

Chapter 5 : Hardware Problems

5.1 VT DGV System Performance

The purpose of this chapter is to discuss some of the hardware problems encountered in the history of the VT DGV system and, in particular, the hardware problems encountered during this research. The reason this chapter is included in this report is because the hardware problems encountered with the VT DGV system were extensive and ultimately led to less than desirable results being obtained by the system when the velocity images were acquired and reduced. Two major hardware problems have plagued the VT DGV system since the first full tests of the system were performed in September-October 2000. These problems are with the Nd:YAG laser and with the 16-bit digital cameras. The Nd:YAG laser has proven to be an unreliable light source for the system. The laser has had optical frequency locking problems since the test of the system performed in 2000. Another problem that has plagued the system is a lack of reliability in the 16-bit digital cameras used by the system. The cameras have had problems with ice crystals forming on the imaging surface, problems with image quality degrading over time, and problems with insufficient cooling for the CCD array in the camera head. In addition to these two problems a problem with the camera modules moving over time while DGV data images were being acquired was detected. When the VT DGV system operates trouble free, the potential of the system becomes obvious, but unfortunately these moments of trouble free operation have been few and far between.

5.2 Nd:YAG Laser

Problems with the Nd:YAG laser were the primary reason why both the VT DGV system tests in 2000 and the tests discussed in this research stopped short of success. The success of the system depends on its capability to measure changes in optical frequency through changes in the transmission ratio calculated from images acquired by the camera modules. Within this constraint, the laser needs to provide a stable source of light for the camera modules to acquire. If the optical frequency of the laser pulses emitted by the laser suffer from large drifts or jumps away from the optical frequency specified by the user, the images acquired by the system will not provide usable data that can be reduced. Also, if the laser cannot regularly fire laser pulses containing the narrow band of optical frequencies needed by the system to calculate the changes in optical frequency due to the Doppler effect, the images acquired by the system will not provide usable data that can be reduced. With this having been said, the stability of the Nd:YAG laser is critical to the performance of the DGV system, and because of this, a great deal of time was spent trying to understand the possible causes of degradation in the performance of the Nd:YAG laser.

5.2.1 Initial Problems

Troy Jones discussed in his M.S. Thesis some of the problems encountered with the Nd:YAG laser during the system tests performed in September-October 2000.⁹⁷ The primary problem encountered with the laser was that toward the end of these tests the laser fired multi-mode pulses more often than it fired usable pulses. A multi-mode pulse is a laser pulse containing a wide range of optical frequencies compared to the normal narrow band of optical frequencies contained in a properly seeded laser pulse. Data images acquired when the data area was illuminated by a multi-mode pulse were unusable because the Doppler shift in the optical frequency of the reflected light was overpowered by the variations in the optical frequency of the unshifted multi-mode laser pulse. Attempts were made to improve the performance of the laser at Virginia Tech, but when no significant improvement occurred the decision was made to send the laser back to the manufacturer for repairs and refurbishment.⁹⁸

5.2.2 Laser Damage

The repairs conducted at Spectra-Physics required roughly 6 months before the laser was ready to be shipped back to Virginia Tech. The laser was thoroughly cleaned, defective parts were replaced, and a factory quality alignment and checkout of the laser was performed before the laser was shipped back to Virginia Tech. When the shipping crates containing the laser arrived, they were damaged. Upon opening the crates it became apparent that whatever damaged the crates also

damaged the outer case of the laser head. Further investigation by a repair technician from Spectra-Physics revealed no apparent damage to the components inside the laser head, but the laser was in need of realignment. Another two months and three service visits passed before the laser was realigned and the performance of the laser was verified. Once the laser was realigned and the proper performance of the laser was verified by researchers at Virginia Tech and the repair technician from Spectra-Physics, the laser was integrated back into the VT DGV system and it was used for preliminary tests of the new laser optics purchased for use with the Nd:YAG laser. It should be noted, however, that it is possible that the damage to this laser could possibly have caused some or all of the problems that occurred with the Nd:YAG laser during the research discussed in this report.

5.2.3 Problems with Iodine Cell Calibrations

The first iodine cell calibrations performed with the Nd:YAG laser, after it returned from the factory, occurred in early July 2002. These initial iodine cell calibrations were used to evaluate the performance of the Nd:YAG laser as well as trying to locate iodine absorption features that could be used for acquiring velocity images. These calibrations also gave the user the opportunity to gain some experience in operating the VT DGV system. The quality of the first 5 calibrations performed in the first two days of testing was very encouraging. None of the acquired images in these first calibrations appeared to contain an image acquired while the laser was in a reset condition or an image acquired while a multi-mode pulse was being fired. Over the course of two iodine cell calibrations acquired on the third day of testing all of this changed. These calibrations showed a sudden degradation in the performance of the Nd:YAG laser. For example, the Q-switch build up time voltage for the images acquired during the first five calibrations was around 1.9 volts. By the end of the third day of testing, this voltage was up to around 2.9 volts. There was no obvious reason for this sudden change in laser performance. The offset voltage range where these calibrations were acquired was in the same general area where the first five calibrations were performed. No changes had been made to the laser or to the other equipment used in the room where these tests were being performed.

5.2.4 Attempts to Improve Laser Performance

The first attempt that was made to diagnose and fix the problems with the sudden degradation in laser performance was to make a small adjustment to the mirrors in the laser head that steered the seed laser beam into the host laser cavity. This caused the Q-switch build up time voltage to decrease slightly but the best reduction that could be achieved was from a voltage of roughly 2.9 volts to a voltage of roughly 2.6 volts. While this improved the Q-switch build up time voltage the laser

continued to perform poorly and a usable iodine cell calibration could not be acquired. At this point some additional diagnostic equipment was brought in. A 500 MHz oscilloscope, a photodetector, and a chart recorder were brought in to attempt to diagnose the problem with the laser further. The oscilloscope and the photodetector were used together to “look” at the quality of the laser pulses produced by the laser. The chart recorder was used to monitor the variations in the Q-switch build up time voltage and the Piezoelectric voltage outputs from the control panel of the seed laser. It was soon learned that when the Nd:YAG laser was performing well, the shape of the trace on the oscilloscope would remain nearly constant from pulse to pulse. If the laser was not performing well, the shape of the trace on the oscilloscope would vary considerably from pulse to pulse. When the laser was performing correctly, the Piezoelectric voltage measured by the chart recorder would oscillate around a specific voltage and this voltage would slowly change with time until the Piezoelectric voltage came within 0.5 volts of the maximum allowable value. At this point the laser would reset. After the laser had run for roughly 30 minutes this voltage changed so gradually that the laser could run for hours without approaching the 0.5 volt tolerance to the maximum Piezoelectric voltage, when the laser was performing correctly. When the chart recorder was connected to the Piezoelectric voltage output from the seed laser control panel, this voltage varied wildly indicating that the laser was resetting very frequently, roughly every 10 to 20 seconds.

The next attempt to fix the problem with the performance of the laser was to replace the coaxial cable connecting the data acquisition card to the Q-switch build up time output on the seed laser control panel. During attempts to diagnose the problem with the laser, the performance of the laser appeared to significantly improve when the original cable was disconnected from the laser. An important fact to note here is that the cables used to connect the laser reset condition, Q-switch build up time, and laser offset voltage input were special high impedance cables. The impedance in these cables was significantly higher than the impedance in the other coaxial cables used in the VT DGV System. These cables were specially made after stability problems occurred with the Nd:YAG laser during Troy Jones’ research. These stability problems were traced back to the lower impedance coaxial cables connecting the Nd:YAG laser to the DGV control computer. A new cable for the Q-switch build up time was made and installed between the data acquisition card and the seed laser control panel. While this change did improve the performance of the laser, reduced the Q-switch build up time to roughly 2.4 volts, and caused frequency with which the laser reset to decrease considerably, the laser performance was still not as reliable as desired. Also during this time it was thought that the control cable between the laser power supply and one of the serial ports on the DGV control computer might have a loose connection so this cable was replaced with a new control cable.

Next, some of the settings on the seed laser were adjusted to try to improve the laser performance. The procedure used to adjust these settings was found in the Spectra-Physics Model 6300 and Model 6350 Instruction Manual.⁹⁹ This was the operation manual for the seed laser inside the Nd:YAG laser. The procedures that were tried were to adjust the frequency overlap of the laser and the procedure to optimize the adjustment of the trim settings. The procedures did not appear to significantly improve the performance of the laser.

At this point it was observed that the laser would frequently reset when the heater in one of the temperature controllers used to control the temperature of the iodine cells turned on. This observation was curious because the temperature controllers were in no way connected to the laser or the DGV control computer used to control the laser and monitor the performance of the laser. It was determined that there must be some RF signal being emitted by the controller and amplified through the cables between the temperature controllers and the camera modules that housed the iodine cells. This RF signal was reduced by placing ferrite toroidal cores on each end of the cable.

5.2.5 Spectra Physics Service Calls

While much was learned from all of these attempts and the performance of the laser did significantly improve after all of these changes were made, the performance of the laser was still erratic. The performance of the laser fluctuated from day to day. So, a service call was placed with Spectra-Physics. During the service call the flash lamp optics were cleaned and the laser was realigned. During this alignment the service technician noticed that the laser would drift out of frequency lock and begin to fire multi-mode pulses. The technician believed that either the Marx Bank or the Piezo driver in the laser was going bad and this was what caused the sudden change in laser performance. The Marx Bank essentially controlled the frequency output of the seed laser. The Piezo driver was essentially a motor that adjusted the position of the high reflector at the back end of the host laser. Another service call was scheduled because the Marx Bank and the Piezo driver needed to be ordered from Spectra-Physics. This second service call was made about three weeks after the first call. It was determined that the Piezo driver was what caused the erratic laser performance. The driver was replaced and the laser was realigned and tuned. Within days of this second service call the laser performance degraded back to where it was before the first call so the repair technician returned again and determined that one of the connectors to the new Piezo driver was defective so the driver was replaced with a new driver. The technician also suggested that the harmonic generator crystal inside the harmonic generator should be adjusted regularly to maintain

maximum power output for the green beam emitted by the laser.¹⁰⁰ While the equipment needed to measure the power output directly was not available while the Nd:YAG laser was being used as part of the VT DGV system, the change in power could be measured indirectly by observing the change in the signal from the photodetector and oscilloscope.

5.2.6 Laser Problems Continue

After the third service call from Spectra-Physics, the VT DGV system was set up in the Virginia Tech Stability Wind Tunnel and prepared to acquire calibration wheel data and flow field data in the wake of a 6:1 prolate spheroid model. While iodine cell calibrations were being acquired, another problem with the Nd:YAG laser was detected. The laser began to have problems with resetting frequently and firing multi-mode pulses. The procedures to adjust the frequency overlap of the laser and to optimize the adjustment of the trim settings, described in the Spectra-Physics Model 6300 and Model 6350 Instruction Manual, were performed again to try to fix these problems.¹⁰¹ These procedures were more successful than when they were tried previously.

Unfortunately, another problem was discovered shortly after these problems were fixed. This problem revealed itself through the iodine cell absorption profiles inexplicably moving up to 2 volts between iodine cell calibrations. The first attempt to deal with this problem was to let the laser fire continuously for an hour or more before attempting to acquire iodine cell calibration data. This was done because a paper from James Meyers, Joseph Lee and Richard Schwartz at NASA's Langley Research Center suggested that the optical frequency variations within a pulse from a Nd:YAG laser decreased as the laser warmed up over several hours.¹⁰² While this did appear to help the laser performance some, the problems with large shifts in the optical frequency of the laser remained. Next, the temperature of the cooling water in the internal cooling system for the laser was monitored. Repair technicians from Spectra-Physics suggested that the problem with the optical frequency changing with time may be related to changes in the cooling water temperature. Once the laser had warmed up for roughly one hour, the water temperature was roughly 86.5° F and remained within a range of $\pm 0.5^\circ$ F over a 6 hour period. According to the repair technician from Spectra-Physics, the cooling water temperature was supposed to be roughly 100° F.¹⁰³ A fan blowing air through a radiator and a temperature sensor in the water reservoir in the power supply of the laser were connected to a control system that was supposed to vary the fan speed to maintain the water temperature at this specified value. A strobotac was used to monitor the speed of the fan to see if the fan speed changed. The fan speed remained constant the entire time the fan speed was monitored.

This suggested that part of this control system was malfunctioning. Unfortunately, this was not realized until very late in the wind tunnel entry and while every effort was made to get a new temperature sensor and control system for the cooling system, the shipment of these parts was delayed and the parts were not received until after the system had been removed from the wind tunnel. After the tunnel entry, the temperature sensor and the control system were replaced and the proper operation of the fan system used to control the water temperature was verified, but the problems with large shifts in the optical frequency of the laser continued.

A problem with the interaction between the Nd:YAG laser and the calibration wheel system was also detected when the images acquired of the rotating calibration wheel were reduced. Over half of these images were acquired while the laser was in a reset condition. There was only one image acquired while the laser was reset in the iodine cell calibration performed just prior to acquiring the calibration wheel images. The most likely cause of the frequent resets during the acquisition of the calibration images was that the calibration wheel was emitting an RF signal of some type that disrupted the performance of the Nd:YAG laser. This problem along with the problem of the optical frequency shifting will have to be investigated further in the future.

The problems with the Nd:YAG laser described above indicate that work needs to be performed to gain a better understanding of how variations in operating conditions where the laser is used affect the performance of the laser. Other researchers have also indicated the importance of operating conditions on the performance of the Nd:YAG laser but most of these reports discuss this in the context of placing the laser in an area where the temperature varies up to 30 degrees and in an area where the laser is directly exposed to air moving through a wind tunnel.¹⁰⁴ It appears from experience gained in this research that temperature and pressure variations much smaller than those discussed previously in literature can have a profound effect on the performance of the Nd:YAG laser. Minimizing these variations should improve the reliability of the Nd:YAG laser performance. Other considerations to possibly improve the performance of the Nd:YAG laser include reducing possible sources of RF signals and reducing exposure to vibration since previous experience indicates both of these factors can have a profound effect on the performance of the laser.

5.3 16-Bit Digital Cameras

Several problems have occurred with the 16-bit cameras used in the VT DGV system. While these problems have not prevented data images from being acquired, they have complicated the procedure used to acquire correction and data images, and potentially reduced the quality of the data

acquired with the VT DGV system. The first problem encountered with one of the 16-bit cameras was when the camera in camera module 3 began to form ice on the CCD array after the camera had been on for roughly one hour. This problem occurred during the research conducted by Troy Jones. The camera was returned to the manufacturer, Spectra-Source, where it was repaired and returned to Virginia Tech. Shortly thereafter, Spectra-Source was bought by another company who decided not to provide support for Spectra-Source's cameras. During the tests of the VT DGV system performed in September and October 2000, another 16-bit camera began to malfunction. The quality of the images acquired by this camera began to degrade after the camera had been on for roughly 10 minutes.¹⁰⁵ This camera was also manufactured by Spectra-Source, and since the camera could not be serviced, it was replaced with a Roper Scientific VersArray 16-bit camera with the same type of CCD array contained in the other two 16-bit cameras in the VT DGV system.

5.3.1 Problems with Camera 3

Shortly after testing for the research discussed in this report began, the Spectra-Source camera that had previously had problems with ice crystals forming on the CCD array started to have problems with ice crystals forming on the CCD array again. Since repairing this camera was not an option, and since money was not available to replace this camera with a new camera, the procedures used to acquire images with the VT DGV system were adapted so the system could be run until ice crystals began to form on the CCD array of this camera. The system could be run for roughly one hour and then the cameras had to be turned off for roughly 30 minutes so the ice crystals would melt. The result of this solution was that it took 12 hours or more to acquire correction images, iodine cell calibrations and velocity data in a single day. Combining this problem with the problems with the Nd:YAG laser meant that a large number of very time consuming iodine cell calibrations were required before calibration wheel or flow field data could be acquired. In addition to the icing problem with this camera, the shutter on this camera began to occasionally stick during image acquisition. This caused a portion of the captured image to be over exposed. Also, the absorption profiles, acquired during tests of the VT DGV system in the Virginia Tech Stability Wind Tunnel, by this camera module, were significantly different from the absorption profiles acquired by the other two camera modules. It is possible that the difference in these absorption profiles could have been caused by a malfunction in this camera.

5.3.2 Problems with Camera 1

In addition to the problem described above, the other remaining Spectra-Source camera started to have problems maintaining the operating temperature needed by the CCD array to operate

properly. This problem appeared toward the end of the wind tunnel entry and there was no immediate effect from this problem detected during these tests. The image quality from this camera appeared to be as good as that of the new Roper Scientific camera, so the Spectra-Source camera continued to be used to the end of the wind tunnel tests. This problem could however prove significant in the future.

5.3.3 Camera Module Movement

As preparations for conducting the first set of preliminary tests of the improved DGV system progressed it became apparent that there was a problem with the camera modules moving on their tripods while data was being taken. This movement translated to a shift in the image acquired of more than 3.18 mm (1/8 inch) over the course of 3 hours. This problem could potentially cause serious problems during DGV data reduction. Images, acquired over several hours, could not be averaged since the warp points used to map the filtered and reference views to their rectangular regions of interest would have moved over the time during which the images were acquired. Over two months were spent trying to diagnose and cure this problem. The tests performed indicated that the tripods were most likely the largest contributor to this problem so the tripods were checked to make sure there wasn't something loose on them. Steps were taken to make sure the feet on the tripod were not moving or that vibration was causing the problem. Tests were also performed to see if air currents were causing the problem. The camera modules were also checked to make sure nothing was loose inside the modules. Once all of these items were checked, a set of camera module supports were designed and constructed. Unfortunately these supports did not entirely eliminate this problem but they have provided some help in stabilizing the camera modules and have reduced the magnitude of the image shifts by roughly $\frac{1}{3}$. The most likely cause of this phenomenon is either the cooling fans in the cameras are causing a slight torque in the tripod/camera support system or thermal expansion inside the cameras is causing the camera to move slightly. The solution used was to track the movement of the camera modules by acquiring dot grid images at regular intervals (roughly every 30 minutes) and adjusting the points used to map the reference and filtered views to their rectangular ROI's as the modules moved. A future solution may be to turn the cameras on and let them sit for an hour and a half to two hours before acquiring images since it appears that the images will move only so far and then will stabilize. This solution wasn't used is because of the problems with the Spectra-Source camera that formed ice crystals on the CCD array.