Remotely Operated Vehicle and Unmanned Surface Vessel Cooperation in Maritime and Port Environments

Prepared for the MSC Summer Research Institute at Stevens Institute of Technology

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ABSTRACT

This summer research project aimed to achieve several distinct goals. The principal goal was to transform the body of an Unmanned Surface Vessel (USV), specifically a Wave Adaptive Modular Vessel (WAM-V), into an autonomous mothership for a Remotely Operated Vehicle (ROV), the VideoRay Pro 4. Another challenge addressed by the research team was finding a way to permanently mount an acoustic Doppler Velocity Log (DVL) to the VideoRay without significantly hindering the VideoRay’s performance. Lastly, the team was tasked with understanding how the DVL recorded data, and how that data could be used to determine location. The Maritime Security Center Summer Research Institute ROV team, located at Stevens Institute of Technology, conducted eight weeks of research to find solutions to these unique challenges.

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"The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Department of Homeland Security."
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I. INTRODUCTION

This research team’s focus was on the inspection of maritime structures using autonomous surface and subsea vehicles. A class of robot that may add new dimensions to this focus is the Remotely Operated Vehicle (ROV); if ROVs are made autonomous, these dimensions may be further expanded. Underwater ROVs, like the VideoRay, allow personnel to inspect underwater objects without putting a diver in the water. Some ports already use ROVs for this function. Unfortunately, ROVs still have limitations with regards to human operation, adaptability, and data collection. This Maritime Security Center research group, in collaboration with the Stevens Institute of Technology Robust Field Autonomy Laboratory (RFAL), aimed to overcome these challenges with autonomous integration. Autonomous maritime devices provide several important benefits to inspectors and operators, including:

1. Force multiplication with field autonomy;
2. Increased safety and situational awareness;
3. Further reachability.

Field autonomy allows the inspection of foreign objects to be evaluated without concurrent supervision of a human operator, thereby improving overall workforce efficiency and allocation of labor. A maritime environment in which the ROV is operating may often be hazardous for a number of reasons, including the natural volatility of weather over large bodies of water, the ambiguity of a foreign object, or overcrowding of a port’s underwater infrastructure. In other words, safety is a vital reason not to include a human diver in underwater inspection. Additionally, an underwater ROV, especially if it surveys the field autonomously, will provide the operator with enhanced situational awareness. Autonomous vehicles that continuously chart the field without exploiting any labor will provide real-time updates and logs of operation and, more importantly, of an inspection. For the last point, in view of its limited range, a remotely operated vehicle such as the VideoRay would benefit from cooperative autonomous integration with an unmanned surface vessel. Maritime inspection vehicles may be developed to perform as autonomous assets by including sensors such as an acoustic Doppler Velocity Log for advanced station-keeping ability so that the vehicle becomes more adaptable to its location and expands its reachability to an object of interest; since limited distance becomes less of an issue.

Currently, there are no organizations that use the WAM-V in conjunction with the VideoRay to inspect maritime structures. There will always be a need to inspect maritime structures whether it be a ship’s hull, an eroding pier, or an aid to navigation. If autonomous vehicles conduct these inspections, then groups like the Department of Homeland Security (DHS) and the United States Coast Guard (USCG) can maximize resource allocation, multiply their workforce, and increase employee safety.
II. METHODOLOGY

The ROV research group—part of the Maritime Security Center’s Summer Research Institute, 2017—separated into three distinct subgroups according to each member’s educational background. Topics for each subgroup included a USV analysis, a ROV mechanical analysis, and a ROV software analysis. Together, the research group focused on how to optimally equip the USV with the ROV while maintaining station-keeping ability.

A. Unmanned Surface Vessel (USV) Analysis

To begin research on the WAM-V, the team first needed to understand how it was assembled. This process was completed in the ABS lab with the help of a YouTube video demonstrating assembly of the WAM-V (AUVSI Foundation, 2013). See Figure 1 below for components of full assembly.

![Figure 1: Assembled WAM-V](image)

The first step of assembly was to inflate the hull assemblies. Each hull assembly has two inflation chambers; a foot pump was included in the shipment. The hull assemblies were placed approximately two meters apart with the hull assembly labeled port on the left and the hull assembly labeled starboard on the right. The back arch was then attached to both hull assemblies using the locking pins. It is important to lean the back arch onto blocks designed to prevent the arch from rotating to 90 degrees from the vertical. Next, the front arch was attached to the front joints on each hull assembly using the pins; the front arch was leaned forward. Then the table was attached first to the front arch using the ball joint, then to the back arch. The back arch was separated in order to attach to the table. Once the table was locked into place, the engine pods were attached. The engine pods are also labeled port and starboard, and were attached using the locking mechanism on the back of the hull assemblies. A full check of all the pins was conducted to ensure that all the safety cords were attached and everything would stay secured. In order to disassemble the WAM-V, all the assembly steps were followed in reverse order.
Assembly and disassembly was completed several times within the first week. One problem that was encountered within the first week was keeping the hull assemblies stable during inflation. This problem was fixed by creating wooden blocks from the WAM-V shipping crate. Once the team gained an understanding of the physical dimensions of the WAM-V in a static environment on land, the next step was to see how it operated in the water.

The team brought the parts of the WAM-V to the De Baun Aquatic Center pool at Stevens Institute of Technology. The team proceeded to assemble the WAM-V on the pool deck, and then deployed it into the pool. Deployment of the WAM-V took 6 people. For approximately 30 minutes, the team carried out various stability tests. Weights, combining a total of 85 pounds, were placed in different configurations atop the WAM-V payload tray. The WAM-V was tested with all 85 pounds fully forward on the payload tray, as well as fully aft. When the weights were on top of the payload tray, team members applied force to different sections of the WAM-V like the port and starboard hull assembly steps, the front arch, and the back arch. Observations regarding the suspension system, draft, payload tray stability, and hull assembly movement were made.

The last task performed by the USV team was to create a power consumption table. This was done on an Excel spreadsheet. First, the power consumption of the planned equipment was found. Then, it was determined that there would be two primary modes in which the WAM-V operates. The first mode was called scanning, and the second inspection. The scanning mode is defined as the WAM-V operating at 10 knots going back and forth over a designated area. The VideoRay would not be operating during this mode and was not accounted for in power consumption. The inspection mode is defined as the WAM-V operating at 2.5 knots and then becoming stationary while the VideoRay carries out an inspection of a maritime structure. The final mode created was a possible mission involving distance to station at 10 knots and time on station at 2.5 knots. The power consumption data is found in Appendix A.

B. Remotely Operated Vehicle (ROV) Mechanical Analysis

The first objective for development of the VideoRay was to design a mount attaching the Doppler Velocity Log (DVL) to the VideoRay. There were several components necessary to consider in the design, including a stress relief cord on the tether, the VideoRay skids, and the DVL power cord. First, to reduce the tension on the tether line during recovery of the VideoRay, there are two small cords that attach to the base of the VideoRay. Only one cord was attached in the preliminary design, so a solution was necessary to permanently fasten the second cord. Additionally, the VideoRay is typically assembled with skids holding lightweight, removable weights for adjusting the VideoRay’s buoyancy. Not only must the skids be incorporated into the design it is also necessary for the skids to open for simple removal or addition of the
small weights. Last to consider was the power cord for the DVL, which is inconveniently long and could potentially cause interference with the propellers and hydrodynamic motion of the VideoRay.

After designing several concepts for a mount in SolidWorks, a 3-D solid modelling program, the design team selected the most economically efficient and mechanically robust design. A bill of materials was then finalized and selected primarily from McMaster-Carr (mcmaster.com, 2017), an online hardware store. Several other suppliers were located for materials and hardware either not offered by McMaster-Carr or that were more economically feasible, including Amazon (amazon.com, 2017) and Clearwater Composites (clearwatercomposites.com, 2017). The chosen suppliers were then checked in the Stevens Institute of Technology online purchasing database for safety and trust verification.

The DVL mount was fabricated at the Stevens Institute of Technology Pond House, where accurately drawn dimensions were provided by the research team and handed to an experienced engineer and manufacturer working for the Maritime Security Center. The process required several cuts, threaded holes, and countersunk holes for several types of material and screws. See Figure 2 below for a photo of the machine required for making screw holes and countersinks.

To account for small misalignments, it was necessary for the design team to drill several holes slightly larger than originally measured; see Figures 3 and 4 above.

C. Remotely Operated Vehicle (ROV) Software Analysis

To begin research on this project, the first step for the software team was to learn the coding languages used by previous developers. This included exposure to the Robotic Operating System (ROS) Platform, as well as MATLAB and C++ to a lesser degree. ROS is used to assist in communication between various systems
in the VideoRay, C++ in developing the commands and procedures that the VideoRay uses while performing its work, and MATLAB in data analysis.

The main focus of the software team was the inclusion of a DVL sensor in the VideoRay's Position Management System. The DVL operates using the principles of the Doppler Effect; it sends out pings that return from objects in the water, then, by measuring the frequency shift of these pings, the DVL is able to record velocities in a three-dimensional plane (The Physics Classroom, n.d.). Next, the team had to test the DVL to ensure the data it was recording was accurate. Through this data it was found that the DVL was experiencing sensor drift. This is where sensors continue to move, or drift, from the baseline position while being used, causing inaccurate results. Other tests were created to confirm this drift, they consisted of moving the DVL in set patterns along set distances, such as straight lines and squares, in addition to being held completely still. The data was then transformed to an inertial (non-moving) plane using the 3-2-1 Aerospace Standard found in Appendix B and then integrated to track position rather than velocity (Weisstein, n.d.a). This transform was necessary to account for the velocity data of the DVL because the velocities in the data were relative to the DVL body, so, the data did not represent orientation changes of the DVL prior to the transformation. Integration is necessary to mathematically convert between velocity and position.

Next, the team got in contact with a quality assurance representative from Rowe Technologies, the manufacturer of the DVL. Working through email, the DVL was configured for shallower water as originally it was intended for much deeper bodies of water than the current scope of this project. After this the next step was to do testing outside, in the Hudson river from the Stevens Pier. These tests returned very different results from the original tests in the tank at Stevens, for a variety of reasons. As the tank is made of reflective concrete and has very clean water, it was not ideal for DVL and may be contributing to the drift. For all these tests, data from the DVL was collected and plotted in MATLAB, using several techniques, the most accurate one tending to be the 4th order integration found in Appendix B (Newton-Cotes Equations, Boole’s Rule) from data filtered using a moving average filter with window size of seven (Weisstein, n.d.bc).

**III. RESULTS**

This research group focused on how to optimally equip the USV WAM-V with the ROV VideoRay while maintaining station-keeping ability and waypoint mapping with the Doppler Velocity Log. To do this, the following categories were addressed.
A. Doppler Velocity Log Sensor Evaluation
After evaluating the DVL sensor it was found that it is indeed capable of station keeping. The sensor was found to be most precise and accurate in open water where it effectively read no position change when it was not being moved, a necessity for the position manager keeping station. It was also concluded that the data from the DVL is much less reliable when it is moving at speed in open water. However, if this data is utilized in a Simultaneous Location and Mapping (SLaM) algorithm it should still be of a high enough resolution to be reliable. The project’s advisor Prof. Englot is hoping to integrate a SLaM algorithm as the next step in this project, with the DVL returning location data and a sonar system mapping the surroundings. Attached in Appendix C is an image displaying the drift found in the testing tank, in this test the ROV was held still in the water, but the DVL reported it moving consistently in one direction. In Appendix D results are plotted from the open water test where it was held as still as the water allowed; in this test, the DVL reported very small amounts of movement consistent with what was observed after being filtered. Graphs of the raw and filtered data are also included. Finally; Appendix E displays the outcome of a test where the ROV was released from the pier and the current carried it a distance. In these three Appendices, there is data that has been transformed and data that has been transformed and filtered, to display the difference between the two.

B. Doppler Velocity Log Integration with VideoRay
To improve maritime mapping, monitoring, and inspection, the laboratory’s Doppler Velocity Log sensor was to be paired with the lab’s VideoRay ROV using the designed mount, as discussed in methodology, section B. Materials and hardware were selected to be resistant to saltwater corrosion and have a tensile strength that would bear the load of the ten-pound DVL. Pictured in Figures 5 and 6 below, selected materials include 3/8-in. thick Delrin acetal plastic base, 1/8-in. thick carbon fiber side panels, and several screw types depending on their mating requirements—a flat head screw for countersinks into carbon fiber, and two sizes of round head screws for mating with the VideoRay and the DVL.
After assembling the mount and adjusting any misalignments, it was possible to equip the DVL to the VideoRay while considering all the original parameters. The complete assembly was first designed in SolidWorks using a solid surface model of the VideoRay retrieved from GrabCAD (grabcad.com, 2014), a DVL scaled and sketched by the research team, and the mount, seen in Figure 5. Justified in Figures 7 and 8 below, the conservative design allows the DVL to fit well within the dimensions of the bottom of the VideoRay, in addition to limiting the DVL cord length, and includes the weighted skids and both stress relief cords.

A final important consideration in continuation is for the Doppler Velocity Log to remain facing downward while it is in operation. This allows the most accurate collection of data and optimizes its secondary function of station-keeping for future development.
C. WAM-V Assembly and Testing

The most important result of the pool test for the WAM-V was the observation of its performance under different load conditions and with different water stresses on the hull. It was discovered by using weights and human bodies that the payload tray is most stable when the majority of the weight is located aft. When the weight was located forward, the springs for the payload tray became fully compressed, nullifying the purpose of the springs and the wave adaptability of the system. With weight placed at the back of the payload tray, the platform remained steady under conditions ranging from raising one hull assembly out of the water to rocking a hull assembly at harmonic frequency. Another major observation was that each hull assembly operated independently, increasing overall stability. Another test involved weights placed on the hull assemblies; the pontoons remained stable and became more resistant to wave action while the payload tray remained stable. This indicates the pontoons can be used for additional sensors and weights as required. Finally, the nature of the engine pods, a metal tube filled with air, ensures that they float without engines attached, but are designed to keep the engines in the water while underway. This was also observed by using human weight and momentum to ballast the engine pods and observe their movement.

D. VideoRay Integration with WAM-V

After mounting the DVL to the VideoRay, the research team returned to the task of how to equip the WAM-V with the VideoRay while maintaining station-keeping ability and waypoint control. There were several components necessary to consider in the design, including operation of the DVL, hydrodynamics, and deployment and recovery of the VideoRay.

When the WAM-V is in operation, the VideoRay and DVL must be able to gather data while in motion. The necessity of the DVL being unobstructed while in use influenced the design of a cage with a large circular hole in the bottom. When the VideoRay is operable in the cage, the DVL fits through a circular hole in the cage limiting obstructions. A cylindrical cage, as seen in Figure 9, was decided upon to optimize hydrodynamic characteristics. The cage will be attached to a preexisting sonar pole that will be integrated into the WAM-V prior to the integration of the VideoRay.

The research team further developed the cage design for deployment and recovery of the ROV by incorporating a tether spool that will recover the VideoRay. When the VideoRay is deployed, the top half of the cage will be retracted by a pulley and the VideoRay will drive itself out of the cage. When it is recovered, the VideoRay will be pulled into the cage by its tether and the top half the cage will be released into the water where it will be negatively buoyant so it will secure the VideoRay while allowing for DVL operation. Pictured below in Figure 9 is the conceptual design that the research team developed.
IV. CONCLUSIONS

The team set out to integrate a VideoRay ROV with a WAM-V USV in mothership configuration for the purpose of autonomous station-keeping, mapping, and navigation. To do this, the team needed to gain an understanding of the WAM-V in a maritime environment, manufacture a mount for the DVL that would not inhibit the operation of the VideoRay, and translate the DVL data into usable navigational data. These tasks were accomplished through eight weeks of research, design, fabrication, and testing, giving consideration to both static and dynamic maritime environments. It is evident from the research that integration of the VideoRay and the WAM-V can significantly increase efficiency in inspection of maritime structures while acting as a force multiplier, securing our shores.

V. RECOMMENDATIONS FOR FUTURE WORK

The Robust Field Autonomy Laboratory in the Mechanical Engineering department at Stevens Institute of Technology will continue to work with the VideoRay, WAM-V, and DVL into the future. One of the major tasks the Lab is working on is developing autonomy for the various systems. Associated with this task, a recommendation for future work is to integrate the DVL data into the autonomous navigation of the VideoRay by developing the VideoRay code to include SLAM algorithms. Another task going forward will be equipping the WAM-V and developing its autonomy. Currently, a proposal has been submitted to acquire funding for the WAM-V. Assuming the funding is granted, the WAM-V will need to be outfitted with its motors, sensors, computers, and batteries in order to become a functioning system. Once it has been outfitted, the autonomy of the system will need to be developed. Additionally, a final task will be the integration of the VideoRay and the WAM-V in such a way that deployment and recovery of the VideoRay is possible. Some preliminary discussion was conducted about the challenges associated with integrating...
the VideoRay and the WAM-V, as well as some modeling of how such a system may look. Future work will involve refining and developing a method to integrate the two systems, and have them work autonomously.

VI. REFERENCES


APPENDIX A: WAM-V POWER CONSUMPTION TABLE

### A-1 Equipment Power Consumption Requirements

<table>
<thead>
<tr>
<th>Item</th>
<th>Equipment</th>
<th>Power Consumption Requirements</th>
<th>Watts</th>
<th>Voltage</th>
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<td>1</td>
<td>32 beam Velodyne LiDAR</td>
<td>12</td>
<td>9.18 DC</td>
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</tr>
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<td>2</td>
<td>32 beam Velodyne LiDAR</td>
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<td>9.18 DC</td>
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<td>Rowe Tech DVL</td>
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<td>5</td>
<td>Kongsberg multibeam SONAR</td>
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<td>12-36 DC</td>
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<td>6</td>
<td>Kongsberg Seapath 133 INS/GNSS</td>
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<td>24 DC</td>
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<td>7</td>
<td>Total</td>
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<td></td>
<td></td>
</tr>
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<td>8</td>
<td>Torqeedo cruise 2.0 RL motors (x2)</td>
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### A-2 Scanning and Inspection Power Consumption

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<th>Equipment Watt-Hour Usage</th>
<th>Motor Watt-Hour Usage</th>
<th>Total Watt-Hour Usage</th>
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### A-3 Mission Power Consumption

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<th>Mode</th>
<th>Distance to Station (Nautical Mile)</th>
<th>Speed to Station (Knots)</th>
<th>Speed on Station (Knots)</th>
<th>Time on Station (Hours)</th>
<th>Available Watt-Hours</th>
<th>Equipment Watt-Hour Usage</th>
<th>Motor Watt-Hour Usage</th>
<th>Total Watt-Hour Usage</th>
<th>Remaining Watt-Hours</th>
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APPENDIX B: CALCULATIONS

B-1

3-2-1 Aerospace Transform

In the "x y z (pitch-roll-yaw) convention," $\theta$ is pitch, $\psi$ is roll, and $\phi$ is yaw.

\[
\begin{bmatrix}
\cos \phi & \sin \phi & 0 \\
-sin \phi & \cos \phi & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\cos \theta & 0 & -\sin \theta \\
0 & 1 & 0 \\
\sin \theta & 0 & \cos \theta
\end{bmatrix}
\begin{bmatrix}
\cos \psi & \sin \psi & 0 \\
-sin \psi & \cos \psi & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

and $A$ is given by

\[
\begin{align*}
a_{11} &= \cos \theta \cos \phi \\
a_{12} &= \cos \theta \sin \phi \\
a_{13} &= -\sin \theta \\
a_{21} &= \sin \psi \sin \theta \cos \phi - \cos \psi \sin \phi \\
a_{22} &= \sin \psi \sin \theta \sin \phi + \cos \psi \cos \phi \\
a_{23} &= \cos \theta \sin \psi \\
a_{31} &= \cos \psi \sin \theta \cos \phi + \sin \psi \sin \phi \\
a_{32} &= \cos \psi \sin \theta \sin \phi - \sin \psi \cos \phi \\
a_{33} &= \cos \theta \cos \psi
\end{align*}
\]

A set of parameters sometimes used instead of angles are the Euler parameters $e_0, e_1, e_2$ and $e_3$, defined by

\[
\begin{align*}
e_0 &= \cos \left(\frac{\theta}{2}\right) \\
e_1 &= e_2 = \frac{\dot{\theta}}{2} \\
e_2 &= \frac{\dot{\phi}}{2}
\end{align*}
\]

Using Euler parameters (which are quaternions), an arbitrary rotation matrix can be described by

\[
\begin{align*}
a_{11} &= e_0^2 + e_1^2 - e_2^2 - e_3^2 \\
a_{12} &= 2(e_1 e_2 + e_0 e_3) \\
a_{13} &= 2(e_1 e_3 - e_0 e_2) \\
a_{21} &= 2(e_1 e_2 - e_0 e_3) \\
a_{22} &= e_0^2 + e_3^2 - e_1^2 - e_2^2 \\
a_{23} &= 2(e_2 e_3 + e_0 e_1) \\
a_{31} &= 2(e_3 e_1 - e_0 e_2) \\
a_{32} &= 2(e_3 e_2 + e_0 e_1) \\
a_{33} &= e_0^2 + e_2^2 - e_1^2 - e_3^2
\end{align*}
\]

B-2

4th order Newton-Cotes, Boole's rule

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<th>Degree</th>
<th>Common name</th>
<th>Formula</th>
<th>Error term</th>
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</thead>
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<td>Trapezoid rule</td>
<td>$\frac{b-a}{2}(f_0 + f_1)$</td>
<td>$-\frac{(b-a)^3}{12} f^{(2)}(\xi)$</td>
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<tr>
<td>2</td>
<td>Simpson's rule</td>
<td>$\frac{b-a}{6}(f_0 + 4f_1 + f_2)$</td>
<td>$-\frac{(b-a)^5}{2880} f^{(4)}(\xi)$</td>
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<td>3</td>
<td>Simpson's 3/8 rule</td>
<td>$\frac{(b-a)}{8}(f_0 + 3f_1 + 3f_2 + f_3)$</td>
<td>$-\frac{(b-a)^5}{6480} f^{(4)}(\xi)$</td>
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<td>4</td>
<td>Boole's rule</td>
<td>$\frac{b-a}{90}(7f_0 + 32f_1 + 12f_2 + 32f_3 + 7f_4)$</td>
<td>$-\frac{(b-a)^7}{1935360} f^{(6)}(\xi)$</td>
</tr>
</tbody>
</table>
APPENDIX C: DVL DRIFT DATA

C-1

Drift example
APPENDIX D: DVL STATIC TEST DATA

D-1

Unfiltered 1st order

D-2

Filtered 1st order
D-3
Unfiltered 4th order

D-4
Filtered 4th order
APPENDIX E: DVL CURRENT RELEASE DATA

E-1

Unfiltered 1st order

[Graph showing 1st order integration]

E-2

Filtered 1st order
E-3
Unfiltered 4th order

E-4
Filtered 4th order
Filtered and raw data