Chapter 4 : Data Reduction

4.1 Reducing DGV Data

Once the iodine cell calibration images or the velocity images had been acquired, these images were processed to extract the useful information they contained. The VT DGV Control Program not only contained the software needed to acquire and save the correction images, iodine cell calibration images, and velocity images, it also contained the data reduction software used to process and reduce these images. The data reduction procedure developed for the VT DGV system was assembled from several sources. A paper from James Meyers at NASA's Langley Research Center published in 1996 gave the basic procedure used to reduce DGV data.[85] Two papers from Robert McKenzie at NASA's Ames Research Center introduced the idea of using a small portion of the laser pulse to monitor pulse to pulse variations in the mean optical frequency.[86, 87] A paper from James Meyers, Joseph Lee and Richard Schwartz at NASA's Langley Research Center provided clarification in some areas as to how the data reduction procedure should proceed and also offered suggestions on how this procedure could be improved.[88] The improvements suggested by this paper were to be implemented as part of this research, but hardware problems delayed this implementation to some future date. While the procedure used to reduce the iodine cell calibration images was in some ways quite similar to the procedure used to reduce the velocity images, the end result was quite different. The desired result from the reduced iodine cell calibration was a mean transmission ratio for each image in the calibration. This mean transmission ratio was determined by calculating the average transmission ratio from the quotient of the sum of the pixel intensities of all of the pixels in the filtered view region of interest divided by the sum of the pixel intensities of all of the pixels in the reference view region of interest. The mean transmission ratios from each image were then used to determine the relationships between transmission ratio, offset voltage and optical frequency. These relationships were used to set the laser to fire at the desired optical frequency and to relate a change in transmission ratio to a change in optical frequency. The relationship between the change in transmission ratio and the change in optical frequency was used to determine the Doppler shift in optical frequency caused by laser light being scattered by a moving particle.

A transmission ratio for each pixel in the filtered and reference regions of interest was calculated as part of the data reduction procedure used to reduce velocity data. These transmission ratios were compared to the relationship calculated from the iodine cell calibration to determine the optical frequency of the light collected at each pixel location. The relationship between transmission ratio and optical frequency for each camera module was also used to determine the actual lasar optical frequency. Next, the difference between the optical frequency of the light collected at each pixel location and the lasar optical frequency was determined. This difference was the Doppler shift caused by laser light being scattered by moving particles. The Doppler shift and the actual lasar optical frequency were used in the governing equation for the technique along with information regarding the direction of laser light propagation and the viewing angles for each camera module to convert the Doppler shifts in optical frequency into velocities. While the description above gives a rough outline of the procedures used to reduce iodine cell calibration data and velocity data, the remainder of this chapter will discuss in detail how these images were reduced as well as how and where each of the corrections described in Chapter 3 were implemented.

The data reduction program used in this research was originally written by Troy Jones as part of his M. S. thesis. Before the program was used in the current research a thorough review of the program was performed. During this review, several errors in the reduction program were located and corrected. One of the first additions made to the VT DGV data reduction program during this research was to change the procedure used to calculate the laser reference transmission ratio so the image corrections used to reduce the data images were performed before the laser reference transmission ratios were calculated. Next, the implementation of the laser reference transmission ratio was changed so that this transmission ratio was used to calculate the unshifted optical frequency of the laser pulse used to acquire the data image. The implementation of the procedures used to reduce average or active DGV data images was changed so that the laser reference transmission ratio calculated for these cases was saved for use in other areas of the data reduction procedure. The program used to calculate and implement the white card correction was changed so an average white card correction ratio for each camera module was saved as part of the white card correction file. Finally, the procedure used to determine the wave number was changed from assuming the wave number was constant to calculating the wave number using the laser reference transmission ratio.

4.2 Reducing Iodine Cell Calibration Data

The Virginia Tech DGV Control Program contained the capability to automatically reduce an iodine cell calibration once all of the images in the calibration were acquired. The program user could also choose to reduce or re-reduce the iodine cell calibration at a later time. The control program also contained an important feature which allowed the active camera configuration, warp point locations, the sizes and locations of the rectangular regions of interest, background correction image file names, pixel sensitivity image file names, white card correction data file names, and other reduction settings for a particular iodine cell calibration or velocity set to be saved between operating sessions. These values could be saved in a configuration file which could be loaded at the beginning of a new operating session. As stated previously in this chapter, the goal of the data reduction procedure used to reduce an iodine cell calibration is to calculate a mean transmission ratio for each image from each camera used in the calibration. Once this was completed the series of mean transmission ratios could be used to determine the relationship between transmission ratio and optical frequency.

Before data reduction began, a decision had to be made regarding what, if any, image corrections were to be applied to the calibration images. The user could choose to apply any combination of these corrections desired, provided the necessary correction images were available. In addition to selecting the corrections to be applied the user could choose which images would be used to perform the correction. For a first attempt to reduce an iodine cell calibration the geometric, background, and pixel sensitivity corrections were usually used. The white card correction could not generally be applied until the offset voltage where the maximum mean transmission ratio occurred had been determined. Once this voltage was determined, white card correction images could be acquired or the iodine cell calibration images near this offset voltage could be used to calculate the white card correction for the camera module in question. Generally the 10 images around the maximum mean transmission ratio were used to determine the white card correction ratio. Once the desired image corrections and the files used to perform these corrections had been selected, the data reduction algorithm could be started.

The iodine cell data reduction algorithm processed the images from one of the camera modules at a time. In other words, the algorithm would process all of the images from a given camera module before proceeding to the images acquired by the next camera. The procedure described below assumes all of the image corrections were performed, if this was not the case the portion of the procedure pertaining to the correction that was not performed was skipped. The first step in the data reduction procedure was to load the image to be reduced into the computer's memory. Once this was completed the background image correction was performed by subtracting the background image from the calibration image. Next, the pixel sensitivity correction was performed by dividing each pixel in the image by the pixel sensitivity value for that particular pixel. Once this correction was completed the filtered view was vertically mirrored so the filtered and reference images were oriented in the same direction. After the filtered view was mirrored, the filtered and reference views were mapped to their rectangular regions of interest. Next, the white card correction was applied by dividing each pixel in the filtered rectangular region of interest by the white card ratio associated with that particular pixel. Once all of the selected image corrections had been performed, the average pixel intensities for the reference and filtered views were calculated. Next, the quotient of the average filtered pixel intensity divided by the average reference pixel intensity was calculated. This quotient was the mean transmission ratio for the image. Figure 4.1 is a chart showing the major steps in the data reduction procedure used to reduce an iodine cell calibration. This procedure was repeated for each image acquired in the iodine cell calibration.

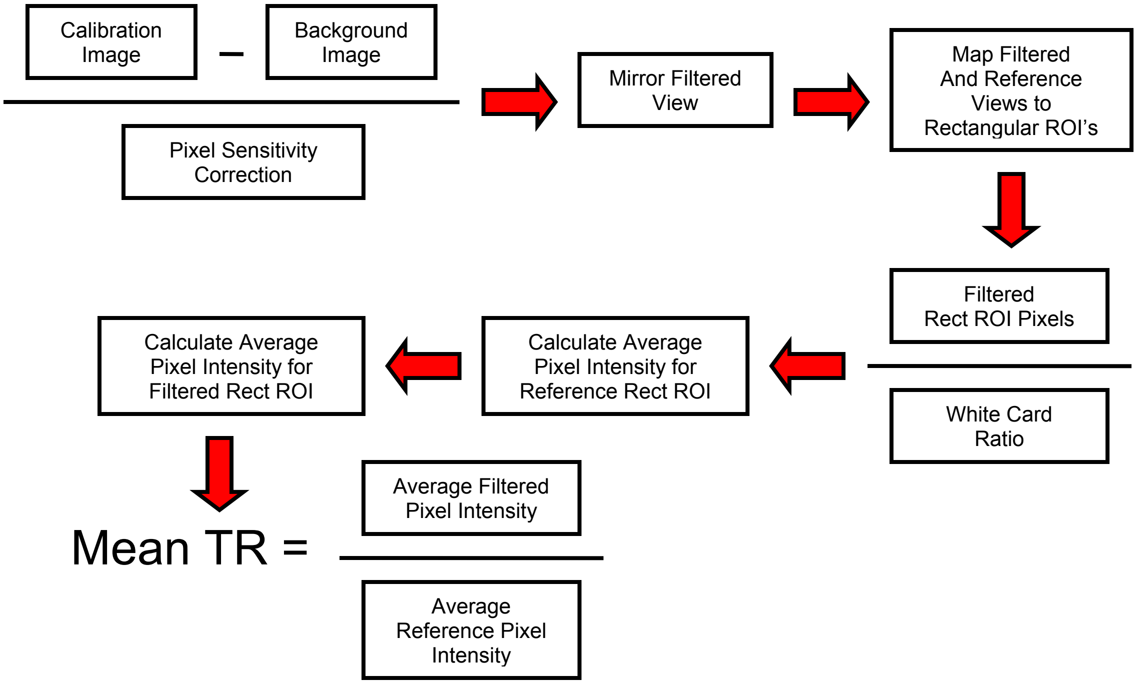


Figure 4.1: Iodine cell calibration procedure

4.3 Converting Mean Transmission Ratio into Optical Frequency

Once the offset voltage where the maximum mean transmission ratio occurred was determined, the white card correction ratio determined, and the iodine cell calibration re-reduced using the white card correction ratio, the reduced data from the iodine cell calibration could be used to determine the relationships between transmission ratio, offset voltage and optical frequency. A FORTRAN program written by J. N. Forkey was used to determine the theoretical light absorption characteristics for an iodine cell of a specified length and with a specified internal pressure.[89] The length of the iodine cells used in this research was 5.08 cm and the pressure could be determined from the "cold-finger" temperature using the following formula:

$$\log P = 9.75715 - \frac{2867.028}{T + 254.180} \tag{14}$$

where T was the "cold-finger" temperature in degrees Celsius, and P was the pressure in torr. Since the iodine cells used in this research were vapor limited and did not have a cold finger, the temperature used to calculate the pressure was the filling temperature 40° C. The range of wave numbers over which the absorption properties were to be calculated and the increment size were also input into the FORTRAN program. The program output a data file containing transmission ratios for the wave numbers in the selected range. Next, the theoretical transmission ratios were plotted and compared to the plotted results of the iodine cell calibration. Identical features on the theoretical plot and the iodine cell calibration plot were used to determine the identity of the absorption features captured in the iodine cell calibration. Once a portion of the theoretical absorption profile was matched to the features present in the iodine cell calibration, the iodine cell calibration data was scaled and plotted with the theoretical data to determine the relationships between the offset voltage, transmission ratio, and wave number (and hence optical frequency). The equation used to convert the offset voltage to a wave number had the form:

$$HighFreq + \left(\frac{HighFreq - LowFreq}{LowVolts - HighVolts} \right) \times \left(Volts - LowVolts \right) \tag{15}$$

where *HighFreq* and *LowFreq* were the maximum and minimum wave numbers (respectively) for the portion of the absorption profile to which the offset voltage was being scaled, *HighVolts* and *LowVolts* were the maximum and minimum offset voltages (respectively) in the iodine cell calibration being scaled, and *Volts* was the offset voltage that was being scaled. The maximum and minimum wave numbers (*HighFreq* and *LowFreq*) were adjusted until the best fit between the iodine cell calibration data and the theoretical absorption profile was achieved. Figure 4.2 shows a theoretical absorption profile with data from an iodine cell calibration overlaid on top of it. This figure shows the agreement between the theoretical data and the calibration data. Once the best fit of the calibration data with the theoretical data was achieved, the portion of the calibration data inside the transition from full transmission to full absorption were re-plotted with wave number on the vertical

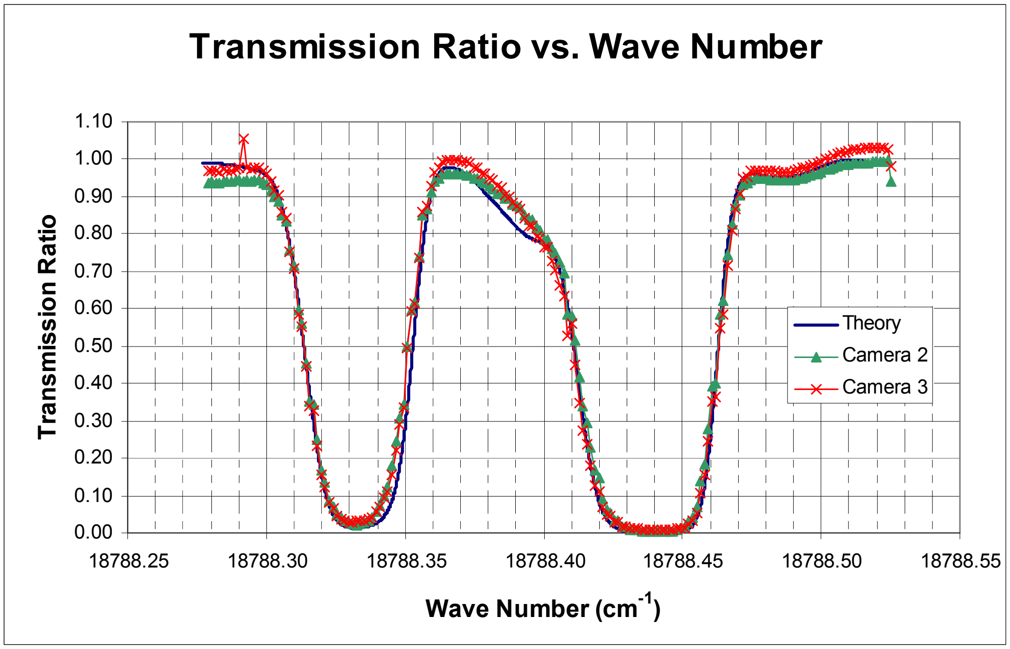


Figure 4.2: Theoretical iodine cell absorption profile with iodine cell calibration data overlaid

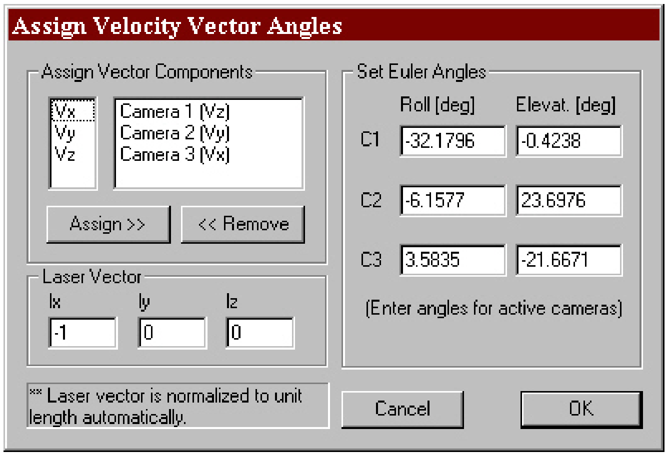
axis and transmission ratio on the horizontal axis. A wave number polynomial, calculated from this plot, was used by the velocity data reduction algorithm to convert measured transmission ratios into optical frequencies which could then be used to calculate velocities. The value output from wave number polynomial had units of cm^{-1}. A separate polynomial was calculated for each camera module because the transmission ratios measured by each of the camera modules differed slightly at a given offset voltage. In fact, in the iodine cell calibrations acquired prior to the final attempts to acquire calibration wheel velocity data and velocity data in the wake of the prolate spheroid model, the transmission ratios measured by camera module 3 were significantly different from the transmission ratios measured by camera modules 1 and 2. This discrepancy will be discussed in further detail in Chapter 6. Previous research indicated a fifth order polynomial would provide the best fit to the calibration data so all of the wave number polynomials calculated in this research were fifth order polynomials.[90]

4.4 Preliminary Steps for Reducing Velocity Data

The VT DGV system was designed to measure instantaneous three component velocities in a data plane within a flow field. The correction images and iodine cell calibration images were acquired and reduced by the VT DGV system for the sole purpose of making it possible to acquire and reduce velocity images. For this reason, all of the correction images discussed in Chapter 3 are optional inputs in the velocity data reduction procedure. As was stated previously, these images are used to improve the quality of the reduced velocity data. Where as the iodine cell calibrations are a critical part of the velocity data reduction procedure since these calibrations provide the relationship between transmission ratio and optical frequency.

4.4.1 Assigning the Velocity Vectors and Entering the Euler Angles

A few preliminary tasks were performed before the VT DGV Data Reduction dialog was opened and any velocity images were reduced. The first task was to assign the velocity vectors in the data plane coordinate system to the camera module. Each camera module was assigned a different velocity vector. Next, the Euler angles calculated using the "*Camera Calibration Toolbox for MATLAB*", written by Jean-Yves Bouguet, were entered into the DGV Control Program.[91] Only two of the three Euler angles, roll and elevation, were needed to reduce the velocity data. The roll angle was the rotation about the x axis of the transformed reference frame and the elevation angle was the rotation about the y axis of the transformed reference frame. The velocity vector assignments and the entered values for the Euler angles were saved as part of the configuration file which also contained the warp points and the sizes and locations of the rectangular regions of interest. Figure 4.3 shows the dialog box used to assign the velocity vectors to the camera modules and to enter the Euler angles.



Assign Velocity Vector Angles

Assign Vector Components

Vx
Vy
Vz

Camera 1 (Vz)
Camera 2 (Vy)
Camera 3 (Vx)

Set Euler Angles

	Roll [deg]	Elevat. [deg]
C1	-32.1796	-0.4238
C2	-6.1577	23.6976
C3	3.5835	-21.6671

(Enter angles for active cameras)

Laser Vector

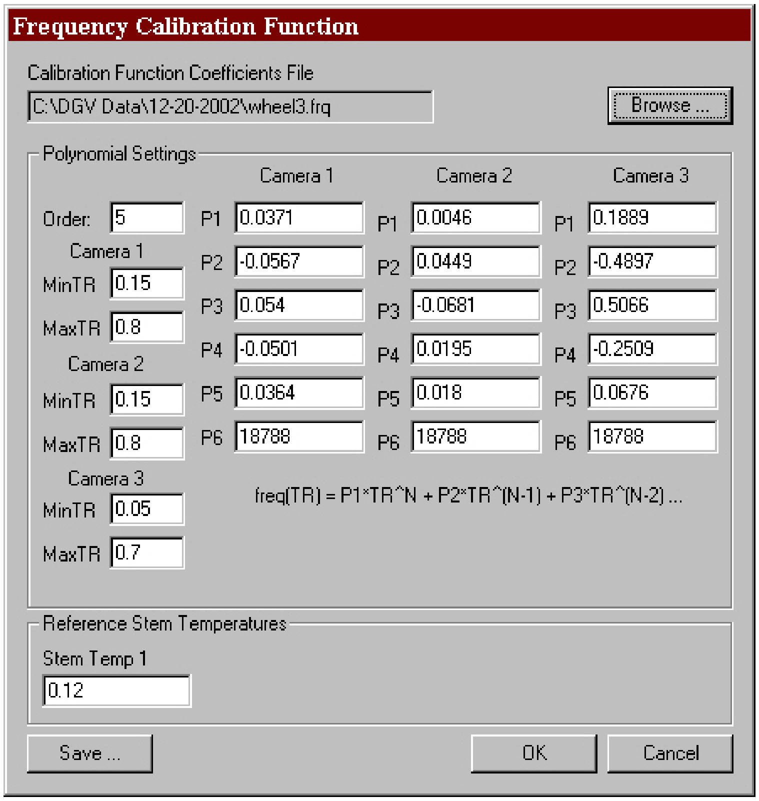
lx	ly	lz
-1	0	0

** Laser vector is normalized to unit length automatically.

Figure 4.3: Dialog box used to assign velocity vectors to the camera modules and to enter Euler angle values for each of the camera modules.

4.4.2 Entering the Coefficients for the Frequency Calibration Functions

Next, the coefficients for the "Frequency Calibration Functions" were entered into the DGV Control Program. These functions were the wave number polynomials discussed in section 4.3. Each camera module used to acquire velocity data had its own "Frequency Calibration Function". The order of the function and the maximum and minimum transmission ratio values where the functions were valid were also entered. The coefficients, order of the polynomials, and maximum and minimum transmission ratios for each function could be saved in a file, different from the configuration file, so these values could be reloaded at the beginning of a new operating session. Figure 4.4 shows the dialog box used to enter the coefficients, order of the polynomials, and maximum and minimum transmission ratios for each function. The dialog box also had controls to save these values and to load a file containing these values. The dialog box also contained a control that allowed a reference stem temperature to be entered. This control was not used in this research because it pertained to the cold finger temperature of the iodine cells. As was discussed in Chapter 2, the iodine cells used in this research were modified to be vapor limited and the cold fingers were removed.



Frequency Calibration Function

Calibration Function Coefficients File: C:\DGV Data\12-20-2002\wheel3.frq

Polynomial Settings

Order: 5

Camera 1
MinTR 0.15
MaxTR 0.8

Camera 2
MinTR 0.15
MaxTR 0.8

Camera 3
MinTR 0.05
MaxTR 0.7

	Camera 1	Camera 2	Camera 3
P1	0.0371	0.0046	0.1889
P2	-0.0567	0.0449	-0.4897
P3	0.054	-0.0681	0.5066
P4	-0.0501	0.0195	-0.2509
P5	0.0364	0.018	0.0676
P6	18788	18788	18788

freq(TR) = P1*TR^N + P2*TR^(N-1) + P3*TR^(N-2) ...

Reference Stem Temperatures

Stem Temp 1: 0.12

Figure 4.4: Dialog box used to enter the coefficient values for the "Frequency Calibration Functions", order of the frequency calibration function polynomials, and maximum and minimum transmission ratios for each function.

4.4.3 Laser Reference Regions of Interest

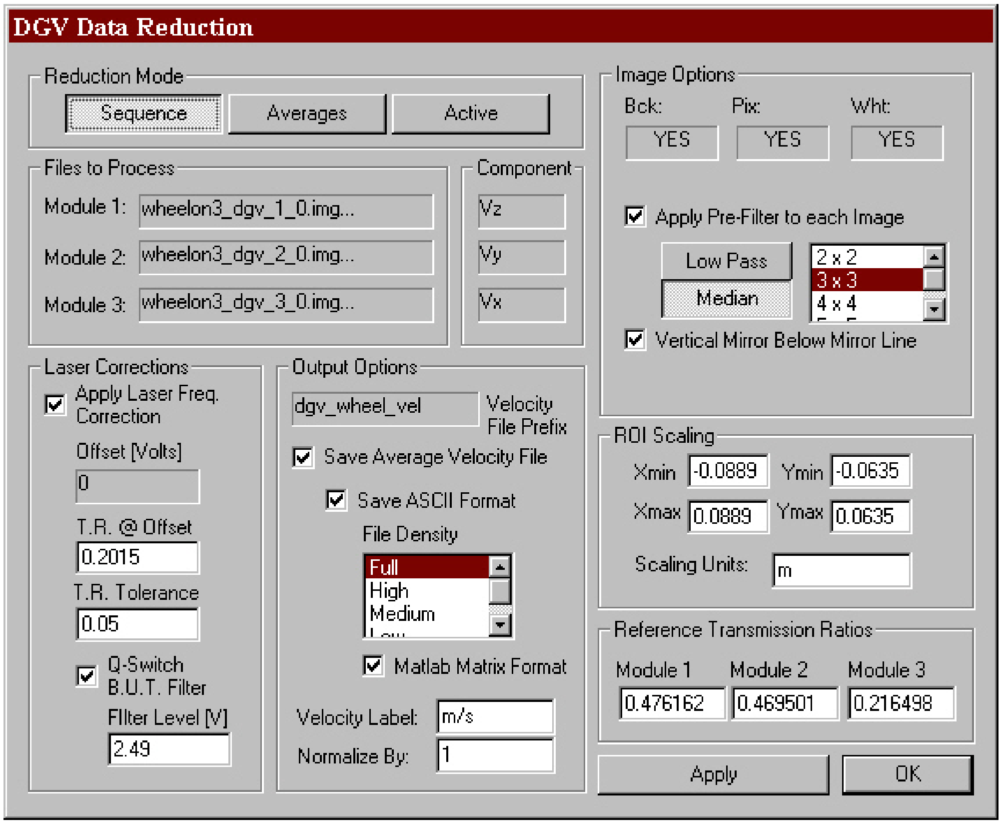
As was discussed in Chapters 1 and 2, one of the drawbacks to using an Nd:YAG laser as a light source for the DGV technique was that the mean optical frequency of the pulses emitted by the laser varied slightly from pulse to pulse. The VT DGV system accounted for these pulse to pulse variations by projecting a small portion of the laser beam to a stationary laser reference tab in the field of view of one of the camera modules. Before velocity images were reduced the laser reference regions of interest were set up in the filtered and reference views of the camera module where the laser reference tab was placed in the field of view. The first step of this process was to load the average image calculated from the images acquired of the stationary target in the data plane prior to acquiring velocity images. Only the average image for the camera module being used to monitor variations in the laser optical frequency was loaded. Once the image was loaded, the active region of interest was set to the reference view, region 1. The next step was to open the laser reference ROI dialog box. Once the dialog box was open, the user designated which camera module was being used to monitor variations in the laser optical frequency. Next, the user entered the pixel coordinates for the center of the laser reference ROI in the active region of interest, in this case region 1. The center of the laser reference ROI was placed roughly in the center of the area where the bleed through laser light hit the laser reference tab. Once the location of the center of the laser reference ROI was entered into the dialog box the size of the laser reference ROI was selected so that the entire ROI fit inside the spot of laser light from the laser reference tab. Once this was done the active region of interest was changed to the filtered view, region 2, and the center of the laser reference ROI was selected using the same criteria used for the reference view. The size of the laser reference ROI in the filtered view was automatically set to be the same as the laser reference ROI in the reference view. The laser reference ROI dialog box also displayed the average laser reference transmission ratio and the uncertainty of the transmission ratio calculated using the selected size and locations of the laser reference ROI's. Once the laser reference ROI's were set up, the background correction, pixel sensitivity correction, and pixel filtering for the camera module could be performed, if these image corrections were to be performed during velocity data reduction, in which case the new value for the laser reference transmission ratio would be recorded for later use.

4.5 Setting Critical Values in the VT DGV Data Reduction Dialog

Once these tasks were completed, the data reduction dialog could be opened and the final preparations for data reduction could be made. Figure 4.5 shows the VT DGV Control Program data reduction dialog box. The data reduction dialog box contained options to determine what data would be reduced, how the data would be filtered, if a laser reference transmission ratio was to be used as part of the data reduction, if a filter based on the Q-switch build up time was to be used to determine which images within a sequence of images were processed and which images were skipped, and how the pixels in the rectangular region of interest would be scaled into "real world" units such as meters, feet, or inches, among other options. The dialog box also provided useful information on which image corrections were to be performed as part of the data reduction procedure and which data images were going to be used in the data reduction. The rest of this sub-section will discuss how the values entered into the data reduction dialog box were determined.

4.5.1 Setting the Reduction Mode

The VT DGV Control Program provided three different "Reduction Mode" options to select the velocity images to be reduced. The "Sequence" option would reduce a sequence of velocity images and output an average velocity profile for each of the camera modules used to acquire the velocity images. The control program also provided an option where the average velocity profiles could be transformed into velocities in the x, y, and z directions for the coordinate frame attached to data plane or left in the "natural" coordinate system, velocities in the $(\hat{a}-\hat{l})$ direction, for each



Files to Process
Module 1: wheelon3_dgv_1_0.img...
Module 2: wheelon3_dgv_2_0.img...
Module 3: wheelon3_dgv_3_0.img...

Component: Vz, Vy, Vx

Image Options
Bck: YES
Pix: YES
Wht: YES
☑ Apply Pre-Filter to each Image
2 x 2
3 x 3
4 x 4
☑ Vertical Mirror Below Mirror Line

Laser Corrections
☑ Apply Laser Freq. Correction
Offset [Volts]: 0
T.R. @ Offset: 0.2015
T.R. Tolerance: 0.05
☑ Q-Switch B.U.T. Filter
FIlter Level [V]: 2.49

Output Options
Velocity File Prefix: dgv_wheel_vel
☑ Save Average Velocity File
☑ Save ASCII Format
File Density: Full
High
Medium
Low
☑ Matlab Matrix Format
Velocity Label: m/s
Normalize By: 1

ROI Scaling
Xmin: -0.0889
Ymin: -0.0635
Xmax: 0.0889
Ymax: 0.0635
Scaling Units: m

Reference Transmission Ratios
Module 1: 0.476162
Module 2: 0.469501
Module 3: 0.216498

Figure 4.5: VT DGV Control Program data reduction dialog box.

camera. The "Average" option was used to reduce the average images for each of the cameras used to acquire a sequence of velocity data images. These average images were determined by calculating the average values for the pixel intensity of each pixel in an image over a sequence of images. The user had the capability to manually choose which images would be used to calculate the average image. This capability was a very useful tool because while the control program could filter an image sequence based on the Q-switch build up time, the program could not filter an image sequence based on whether the Nd:YAG laser reset while a velocity image was being acquired. The "Active" option was used to reduce the images currently displayed in the parent window of the VT DGV Control Program, and hence currently loaded into computer memory. This option provided the capability to reduce a single data acquisition realization. In other words, this option allowed a single image from each of the camera modules used to acquire velocity data to be reduced.

4.5.2 Pixel Filtering

The data reduction dialog box also provided options to select whether a pixel filter would be applied to the velocity images and to choose the type of pixel filter to be applied. Pixel filtering was used primarily to reduce the effects of laser speckle on the acquired images. It also reduced the effects of small alignment errors between the filtered and reference views of a given image.[92] This was the type of filtering recommended by Robert McKenzie to reduce spatial noise, as discussed in Chapter 1.[93] There were two major types of pixel filters available in the VT DGV Control Program, a low pass filter and a median filter. Both types of filter used an area process called a convolution. In a low-pass filter convolution, the pixels in a predetermined area, referred to as a neighborhood, around a pixel being filtered, including the pixel being filtered, are multiplied by a value from a convolution kernel, essentially a matrix of weighting factors. Next, the sum of the weighted values in the neighborhood is calculated and the intensity value for the pixel being filtered is replaced with this sum. The standard size of the neighborhood and convolution kernel for the low-pass filters incorporated into the VT DGV Control Program was 3 x 3 pixels. The median filters included in the VT DGV Control Program operated by looking at the pixel intensity values for the pixels in the neighborhood of the pixel being filtered and determining what the median pixel intensity value was and assigning that value to the pixel being filtered. The performance of the median filter could be changed by changing the size of the neighborhood used to determine the median pixel intensity value. The neighborhood sizes for the median filter set up within the VT DGV Control Program were 2 x 2, 3 x 3, 4 x 4, and 5 x 5 pixels.[94] The low-pass and median filtering algorithms used in the control program can be found in reference 95. The pixel filter used for reducing data from this research was a low-pass filter with a 3 x 3 pixel neighborhood. All of the weighting values used in this filter were set to 1/9. This filter was chosen because it was the filter recommended by McKenzie.[96]

4.5.3 Laser Frequency Correction and Q-Switch Build Up Time Filtering

The VT DGV data reduction dialog box provided options regarding whether a laser frequency correction would be applied. If a laser frequency correction was to be applied, a reference value for the laser reference transmission ratio and a tolerance were entered in text boxes in the dialog box. The reference value and tolerance were used to filter a sequence of velocity images by rejecting images where the laser reference transmission ratio was outside of the maximum or minimum allowable values. If the laser reference correction was performed as part of the data reduction procedure for average or active images, the reference value and tolerance were not used to filter out images where the laser reference transmission ratio was outside of the maximum and minimum allowable values. In addition to being used to filter out images outside of the desired tolerance, the reference transmission ratio was used to establish a relationship between the laser reference transmission ratio and the transmission ratios measured by the camera modules for the regions of interest where velocity data were acquired. This relationship will be discussed in greater detail later in this chapter. Depending on what image corrections were performed during the reduction of the velocity data, either the laser reference transmission ratio calculated at the end of section 4.4.3 could be directly entered into the data reduction dialog box, (if the white card correction was not being performed), or the laser reference transmission ratio calculated at the end of section 4.4.3 was divided by the average white card ratio, for the laser reference camera module, calculated at the end of section 3.4.4, and the resulting value was entered in the data reduction dialog box. The tolerance value was determined by trial and error. The final tolerance value used in the data reduction procedure was 0.05. It would have been desirable to decrease this tolerance further but problems with the Nd:YAG laser made it necessary to use this value.

An option to filter a sequence of velocity images by rejecting images acquired when the Q-switch build up time voltage was above a user selectable level was also included within the laser frequency correction portion of the data reduction dialog box. The procedure used to determine the cut off point for these Q-switch build up time voltages was to manually look through the laser monitoring file where the average Q-switch build up time and the laser reset condition were recorded for each velocity image acquired. The larger Q-switch build up time voltages and the corresponding reset conditions for these voltages were noted. If the Q-switch build up time voltage was significantly larger than most of the other Q-switch build up time voltages or if there appeared to be a correlation between a larger Q-switch build up time voltage and the laser resetting this was used as the cut off value.

4.5.4 Saving the Reduced Data

The VT DGV data reduction dialog box also included options so the user could determine if and how the reduced data would be saved. If the reduced data was to be saved the user had the option to save the data in ASCII format, otherwise the data would only be saved in binary format. Also, the user could select the file density. The file density determined the spatial resolution of the data contained in the data file. As the file density decreased, the number of data points within the data file also decreased. The user also had the option to save the reduced data in a format that could be used by MATLAB to plot the data. In this format the data were saved in between three and five different data files depending on how many camera modules were used to acquire velocity data. The x coordinate for each data point in the reduced data was contained in one file. The y coordinate for each data point in the reduced data was contained in another file. Finally the velocity data for each camera module was contained in a separate data file. The data reduction dialog box also contained a pair of text boxes which were used to designate the units for the velocities contained in the data file(s) and to enter a scaling factor which could be used to convert the velocity data from the standard units of meters per second into whatever units were desired by the user.

The next option included in the VT DGV data reduction dialog box allowed the dimensions and units for the data area to be entered. This was done by entering the minimum and maximum values for the x and y coordinates in the data area and the data area units. The minimum and maximum values for the x and y coordinates were used to scale the pixels in the reduced data into "real world" units such as meters, feet, or inches. All of the data planes in this research were scaled to units of meters.

4.5.5 Reference Transmission Ratios for the Camera Modules

Finally, the VT DGV data reduction dialog box contained text boxes where a reference transmission ratio for each camera module could be entered. The images acquired of the stationary target just prior to acquiring velocity data images, were used to calculate these reference transmission ratios. As described in sections 3.7 and 3.8, a series of 10 images were acquired of the stationary calibration wheel or a solid white target plate, (depending on whether calibration wheel data or flow data were to be acquired), illuminated by the Nd:YAG laser at the same offset voltage to be used while velocity data images were acquired. Average images calculated from these images were used to calculate the reference transmission ratios entered in the data reduction dialog box. Once the average stationary image from each camera module used to acquire velocity data images was loaded, the image corrections to be applied to the velocity data images as part of the data reduction procedure were applied to the average stationary image from each camera module. If all of the image corrections were to be performed, the corrections were applied as follows. First, the background image was subtracted from the average stationary image. Next, the pixel sensitivity correction was applied to the average stationary image by dividing each pixel in the average stationary image by its pixel sensitivity value. Once the pixel sensitivity correction was applied, the filtered view was vertically mirrored. After the filtered view was mirrored, the reference and filtered views were mapped to their rectangular regions of interest. Next, the pixel filter was applied to the filtered and reference rectangular regions of interest. Finally, the average transmission ratio for the image was calculated and assigned to the reference value, for the camera from which the image was taken, using the "Brightness Levels" menu option in the reduce menu of the VT DGV Control Program. This procedure was repeated for each of the camera modules used to acquire velocity data images. Once all of the needed options had been selected and all of the required values had been entered into the data reduction dialog box, the velocity data reduction procedure could be started.

4.6 Reducing DGV Velocity Data

4.6.1 Laser Reference Transmission Ratio

If the laser frequency correction was to be applied to the velocity images being reduced, the laser reference transmission ratio was calculated before these images were reduced. The first step of this calculation was to load the velocity image(s) from the camera module being used to monitor the laser optical frequency. If a sequence of velocity images was being reduced, the images were loaded and processed one at a time. Once the velocity image was loaded, the image corrections and pixel filter chosen to be applied to the velocity images were applied. The first correction to be applied was the background correction. This correction was applied by subtracting the selected background image for the camera module from the velocity data image. Next, the pixel sensitivity correction was performed by dividing each pixel in the velocity data image by its pixel sensitivity factor. Once the pixel sensitivity correction had been applied, the chosen pixel filter was applied as described in section 4.5.2. After the pixel filter had been applied, the average of the pixel intensities for the pixels inside the laser reference ROI of the reference view was calculated. Next, the average of the pixel intensities for the pixels inside the laser reference ROI of the filtered view was calculated. Next, the white card correction was applied to the average pixel intensity from the filtered view by dividing the average pixel intensity value from the filtered view by the average white card correction ratio for the camera module being used to calculate the laser reference transmission ratio. Once the white card correction had been applied the average value of the pixel intensities in the filtered view, adjusted with the while card correction, was divided by the average value of the pixel intensities in the reference view. This ratio was the laser reference transmission ratio for the image. Figure 4.6 is a chart showing the procedure used to calculate the laser reference transmission ratio. For the average velocity image reduction mode case and the active velocity image reduction mode case this ratio was just saved for later use.

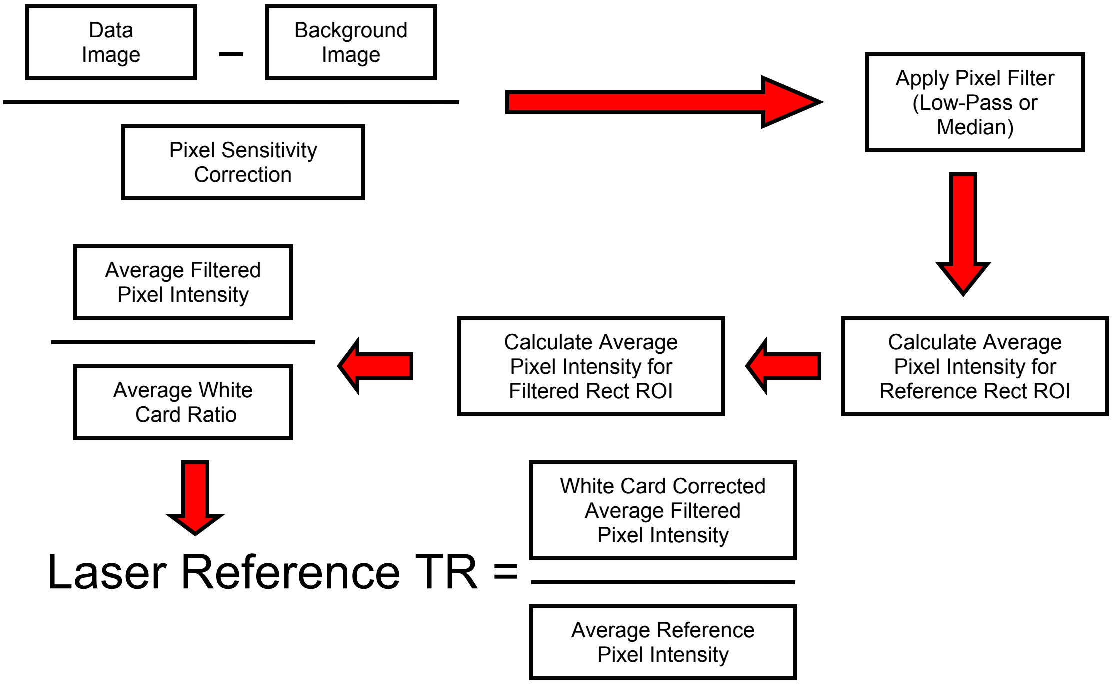


Figure 4.6: Procedure used to calculate laser reference transmission ratio

For the sequence velocity image reduction mode case, the transmission ratio and the Q-switch build up time for the velocity image were evaluated to see if the image would be processed. Once the laser reference transmission ratio for the image had been calculated it was compared to the maximum and minimum allowable values for this transmission ratio calculated from the laser reference transmission ratio and tolerance entered into the data reduction dialog box. If the actual laser reference transmission ratio was outside of the maximum and minimum allowable values the image was skipped during the velocity data reduction procedure. Next, the Q-switch build up time voltage for the image was checked. If the Q-switch build up time voltage was above the maximum value set in the data reduction dialog box the image was skipped during the velocity data reduction procedure. The laser reference transmission ratio for the images that passed the transmission ratio test and the Q-switch build up time voltage test were saved and an average laser reference transmission ratio for these images was calculated for later use.

4.6.2 Calculating Transmission Ratios for the Velocity Data

Once the laser reference transmission ratio(s) had been calculated, the velocity data images were processed and a transmission ratio for each pixel in the filtered and reference rectangular regions of interest was calculated. The procedure used to process the velocity images was very similar to the procedure used to reduce the iodine cell calibration data. All of the velocity images from a given camera module were processed before the images from the next camera module were processed. The procedure used to process a velocity image was as follows. The procedure described below assumes that all of the image corrections were applied and a pixel filter was also applied to the velocity image. As was the case in previous data reduction procedures, the first step was to load the image to be processed into computer memory. Once the image was loaded, the background correction was applied to the image by subtracting the background image, for the particular camera module from which the velocity image was acquired, from the velocity image. Next, the pixel sensitivity correction was performed by dividing each pixel in the velocity image by the corresponding pixel sensitivity factor. Once the background correction and pixel sensitivity corrections had been performed, the filtered view in the velocity image was vertically mirrored so the filtered and reference views were oriented in the same direction. After the filtered view was mirrored, the filtered and reference views were mapped to their respective rectangular regions of interest. Next, the pixel filter selected by the user was applied as described in section 4.5.2. After the pixel filter had been applied the white card correction was performed on the pixels in the filtered region of interest by dividing each pixel in the filtered region of interest by the white card ratio calculated for that particular pixel. Next, each pixel in the filtered rectangular region of interest was divided by its corresponding pixel in the reference rectangular region of interest and the results stored in a computer buffer. For the “Average” reduction mode and the “Active” reduction mode the procedure moved on to the next camera module, but for the “Sequence” reduction mode the above procedure was repeated and the transmission ratios calculated for the next image were added to the transmission ratios calculated for the previous image. The procedure was repeated until all of the images in the sequence, from the camera module being processed, that passed the transmission ratio filter and Q-switch build up time filter, were processed and each pixel buffer location contained the sum of all of the transmission ratios calculated for that particular pixel. After all of the images from a particular camera module had been processed the sum of the transmission ratios for a given pixel in the data area was divided by the number of images processed for the particular camera module, thus calculating an average transmission ratio for the pixel. Figure 4.7 is a chart showing the basic procedure used to process velocity data images to obtain a transmission ratio at each pixel location. An array of transmission ratios was stored in computer memory for each camera module used to acquire velocity images. These arrays were used later in the data reduction procedure to first calculate the change in optical frequency at each pixel location which were then used to calculate the velocity at each pixel location.

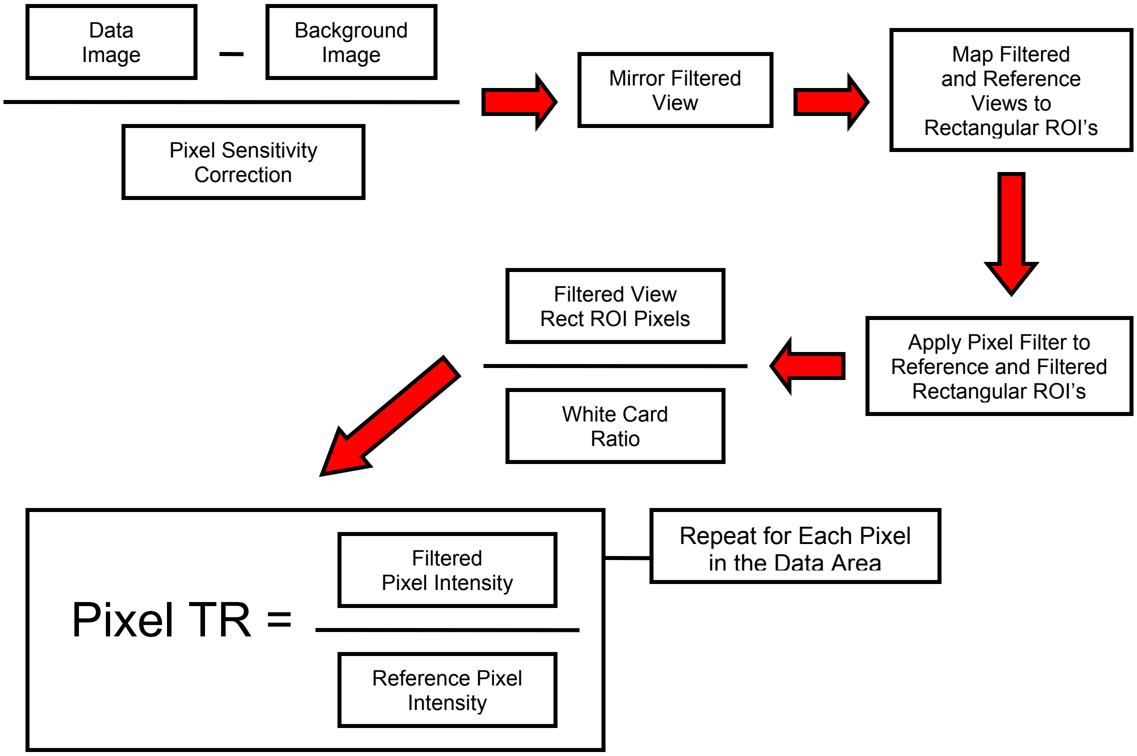


Figure 4.7: Procedure used to calculate transmission ratio for the pixels in the data area.

4.6.3 Converting Transmission Ratio into a Change in Optical Frequency

Once transmission ratios had been calculated for each pixel in the data plane and from each camera module used to acquire velocity images, these transmission ratios could be converted to a change in optical frequency. There were two major paths this conversion could take depending on whether the laser frequency correction option was selected. If this option was not selected, the reference transmission ratio, calculated at the end of section 4.5.5, for the camera module was used to calculate the wave number for the laser pulse before it was shifted through the Doppler effect. The wave number for the laser pulse was calculated by inserting the calculated transmission ratio into the frequency calibration function for the camera module from which the velocity image being reduced was acquired. Next, the function was solved for the wave number. Calculating the wave number in this way would not account for pulse to pulse variations in the optical frequency of each laser pulse.

If the laser frequency correction option was selected, the laser reference transmission ratio, calculated in section 4.6.1, the reference transmission ratio, calculated at the end of section 4.5.5, for each camera module, and the reference value for the laser reference transmission ratio, calculated in section 4.5.3, were used to calculate the wave number of the laser pulse before it was shifted through the Doppler effect. A relationship between the laser reference transmission ratio and the reference transmission ratio for each camera module was needed because even when all of the image corrections were performed on the images from each camera module there were differences in the transmission ratio measured by each camera module for the stationary target plane illuminated by the same laser pulse. This relationship was established by calculating the difference between the reference transmission ratio calculated for each camera module and the reference value of the laser reference transmission ratio. After this relationship was established, the laser reference transmission ratio was added to the difference between the reference transmission ratio calculated for the camera module and the reference value for the laser reference transmission ratio. This value was used to calculate the wave number for the laser pulse before it was shifted through the Doppler effect. The wave number for the laser pulse was calculated by inserting the calculated transmission ratio into the frequency calibration function for the camera module from which the velocity image being reduced was acquired. Next, the function was solved for the wave number.

Once the wave number for the laser pulse was calculated, the wave number for each pixel in the data area was calculated and then the change in optical frequency was calculated. The wave number for each pixel in the data area was calculated by inserting the transmission ratio for the pixel into the frequency calibration function for the camera module from which the velocity image being reduced was acquired and then solving the function for the wave number. Next, the difference between the wave number for the pixel and the wave number of the laser pulse was calculated. This difference was then converted into a change in optical frequency by multiplying the change in wave number by 100 x speed of light (299792458 m/s). Finally, the change in optical frequency was saved in the computer buffer that previously held the transmission ratio for the pixel. The procedure described in this section was repeated for the pixel buffers from each camera module used to acquire velocity images.

4.6.4 Calculating Wave Number

The wave number for the laser pulse must be calculated for use in the governing equation of the DGV technique which will be used to calculate velocities from the change in optical frequency calculated in the previous section. In the previous version of the DGV Control Program the wave number was assumed to be constant. In reality this is not the case since the wave number is a function of the wavelength and wavelength is proportional to the optical frequency of the light emitted by the laser. As was the case in the previous section, the procedure used to calculate the wave number used in the DGV governing equation depended on whether the laser frequency correction was performed. If the laser frequency correction was not performed, the reference transmission ratio, calculated at the end of section 4.5.5, for each of the camera modules used to acquire velocity images was used to calculate the wave number. Each reference transmission ratio was plugged into the frequency calibration function corresponding to the camera module from which the reference transmission ratio was acquired, and the function was solved for the wave number. Next, the average of the wave numbers from the camera modules used to acquire velocity images was calculated and this value was saved and used as the wave number in the governing equation for the DGV technique to solve for velocity. This procedure did not account for pulse to pulse variations in the optical frequency of the laser beam. The only way to account for these variations was to make use of the laser frequency correction.

If the laser frequency correction was performed, the laser reference transmission ratio, calculated in section 4.6.1, the reference transmission ratio, calculated at the end of section 4.5.5, for each camera module, and the reference value for the laser reference transmission ratio, calculated in section 4.5.3, were used to calculate the wave number of the laser pulse before it was shifted through the Doppler effect. The same procedure described in section 4.6.3 was used to calculate the relationship between the reference value of the laser reference transmission ratio and the reference transmission ration for each camera module. Once this was done the laser reference transmission ratio, calculated for the velocity images being reduced, was added to the difference between the reference transmission ratio calculated for the camera module and the reference value for the laser reference transmission ratio. Next, the wave number for the laser pulse was calculated by inserting the calculated transmission ratio into the frequency calibration function for the camera module from which the velocity image being reduced was acquired. Next, the function was solved for the wave number. This procedure was repeated for each of the camera modules used to acquire the velocity images. Once the wave numbers for all of the camera modules used to acquire velocity images had been calculated the average of these wave numbers was calculated and this average wave number was saved and used as the wave number in the governing equation for the DGV technique to solve for velocity.

4.6.5 Calculating Velocity from the Change in Optical Frequency

Once the transmission ratio at each pixel in the data area had been converted into a change in optical frequency, the governing equation for the DGV technique could be used to calculate the velocity at the pixel location. The governing equation for the DGV technique was given in Chapter 1 but for the purpose of this discussion it is rewritten below. The governing equation for the DGV technique is:

$$\Delta\nu = \frac{\nu_o}{c}(\hat{a} - \hat{l}) \cdot \vec{V} \tag{1}$$

where $\Delta\nu = \nu_D - \nu_o$ which is the change in optical frequency of the light reflecting off of the seed particles passing through the laser sheet (ν_D is the optical frequency of the Doppler shifted light and ν_o is the optical frequency of the unshifted incident laser light), c is the speed of light, $\hat{a}$ is the unit vector pointing toward the direction in which the data area is being viewed, $\hat{l}$ is the unit vector pointing in the direction in which the laser light is propagating, and $\vec{V}$ is the velocity vector. In the previous two subsections of this chapter the procedures used to calculate the change in optical frequency, $\Delta\nu$, and the wave number ν_o/c were described. Section 3.5 described the procedure used to calculate the Euler angles for the transformation from the coordinate system reference frame attached to the data plane to the coordinate system reference frame attached to the camera. These Euler angles can be used to calculate, $\hat{a}$, the unit vector pointing toward the direction in which the data area is being viewed. Once this vector has been calculated, all that remains is to determine the vector $\hat{l}$, rearrange governing equation, and solve for the velocity vector $\vec{V}$. The discussion below assumes that all three camera modules are being used and three components of velocity are being calculated. The procedure used to calculate one or two components of velocity follow a similar line of reasoning.

Determining the vectors $\hat{a}$ and $\hat{l}$ will be considered together. The vector $\hat{a}$ is a unit vector pointing from the data plane toward the camera module viewing the data plane. As mentioned above, this vector can be calculated using the Euler angles since the z axis in the coordinate reference frame attached to the camera module points away from the camera toward the data plane. So the $\hat{a}$ vector in the camera module coordinate system is essentially:

$$\{\hat{a}\}_2 = \begin{Bmatrix} 0 \\ 0 \\ -1 \end{Bmatrix}_2 \tag{16}$$

where $\hat{a}_2$ is the $\hat{a}$ vector in the camera module coordinate system. Using the Euler angles calculated in section 3.5, the $\hat{a}$ vector can be transformed into the data plane coordinate system using rotation matrix of the form:

$$T_{12} = \begin{bmatrix} \cos\theta_y \cos\theta_z & \cos\theta_y \sin\theta_z & -\sin\theta_y \\ (\sin\theta_x \sin\theta_y \cos\theta_z - \cos\theta_x \sin\theta_z) & (\sin\theta_x \sin\theta_y \sin\theta_z - \cos\theta_x \cos\theta_z) & \sin\theta_x \cos\theta_y \\ (\cos\theta_x \sin\theta_y \cos\theta_z - \sin\theta_x \sin\theta_z) & (\cos\theta_x \sin\theta_y \sin\theta_z - \sin\theta_x \cos\theta_z) & \cos\theta_x \cos\theta_y \end{bmatrix} \quad (17)$$

The transformed $\hat{a}$ vector is calculated using the following equation:

$$\{\hat{a}\}_1 = T_{12}\{\hat{a}\}_2 \quad (18)$$

After the transformation has been performed the $\hat{a}$ vector in the data plane coordinate system has the form:

$$\{\hat{a}\}_1 = \begin{Bmatrix} \sin\theta_y \\ -\sin\theta_x \cos\theta_y \\ -\cos\theta_x \cos\theta_y \end{Bmatrix}_1 \quad (19)$$

This form of the vector $\hat{a}$ was used to solve for the velocities in the data plane. Each camera module had its own $\hat{a}$ vector since each camera module viewed the data plane from a different location.[85] The vector $\hat{l}$ did not require such a transformation because this vector is generally expressed in the data plane coordinate system. This vector did not vary from camera module to camera module. For the purposes of this discussion, the laser vector is assumed to have the form:

$$\{\hat{l}\}_1 = \begin{Bmatrix} l_x \\ l_y \\ l_z \end{Bmatrix}_1 \quad (20)^{86}$$

Now that the form of the $\hat{a}$ and $\hat{l}$ vectors have been determined, the governing equation for each of the camera modules can be expressed in the following form:

$$\Delta\nu_1 = \frac{\nu_o}{c}\left[\begin{Bmatrix} \sin\theta_{y1} \\ -\sin\theta_{x1} \cos\theta_{y1} \\ -\cos\theta_{x1} \cos\theta_{y1} \end{Bmatrix}_1 - \begin{Bmatrix} l_x \\ l_y \\ l_z \end{Bmatrix}_1\right] \cdot \begin{Bmatrix} V_x \\ V_y \\ V_z \end{Bmatrix}_1 \quad (21)$$

$$\Delta\nu_2 = \frac{\nu_o}{c}\left[\begin{Bmatrix} \sin\theta_{y2} \\ -\sin\theta_{x2}\cos\theta_{y2} \\ -\cos\theta_{x2}\cos\theta_{y2} \end{Bmatrix}_1 - \begin{Bmatrix} l_x \\ l_y \\ l_z \end{Bmatrix}_1\right]\cdot\begin{Bmatrix} V_x \\ V_y \\ V_z \end{Bmatrix}_1 \tag{22}$$

$$\Delta\nu_3 = \frac{\nu_o}{c}\left[\begin{Bmatrix} \sin\theta_{y3} \\ -\sin\theta_{x3}\cos\theta_{y3} \\ -\cos\theta_{x3}\cos\theta_{y3} \end{Bmatrix}_1 - \begin{Bmatrix} l_x \\ l_y \\ l_z \end{Bmatrix}_1\right]\cdot\begin{Bmatrix} V_x \\ V_y \\ V_z \end{Bmatrix}_1 \tag{23}$$

These three equations form a system of three equations in three unknowns. This system of equations can be expressed as follows:

$$\begin{Bmatrix} \Delta\nu_1 \\ \Delta\nu_2 \\ \Delta\nu_3 \end{Bmatrix} = \frac{\nu_o}{c}\begin{bmatrix} \sin\theta_{y1} - l_x & -\sin\theta_{x1}\cos\theta_{y1} - l_y & -\cos\theta_{x1}\cos\theta_{y1} - l_y \\ \sin\theta_{y2} - l_x & -\sin\theta_{x2}\cos\theta_{y2} - l_y & -\cos\theta_{x2}\cos\theta_{y2} - l_y \\ \sin\theta_{y3} - l_x & -\sin\theta_{x3}\cos\theta_{y3} - l_y & -\cos\theta_{x3}\cos\theta_{y3} - l_y \end{bmatrix}\cdot\begin{Bmatrix} V_x \\ V_y \\ V_z \end{Bmatrix}_1 \tag*{(24)[87]}$$

A system of equations of the form:

$$\{b\} = A\{x\} \tag{25}$$

where $\{b\}$ is a vector of results, A is a matrix of coefficients, and $\{x\}$ is a vector of unknowns can be solved for $\{x\}$ in the following manner:

$$\{x\} = A^{-1}\{b\} \tag{26}$$

where A^{-1} is the inverse matrix of A. The system of equations shown in equation 24 can be placed into the same form as equation 25 and thus solved using equation 26. All that is needed is to calculate the inverse matrix of A. Consider a three by three matrix of the form:

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \tag{27}$$

The first step in calculating the inverse of A is to calculate the determinate of A. The determinate of A is calculated as follows:

$$\det A = a_{11}(a_{22}a_{33} - a_{32}a_{23}) - a_{12}(a_{21}a_{33} - a_{31}a_{23}) + a_{13}(a_{21}a_{32} - a_{31}a_{22}) \tag{28}$$

Next the value for each term in the inverse matrix can be calculated as follows:

$$a_{11}^{-1} = \frac{1}{\det A}\left(a_{22}a_{33} - a_{32}a_{23}\right) \tag{29}$$

$$a_{21}^{-1} = \frac{1}{\det A}\left(-a_{21}a_{33} + a_{31}a_{23}\right) \tag{30}$$

$$a_{31}^{-1} = \frac{1}{\det A}\left(a_{21}a_{32} - a_{31}a_{22}\right) \tag{31}$$

$$a_{12}^{-1} = \frac{1}{\det A}\left(-a_{12}a_{33} + a_{32}a_{13}\right) \tag{32}$$

$$a_{22}^{-1} = \frac{1}{\det A}\left(a_{11}a_{33} - a_{31}a_{13}\right) \tag{33}$$

$$a_{23}^{-1} = \frac{1}{\det A}\left(-a_{11}a_{32} + a_{31}a_{12}\right) \tag{34}$$

$$a_{13}^{-1} = \frac{1}{\det A}\left(a_{12}a_{23} - a_{22}a_{13}\right) \tag{35}$$

$$a_{23}^{-1} = \frac{1}{\det A}\left(-a_{11}a_{23} + a_{21}a_{13}\right) \tag{36}$$

$$a_{33}^{-1} = \frac{1}{\det A}\left(a_{11}a_{22} - a_{21}a_{12}\right) \tag{37}$$ [88]

Now that the inverse matrix has been calculated the system of equations shown in equation 24 can be solved. The matrix A and the inverse matrix A^{-1} were only calculated once during the data reduction procedure since the values in these matrices did not change. The values in the inverse matrix A^{-1} were used to solve a system of equations, in the form shown in equation 26, for the V_x, V_y, and V_z velocity components at each pixel location in the data area.

The data reduction algorithm in the VT DGV Control Program also provided the capability to calculate the velocity at each pixel value in the data plane in the “natural” coordinate system for the camera module. For this coordinate system, $(\hat{a}-\hat{l})=1$, so:

$$V_1 = \Delta \nu_1 \frac{c}{\nu_o} \tag{38}$$

$$V_2 = \Delta \nu_2 \frac{c}{\nu_o} \tag{39}$$

$$V_3 = \Delta \nu_3 \frac{c}{\nu_o} \tag{40}$$

These equations would be solved at each pixel location in the data plane and for each camera module used to acquire velocity images.