept considerably higher than the temperature of the cold finger so that any crystals that form in the cell form in the cold finger. An important consideration for this type of iodine cell was that the temperature of the cold finger controlled the absorption properties of the cell and therefore needed to be closely monitored. In fact a change in the cold finger temperature of 0.1˚C resulted in a change of 3 m/s in the measured velocity.[61] This sensitivity required great care to be taken in monitoring and controlling cold finger temperature in an attempt to minimize the measurement uncertainty caused by variations in the cold finger temperature.

Recently, another novel approach has been taken. A few researchers have started using "vapor limited" iodine cells.[62, 63, 64] A vapor limited iodine cell does not have a cold finger. The cell is filled with iodine gas at a specified temperature, and so long as the cell temperature is above the

temperature of the iodine gas as it was injected into the cell, no iodine crystals will form inside the cell. In addition to this, the iodine cell absorption properties will remain constant.[65]

The iodine cells previously used in the Virginia Tech DGV system had a cold finger, which contained crystallized iodine that acted as a temperature dependent reservoir. This arrangement required the cold finger temperature to be monitored very closely. The three iodine cells used in previous tests of the VT DGV system were modified to be vapor limited at temperatures above 40˚C. The iodine cells were manufactured and refurbished by Opthos instruments. Each of these cells was 5.08 cm in length and 5.08 cm in diameter. The ends of the cell were sealed with ¼ wave flat windows. The windows were treated with an anti-reflective coating for light wavelengths near 532 nm. The iodine cells were filled with 99.9% pure diatomic iodine vapor and were permanently sealed to prevent the iodine vapor from escaping the cell.[66]

2.4.3 Temperature Control

Each iodine cell was wrapped with a heating mat and enclosed in an aluminum box. The aluminum box was mounted inside the camera module. An RTD, resistive temperature probe, was inserted into the aluminum box to monitor the temperature of the iodine cell body. The heating mat and RTD probe were connected to a Scientific Instruments Inc., Dyna-Sense Mk III temperature controller. This temperature controller contained a Proportional Integral Derivative (PID) control unit, which used temperatures measured by the RTD probe as feedback and turned the heating mat on and off as needed to maintain the cell body temperature near the desired body temperature. The rated temperature stability for this controller was ±0.1˚C. The temperature controllers used to monitor and control the temperature of the cold fingers on the iodine cells in the previous version of the VT DGV system were eliminated from the system. The set point temperatures on the temperature controllers for the body of the iodine cells were set to keep the temperature of the iodine cells near 60˚C.[67]

2.5 Calibration Wheel

The most common procedure used to test and validate DGV systems is to acquire data while viewing a disk or wheel rotating at a known angular velocity. Many researchers have used analog DC motors to drive their wheel systems and "optical tachometers" to keep track of the variations in wheel speed.[68] In fact the "optical tachometer" is really nothing more than a light source illuminating the back of the wheel which has a white line painted on it. The flash of light reflected off of the wheel when the white line passes through the beam of light is detected using a photodiode.[69] While this system may work well for some, it does not give any information about variations in wheel velocity

over the course of each revolution, thus producing a source of error in DGV measurements using the wheel and in calibrating the iodine cells if the wheel is used in the calibration procedure.

The calibration wheel system designed for the Virginia Tech DGV system contains a feedback control system to make sure the wheel speed is held constant. The calibration wheel system also has the capability to make instantaneous quantitative measurements of the wheel speed. Figure 2.11 is a diagram showing the control system architecture for the new calibration wheel system. An IBM compatible personal computer is used to write maneuver programs for the calibration wheel. These programs are downloaded to the servo motor controller (a Baldor 1-Axis Smartmove Servo Controller). The controller sends a reference voltage to the servo amplifier (Advanced Motion Controls Model #BE25A20-AC). This voltage is proportional to the current sent from the servo amplifier to the motor. An optical encoder (Hewlett Packard Model # 5640-A06) is attached to the motor to measure the position and angular velocity of the motor shaft. The signal from the encoder is used as feedback for the servo amplifier and the controller. The encoder signal can also be used by the controller to record information about the motor performance, such as wheel speed, position and following error. The motor was connected to a 304.8 mm (12 inch) long shaft through a motor coupler. The 304.8 mm (12 inch) shaft was supported by two roller bearings. A 254 mm (10 inch) diameter aluminum disk was connected to the other end of the 304.8 mm (12 inch) shaft. Sandpaper (400 grit) was applied to the side of the disk facing away from the motor. The sandpaper and outer edge of the disk were painted white. An enclosure was constructed to keep parts from flying away from the motor and shaft assembly in the event something in the motor or bearing assembly came loose or broke away. Figure 2.12 shows the calibration wheel and protective enclosure and figure 2.13 is a dimensioned drawing of the mechanical portion of the calibration wheel system inside the protective enclosure.
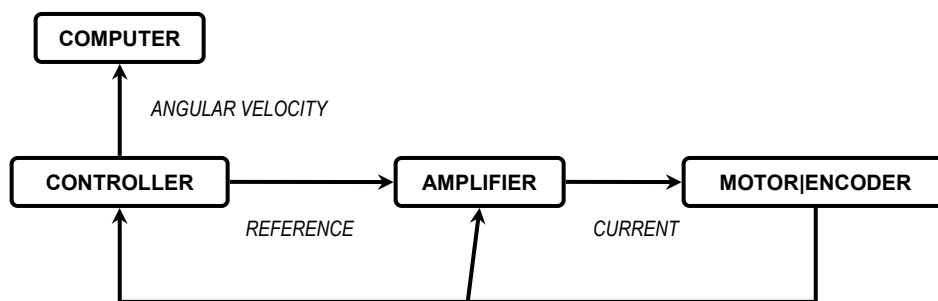

Figure 2.11: Calibration wheel control system diagram

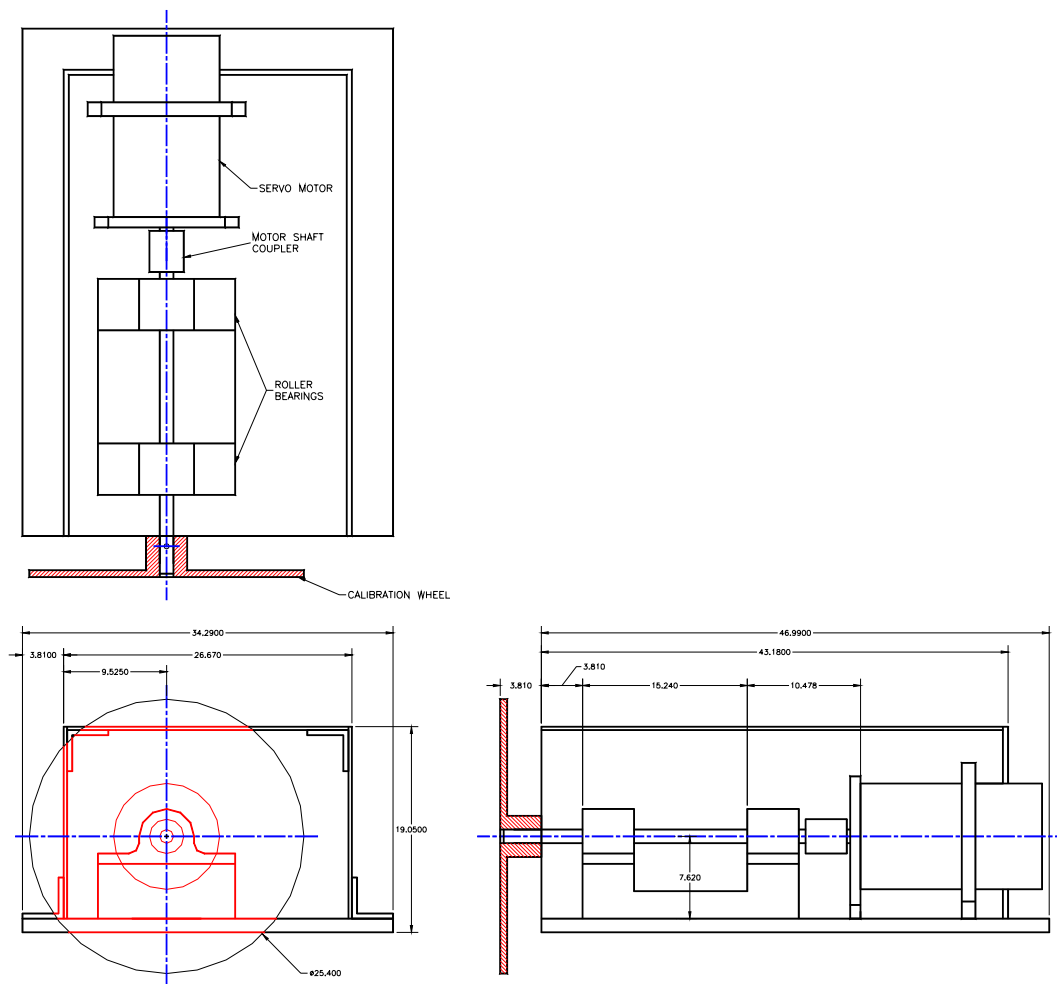*Figure 2.12: VT DGV calibration wheel*

Figure 2.13: Dimensioned drawing of the mechanical portion of the calibration wheel system.

The motor controller provides two different methods for monitoring the performance of the motor. The controller can acquire and store motor velocities in an array that can be uploaded to the host computer. This capability was used to acquire an array of wheel velocity data for a series of maneuvers similar to the maneuver that will be used in calibrating the VT DGV system. Figure 2.14 shows a plot of the wheel rotation speed versus time in seconds. Data were collected at 2 millisecond intervals for 9.9 seconds, but for display purposes the plot shown in figure 2.14 contains data taken at 10 millisecond intervals. For the maneuver shown, the commanded wheel speed was 60 revolutions per second. The average wheel speed during the constant portion of the maneuver was 60.1851 revolutions per second. The standard deviation of the wheel speed measurements was 0.2207 revolutions per second. The controller can also output a voltage that is proportional to the motor velocity. This capability and the ability to store an array of velocity data were used to calibrate the wheel system.
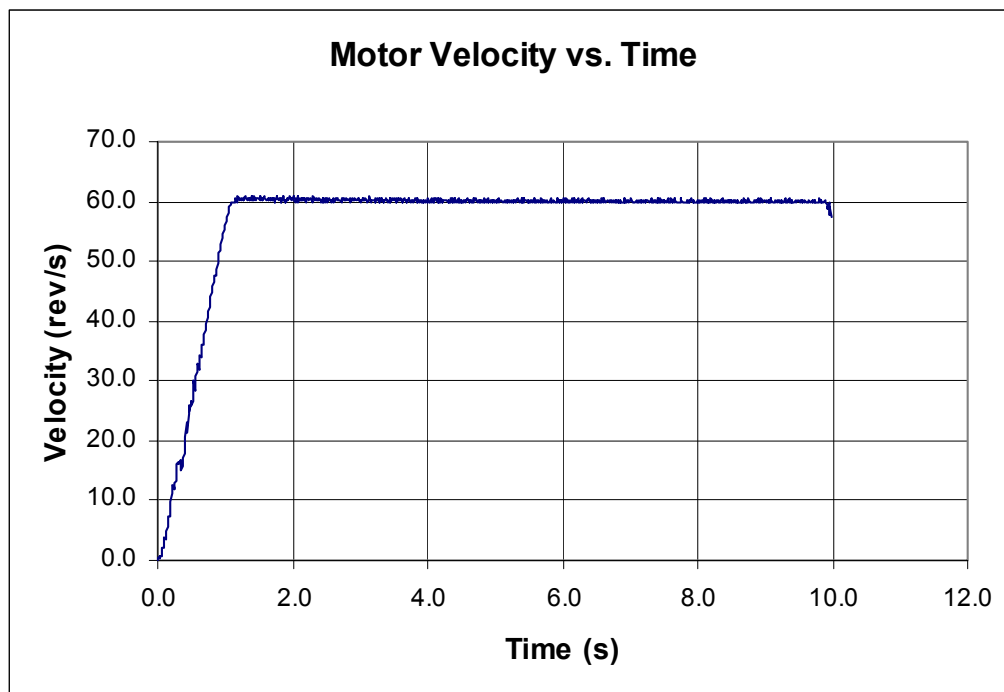

Figure 2.14: Calibration wheel test data (commanded speed: 60 rps)

2.6 Computers and Software

2.6.1 DGV Computers

Two PC compatible computers were used by the Virginia Tech DGV system. The first computer, designated DGV1, was a Pentium 160 MHz computer and contained interface cards for each of the three 16-bit digital cameras as well as a 16 channel Measurement Computing PCI-

DAS1602/16 data acquisition board. The data acquisition board was used to send digital signals from the laser shutter and to send and receive analog signals to set the optical frequency of the laser and monitor the performance of the laser. The second computer, designated DGV2, was a Celeron 700 MHz computer. This computer was used to program the calibration wheel controller and to archive DGV data files. This computer is available for use in the future to run a fourth camera module to monitor laser performance. The fourth camera module cannot be run by DGV1 because all available slots in this computer have been filled.

2.6.2 DGV Software

The DGV Control Program used to acquire and reduce DGV data was originally written by Troy Jones.[70] This Windows based program was written in Visual C++ Version 6. The program could acquire single or multiple images from any combination of the three 16-bit cameras. The user could choose whether or not to save these images and could also choose the exposure time. Images from each camera could be viewed one at a time. The program could automatically perform a variety of operations on a sequence of images. Some of these operations included: setting separate regions of interest for the filtered and reference views, setting separate regions of interest on one of the three camera views to monitor mean variations in laser optical frequency, image addition and subtraction, image division, image de-warping, image mirroring, image filtering, and applying image intensity corrections. The program could automatically acquire iodine cell calibrations and reduce the acquired data to obtain an absorption profile in terms of laser offset voltage for each of the three 16 bit cameras. It could also automatically reduce a sequence of DGV velocity images, or an average DGV velocity image to obtain a velocity field for the plane in which data was taken. This program was also used to set the power and operating mode of the Nd:YAG laser, operate the laser shutter and monitor the cold finger temperature.[71] Figure 2.15 shows the Graphic User Interface for the DGV Control Program.

Over the course of this research several changes were made to the DGV Control Program. The software used to run the malfunctioning Orbis 16 camera was replaced with software needed to run the new VersArray 16-bit camera. Since the cold fingers on the iodine cells were removed, to make the iodine cells vapor limited, portions of the program which monitored the cold finger temperature or used the temperatures obtained were disabled but left in place where possible and deleted if necessary. Software was added to turn the calibration wheel on and off from DGV1 using a digital output from the data acquisition board. The control program now has the ability to acquire voltages from the calibration wheel controller proportional to the wheel speed. This was done using

one of the analog inputs from the data acquisition board. The DGV Control Program can convert these voltages into angular velocities, and can store the voltages, standard deviations of the voltages, angular velocities, and standard deviations of the angular velocities in a file during DGV velocity data acquisition or merely sample and display the output voltage from the calibration wheel controller. Software was also added to allow the smoke machine to be turned on and off by DGV1 but this portion of the program was not used during data acquisition. Also, extensive modifications to the data reduction portion of the program were made. Some of the changes made to the data reduction algorithm included: changes to apply background and white card corrections to each image before the mean laser reference transmission ratio was calculated, the single frequency calibration function used to calculate the optical frequency from a transmission ratio was changed so that each camera module had its own frequency calibration function, the procedure used to apply the laser reference transmission ratio was changed, and the method used to calculate the wave number used as part of the data reduction procedure was changed. These changes corrected some significant problems with the data reduction procedure.
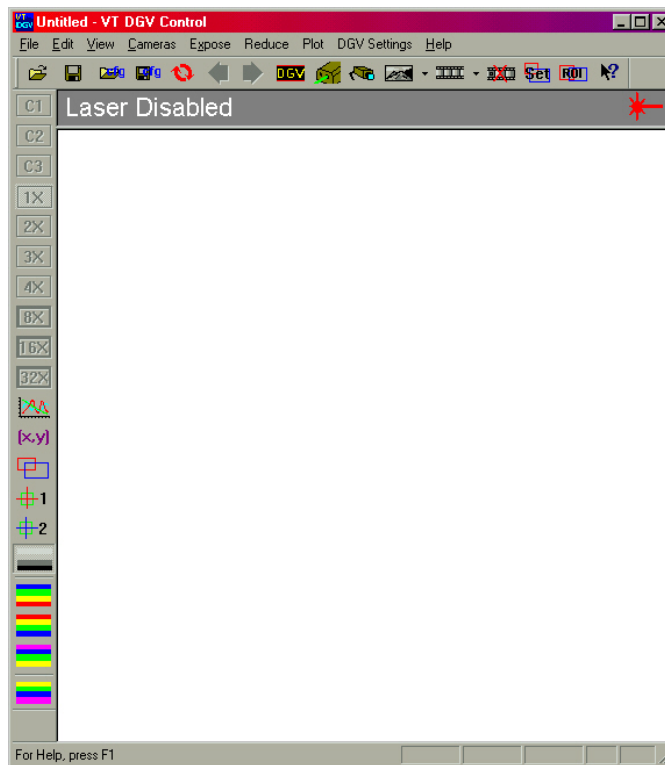

Figure 2.15: Graphic User Interface (GUI) for the Virginia Tech DGV Control Program.

A FORTRAN program written by J. N. Forkey was used to determine the theoretical absorption profile for the iodine cells.[72] This theoretical absorption profile was compared to the

profile measured during an iodine cell calibration to determine the mean optical frequency the laser was operating at for a given laser offset voltage. The iodine cell dimensions, vapor temperature, wave number range and wave number increment size were input to the program and transmission versus wave number were output by the program. More information regarding the physical principles simulated by this program and information on how this program works can be found in reference 73.

A MATLAB toolbox "Camera Calibration Toolbox for MATLAB" written by Jean Yves Bouguet, Ph.D. at California Institute of Technology, was used to determine the rotation matrix to transform the coordinate system of the data plane to the coordinate system of each camera module.[74] This was done by measuring reference points on a series of images of a checkerboard. A corner extraction program, incorporated into the toolbox, allowed the user to mouse click on an acquired image of a checkerboard near one of the box intersections and the program would automatically determine the intersection coordinates for all checkerboard intersections within the user specified region on the image. For this reason images of a checkerboard pattern were acquired to determine the rotation matrix as well as to de-warp images during the DGV data reduction procedure. The rotation matrix calculated by the toolbox was used to determine a set of Euler angles for each of the camera modules which were used in the data reduction portion of the DGV Control Program. The MATLAB toolbox used machine vision techniques to determine the rotation matrix. This toolbox was also capable of measuring and correcting for optical distortion of images captured by a digital camera. This portion of the toolbox could not be used for the camera calibration images acquired by the DGV system, because the digital cameras used in the DGV system used zoom lenses and were observing the data plane from a long distance. More information about machine vision techniques, the capabilities of this MATLAB toolbox and how to use the toolbox can be found in reference 75.

2.7 Virginia Tech Stability Wind Tunnel

The Virginia Tech Stability Wind Tunnel was used in the tests of the Virginia Tech DGV system. This tunnel has a test section that is 182.9 cm (6 feet) high by 182.9 cm (6 feet) wide and 731.5 cm (24 feet) long. The contraction ratio for the tunnel is 9:1.[76] Air is moved in the tunnel by a 600 hp D.C. motor which drives a 426.7 cm (14 foot) diameter propeller. The tunnel is capable of running at a Reynolds number per meter of 505968 (Reynolds Number per foot of 1.66×10^6) with the test section used for this experiment. The turbulence intensity in the empty test section of this tunnel is less than 0.05% and the variation of the dynamic pressure is approximately 0.05% across the test section. The vertical flow angularity in this tunnel is approximately ±1˚(previously measured through a vertical sweep of the test section). In the middle of the test section the flow angularity is

less than 0.25. The flow speed in the wind tunnel was measured using a Pitot static probe mounted in the test section. Temperature in the wind tunnel can be measured using a thermocouple, also mounted in the test section.[77]

2.8 6:1 Prolate Spheroid Model

A 6:1 prolate spheroid model was used in these tests. This model was the same model that was used by Chesnakas *et al.*[78] The model was 1.37 m long (53.9 inches) and had a maximum diameter of 0.229 m (9 inches). The model was constructed in three sections. Each section had a fiberglass skin bonded to an aluminum frame. A trip strip was placed around the circumference of the model at x/L = 0.2. This trip strip consisted of circular cylindrical posts 1.2 mm (0.047 inches) in diameter and 0.7 mm (0.028 inches) high, spaced 2.5 mm (0.098 inches) apart. Screw holes and seams between model sections were filled with red wax to smooth these irregularities out. The model had two windows which allowed optical access for an LDV system used in previous tests. These windows were covered with plastic sheeting and the entire model was painted with flat red primer. A 0.75 m (29.5 inch) sting protruded out of the rear of the model. The sting was mounted to a vertical post attached to a turntable beneath the test section floor.[79] Figure 2.16 shows the prolate spheroid model mounted in the wind tunnel test section.

Figure 2.16: 6:1 prolate spheroid mounted in wind tunnel test section.

Chapter 3: Procedures and Techniques