Estimating flow velocities of the water column using the motion response of an Autonomous Underwater Vehicle (AUV)

S. A. T. Randeni P.[a,*] , A.L. Forrest[a,b] , R. Cossu[a] , Z. Q. Leong[a] , and D. Ranmuthugala[a]

[a] Australian Maritime College,
University of Tasmania, Launceston, Australia.
*Supun.Randeni@utas.edu.au

[b] Tahoe Environmental Research Center,
University of California – Davis, Incline Village, NV, USA.

***Abstract* — The WVAM method is a nonacoustic method to calculate the velocity components of a turbulent water column using the motion response of an Autonomous Underwater Vehicle (AUV) without the aid of an Acoustic Doppler Current Profiler (ADCP). This study analyses water velocity measurements estimated using the WVAM method as a function of the turbulence level of the environment by testing the method in an estuary that exhibits strong tidal currents (around 2 m/s). The uncertainty of this method at different water column conditions was computed by comparing the velocity measurements from the WVAM method with those obtained from the AUV mounted ADCP. The WVAM method determines the water velocities by comparing the motion response of the vehicle when operating within turbulent and calm water environments respectively. The motion of the vehicle in the calm water environment was obtained by conducting simulations of the vehicles in calm water under the same control commands executed during the field experiments in turbulent conditions. A reduction in the accuracy of the method in rougher water environments was observed due to the hydrodynamic coefficients of the simulation model reaching their nonlinear range limits. A possible strategy to overcome this limitation and improve the WVAM method's ability to accurately estimate the flow field in the vicinity of AUVs operating in highly turbulent environments is also provided.**

Keywords—water column velocity; flow measurements; Autonomous Underwater Vehicles (AUVs); Acoustic Doppler Current Profilers (ADCPs)

I. INTRODUCTION

Many marine surveys, from physical oceanography to hydraulic engineering, involves measuring water column velocities; for example, determining the sediment load in a stream [1] and assessing the turbulent flux in the surface mixed layer [2]. Traditionally, equipment such as broadband Acoustic Doppler Current Profilers (ADCPs), Acoustic Doppler Velocimeters (ADVs) and High Resolution (HR) profilers are used to measure the water column velocities [3, 4]. These acoustic instruments determine the water column velocity profiles using the Doppler frequency shift of a sound wave transmitted by the device and reflected from particles in the water column itself [5]. These devices are used as stationary moorings to determine the flow speeds at fixed locations as well as on moving platforms in order to map spatial distributions of velocity fields.

ADCPs mounted on Autonomous Underwater Vehicles (AUVs) are gradually being adopted to capture water column velocities due to their capability to undertake missions in areas logistically difficult or inaccessible to surface vessels and other types of underwater vehicles such as under-ice operations [6]. In addition, their relative maneuvering stability and the decoupling from surface noise and reflectance allows them to provide enhanced flow measurements as compared to other moving platforms [7].

Acoustic instruments such as ADCPs are generally expensive and therefore, not feasible for low-cost AUVs that are being developed for commercial and scientific applications [8-10]. Furthermore, ADCPs have a blanking distance (i.e., a dead zone) in proximity to the device (typically around 0.5 m to 5 m, depending on the sampling frequency and selected bin size of the instrument), in which the flow velocity data remains unresolved [5]. In order to minimize these effects, the authors previously introduced a new method to calculate the water velocity components of a turbulent water column using the AUV motion response without the aid of an ADCP, referred to as the WVAM Method [11]. In this method, the water velocities are determined by comparing the performance (i.e., the motion response) of the vehicle when operating within turbulent and calm water environments.

The study presented in the paper investigates the variation of the WVAM method's accuracy with the turbulence level of the water column through field deployments in the Tamar estuary located in Tasmania, Australia that exhibits strong tidal currents. The uncertainty of the method was calculated by comparing with the velocity measurements obtained from the AUV's ADCP at different stages within the tidal range. A potential technique to improve the capability of the WVAM method is also discussed.

978-0-933957-43-5

II. METHODOLOGY

A. Instruments

A *Gavia*-class modular AUV [12] was used to test the WVAM method, with the AUV configured to an overall length of 2.7 m, diameter of 0.2 m, and a dry weight in air of approximately 70 kg. The modularized vehicle in the tested configuration consisted of a Nose Cone, Battery, Geoswath Interferometry Sonar, 1200 kHz RDI ADCP, Inertial Navigation System (INS), Control and Propulsion Modules. The ADCP module of the AUV included two 4-beam ADCPs arranged in a vertical plane to scan up and downwards from the vehicle (see Fig. 1). The ADCPs were set to profile the 9.94 meters of water column in 0.5 m range bins so that the three directional water velocity components in the vehicle's body-fixed coordinate system are measured in each bin. However, adjacent to the transducers (both above and below) there was a blanking distance of 0.44 m as shown in Fig. 1.

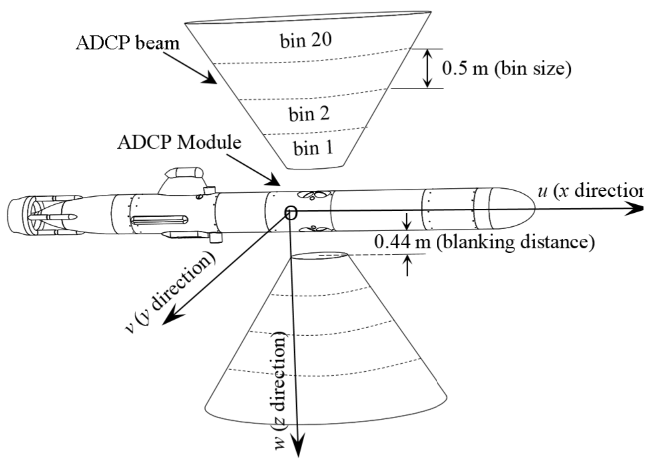

Fig. 1. Body fixed coordinate system of the *Gavia* AUV showing the ADCP beam geometry. The origin of the coordinate system is at the centre of buoyancy of the vehicle (marked by the 'O').

B. Site description

The objective of this study was to determine the variation of the WVAM method's accuracy at water columns with different flow velocities. To achieve this, the WVAM method was tested in the Tamar estuary near the Batman Bridge, which is located in Tasmania, Australia (see Fig. 2a and 2b). Due to the proximity to the open sea, Tamar estuary exhibits strong tidal currents with maximum flow velocities of up to 2.5 m/s.

Nine AUV runs were conducted along the track line shown in Fig. 2b. Out of the nine, the first five were conducted on 14 April, 2015 and the last four on 15 April, 2015. Runs 1 to 3 and 6 to 9 were conducted during slack water as shown in the tidal curve given in Fig. 2c. The velocity of the tidal currents during the first runs on each day (i.e., runs 1 and 6) was approximately 0.25 m/s. Due to the development of the strong flood tide, the flow speeds increased rapidly during the following next runs. Runs 4 and 5 were carried out at partially and fully developed flood tide conditions with strong tidal currents (around 2 m/s).

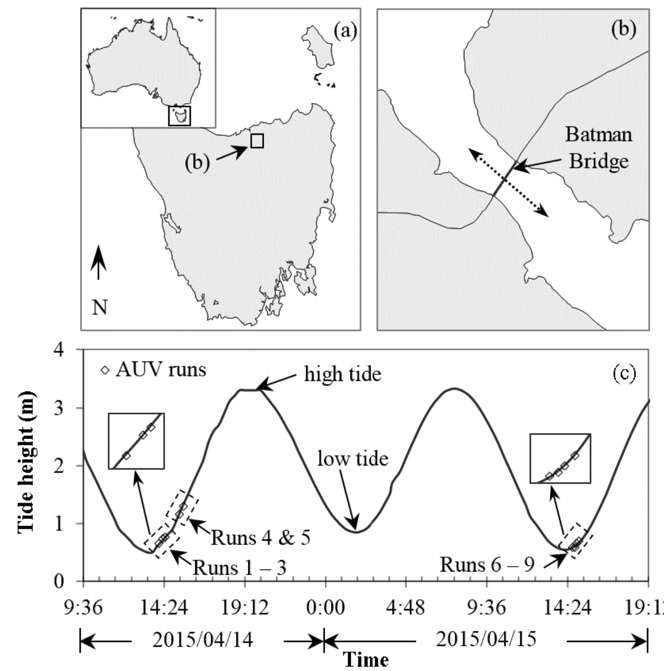

Fig. 2. (a) The experimental field site in Tasmania, Australia (inset); (b) Tamar estuary with the AUV track illustrated by the dotted line. (c) The tidal heights observed on 14th and 15th April, 2015. The time periods the AUV runs were conducted are shown by the diamond markers.

C. WVAM method

For the WVAM method [11], the AUV needs to undergo a straight-line, constant depth mission through the region where the water column velocities are to be measured. Typically, when an AUV is operating in an environment with fluctuating water velocities, the forces and moments induced by these velocities can interrupt the control stability and change the vehicle speed, depth, pitch and yaw angles (i.e., motion response of the AUV) from the pre-set values. In order to compensate for such changes in performance, the vehicle's dynamic control system adjusts the revolution speed of the propeller and the angles of the four control surfaces. According to these adjustments, the motion response of the AUV will change and the AUV will return to the initially prescribed mission track unless the propeller and the control surfaces are unable to compensate for the external forces [13].

The WVAM method uses the compensation commands given by the vehicle's controller to the propulsion motor and control surfaces (recorded in the vehicle log) and executes these commands within a simulation model representing a calm water environment. Since there are no disturbing forces due to flow variations in calm water conditions, the simulated vehicle motion will be different to the actual motion. The difference between the two motion responses provides an estimation of the water column velocities relative to the earth.

Equation (1) gives a generalized form of the water velocity calculation:

$$\bar{v}_{water(t)} = \bar{v}_{AUV(turbulent)(t)} - \bar{v}_{AUV(calm)(t)} \quad (1)$$

where, $\bar{v}_{water}$ is the velocity component of the surrounding water column relative to earth in the body-fixed coordinate system, $\bar{v}_{AUV(turbulent)}$ is the velocity component of the AUV observed in the turbulent environment and $\bar{v}_{AUV(calm)}$ is the velocity component of the vehicle obtained from the calm water simulation utilizing the control commands recorded from the field tests. Subscript t indicates the time-step. To estimate the water velocity component in the x, y and z axes, $\bar{v}_{AUV}$ is replaced with the surge, sway and heave velocity components (i.e., u, v and w) of the vehicle in the body-fixed frame of reference respectively.

D. *Simulation model and hydrodynamic coefficients*

The maneuvering simulation model of the *Gavia* AUV was developed to reproduce the vehicle's trajectory in a calm water environment in response to the time series input of the control commands. It requires an accurate approximation of the associated hydrodynamic coefficients (i.e., a representation of the forces and moments acting on the vehicle at different orientations and velocities) to adequately predict the motion of the AUV. Generally, the forces and moments acting on submerged bodies in Six-Degree-of-Freedom (6-DOF) are highly nonlinear [14]. For example, the vertical hydrodynamic force acting on the AUV varies linearly with its pitch angle up to a value of around ±8º, beyond which it becomes nonlinear (see Fig. 3). Similarly, threshold values exist for other hydrodynamic forces and moments as well. Therefore, the hydrodynamic coefficients estimated for the linear ranges are only valid up to a certain threshold angle [14].

During the initial development of the WVAM method, a basic curve fitting method was utilized to determine the hydrodynamic coefficients due to its relative simplicity [11]. The coefficients obtained from this method were limited to small angles of incidence (i.e., generally below 8º) restricting them to their linear range. When an AUV operates in turbulent environments, its pitch and yaw angles typically fluctuate around the baseline values. The magnitude of these fluctuations increases with increasing level of turbulence due to the inability of the AUV's dynamic controller to adequately and/or quickly compensate for the severe disturbance forces [13]. Therefore, in extremely turbulent water columns, these fluctuation angles will be greater than ±8º. Thus, a simulation model that is limited to linear hydrodynamics data will not be able to adequately replicate the motion of the vehicle in extreme environments.

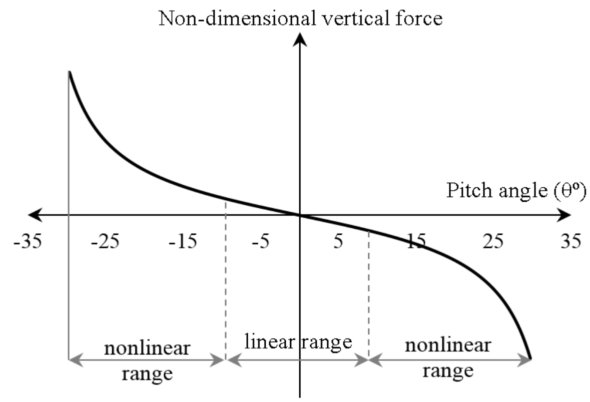

Fig. 3. Typical variation of the force acting on the AUV in z direction with the pitch angle [15]. The threshold angle that the linear variation changes to nonlinear is around ±8º.

III. RESULTS AND DISCUSSION

The water velocity components determined using the WVAM method were compared with the ADCP velocity measurements in order to validate the former method. Figs. 4a, 4b and 4c compare ADCP water velocity components in the x, y and z directions obtained from the first AUV run with WVAM estimates. It is evident from these plots that the WVAM method provides a good replication of the flow velocities measured using the on-board ADCP.

The uncertainty of the water velocity measurements from the WVAM method compared to the ADCP results was quantified using equation (2) that approximates the Standard Error (SE) with a percentage confidence of 99.7% [16],

$$SE = \frac{3}{\sqrt{n}} \sqrt{\frac{\sum_{t=1}^{n} \left(\bar{v}_{water(ADCP)} - \bar{v}_{water(WVAM)} \right)^2}{n}} \quad (2)$$

where, $\bar{v}_{water(ADCP)}$ is the water velocity measured using the ADCP, $\bar{v}_{water(WVAM)}$ is the water velocity calculated using the WVAM method, and n is the number of time steps.

The standard errors for the velocity components in the x, y and z directions for the first run were ±0.068 m/s, ±0.017 m/s and ±0.045 m/s respectively. These numbers represent the difference between WVAM and ADCP velocity predictions in each of the three directions, with the greatest error seen in the x-direction.

Runs 1 to 3 and 6 to 9 were conducted in lower turbulent environments compared to the Runs 4 and 5. Due to the developing flood tide, the level of turbulence increased gradually with each run; i.e., the flow conditions were usually more turbulent than in previous runs. Figs. 5a to 5e presents the vertical velocity component of the water column obtained from the AUV runs conducted on 14th April, 2015 (i.e., Runs 1 to 5). The standard errors between the WVAM and ADCP results (also called as the uncertainty of the WVAM method) for these runs are given in Table I. The uncertainty of the vertical water velocity prediction generally increases with the increasing turbulence level of the water column. The development of increased divergence between the two results with the level of turbulence is clearly seen in Fig. 5.

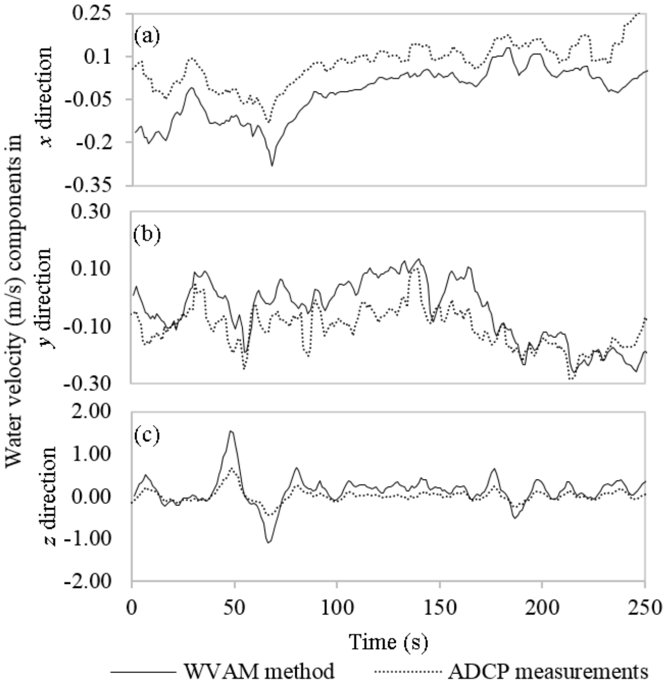

Fig. 4. Comparison between the velocity components of the water column in the *x*, *y* and *z* directions (panels a, b and c respectively) calculated using the WVAM method (solid black line) and those obtained from the on-board ADCP (dashed grey line). Data were obtained from Run 1 when the AUV was moving with the predominant tidal currents.

The averaged fluctuation of the vehicle's yaw angle, pitch angle and surge speed from the target values are given in Table I. If the AUV's control system is capable of guiding the vehicle accurately along the prescribed path in turbulent environments, these values would be close to zero.

The uncertainties of the vertical and transverse water velocity predictions are larger when the averaged fluctuations of the pitch and yaw angles (respectively) increase (see Table I). For example, in Run 2 the averaged deviation of the yaw angle is around ±17º and the standard error of the transverse velocity prediction is much larger than for Run 1 (i.e., 0.153 m/s). Run 1 has a smaller deviation of the yaw angle of around ±1.5º results in a much smaller uncertainty in the vicinity of 0.017 m/s. A similar outcome is seen in the vertical water velocity component. In Run 9, the averaged deviation of the pitch angle is ±7.5º giving a standard error in the vertical water velocity prediction of around 0.1 m/s. However, in Run 6 the deviation of the pitch angle is comparatively lower at ±3.1º resulting in a smaller standard error of the velocity of around 0.05 m/s.

Generally, a standard error up to 0.1 m/s is acceptable as the uncertainty of the measurements from an AUV mounted ADCP is around ±0.1 m/s [7]. The threshold averaged deviation of the pitch and yaw angles that provide the water column velocities with a standard error below 0.1 m/s is around 7º to 8º. Above this threshold angle the hydrodynamic coefficients usually become nonlinear. The hydrodynamic coefficients estimated for the simulation model using the curve fitting method are only valid for small angles of incidence of the vehicle, i.e. where the coefficients are in the linear range [11]. Therefore, when yaw and pitch angles are larger, the accuracy of the simulation model decreases and hence the uncertainty of the vertical and transverse water velocity components obtained from the WVAM method increases.

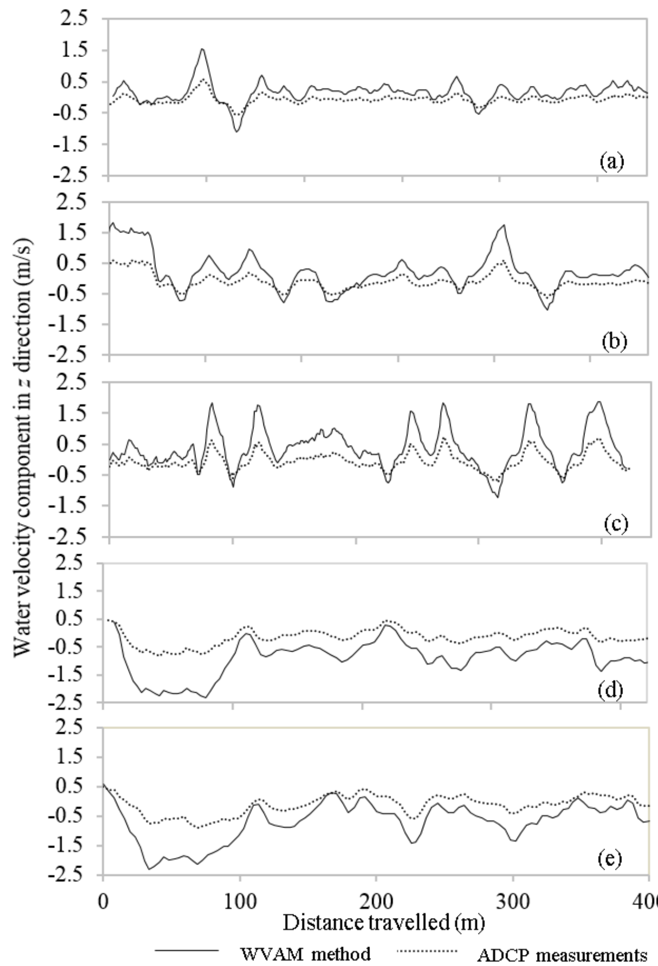

Fig. 5. The vertical water velocity components from the WVAM method and ADCP measurements for AUV runs 1 to 5. Panels (a) to (e) sequentially present the data for these runs.

The accuracy of the water velocity component in the *x* direction remains generally the same for all the runs regardless of the turbulence level of the environment. During the development of the simulation model, the hydrodynamic coefficients dominating the motion in the *x* direction were estimated for a propeller RPM range of 525 to 825 (i.e., a speed range of 1.43 m/s to 2.46 m/s in a calm environment). During this study, the AUV runs were conducted at 700 RPM, which typically provides a mean forward speed of around 2.04

m/s in calm water with a standard deviation of 0.01 m/s. The observed speed during the runs varied as much as ±1.6 m/s from the calm water speed of 2.04 m/s, especially in Runs 5 and 6 due to the AUV being 'dragged' by the strong tidal currents. Even though the actual speed deviated, the prescribed propeller speed of 700 RPM provides a calm water speed of around 2.04 m/s which is within the identified limits of the hydrodynamic coefficients dominating the forward motion. Therefore, the simulation model provided accurate prediction of the calm water based forward speed response of the AUV. Hence, the standard error between the WVAM and ADCP results in the *x* direction generally remained unrelated to the turbulence level of the water column.

Table I. Standard errors of the water velocity components determined from the WVAM method compared to the on-board ADCP measurements and the associated averaged deviations for the prescribed parameters.

Run Number	**Standard error**			**Averaged deviation from the prescribed value**		
	u	***v***	***w***	**Yaw angle (degrees)**	**Pitch angle (degrees)**	**Surge speed (m/s)**
1	0.068	0.017	0.045	±1.5	±3.6	±0.2
2	0.029	0.153	0.075	±17.4	±7.1	±0.6
3	0.041	0.095	0.108	±3.5	±7.5	±0.7
4	0.063	0.061	0.241	±2.8	±9.2	±1.6
5	0.035	0.079	0.191	±5.6	±9.7	±1.6
6	0.042	0.063	0.052	±3.1	±3.1	±0.1
7	0.048	0.058	0.067	±2.6	±6.4	±0.3
8	0.025	0.104	0.092	±14.5	±7.4	±0.4
9	0.054	0.082	0.097	±5.8	±7.5	±0.6

IV. RECOMMENDATIONS AND FUTURE WORK

In order to expand the threshold of the WVAM method to higher turbulent environments, the simulation model should be improved to enable it to replicate the motion response of the vehicle in linear as well as nonlinear ranges. The hydrodynamic coefficients of an AUV could be obtained more accurately using techniques such as captive model experiments [17], Computational Fluid Dynamics (CFD) simulations [17] and system identification [18]. These methods could be employed to determine the coefficients within the linear and nonlinear ranges to improve the associated simulations and thus the predictions of the WVAM method.

V. CONCLUSIONS

The WVAM method is a nonacoustic technique to determine the water velocity components of a turbulent water column using the motion response of an AUV. This study investigated the accuracy of the WVAM method subject to the level of turbulence of the water column. Nine AUV runs were conducted along the same AUV track line within the Tamar estuary in Tasmania, Australia, at different times in the tidal cycle.

Typically, when an AUV undertakes missions in rough water environments, the yaw and pitch angles of the vehicle fluctuate around the target values due to the inability of the AUV's dynamic controller to adequately compensate for the external disturbing forces. The greater the turbulence level of the water, generally larger are the fluctuations. The estimated water velocity components in the *y* and *z* directions using the WVAM method agreed well with the measurements from the AUV's on-board ADCP for low turbulent conditions where the averaged deviations of the vehicle's yaw and pitch angles are below 7º to 8º.

The hydrodynamic coefficients for the simulation model utilized in the WVAM method were determined using a curve fitting technique. These estimated coefficients were only valid for small angles of incidence of the vehicle, where the coefficients are in their linear range. Therefore, as the yaw and pitch angle fluctuations become larger, the accuracy of the simulation model decreases adversely affecting prediction of the vertical and transverse water velocity components using the WVAM method. During the AUV missions, the vehicle speed was maintained within the identified limits for the hydrodynamic coefficients dominating the forward motion. Therefore, the simulation model was able to provide an accurate prediction of the forward speed of the vehicle enabling the WVAM method to accurately determine the water velocities in *x* direction.

The WVAM method can be improved by upgrading the simulation model to replicate the motion response of the vehicle in both the linear and nonlinear ranges. The authors are expecting to achieve this by determining the hydrodynamic coefficients of the simulation model for a larger range using a comprehensive system identification study.

ACKNOWLEDGMENT

This study was partially funded through the Research Enhancement Grant Scheme of the University of Tasmania. The authors would like to thank Jeff Watts, Nathan Kemp, Isak Bowden-Floyd, Karl Manzer and Jun Lee at the Australian Maritime College, Uni. of Tasmania for their support during the AUV field experiments. The authors also thank Helgi Þorgilsson (Senior Systems Engineer at Teledyne Gavia) and Hordur Johannsson (Senior Software Engineer at Teledyne Gavia) for the continued technical support and assistance.

REFERENCES

[1] M. G. Hughes, G. Masselink, and R. W. Brander, "Flow velocity and sediment transport in the swash zone of a steep beach," *Marine Geology,* vol. 138, pp. 91-103, 1997.

[2] D. R. Hayes and J. H. Morison, "Determining turbulent vertical velocity, and fluxes of heat and salt with an autonomous underwater vehicle," *Journal of Atmospheric and Oceanic Technology,* vol. 19, pp. 759-779, 2002.

[3] E. Horstman, T. Balke, T. Bouma, M. Dohmen-Janssen, and S. Hulscher, "Optimizing methods to measure hydrodynamics in coastal wetlands: evaluating the use and positioning of ADV, ADCP AND HR-ADCP," *Coastal Engineering Proceedings,* vol. 1, p. 51, 2011.

[4] M. A. de Schipper, R. De Zeeuw, S. De Vries, M. Stive, and J. Terwindt, "Horizontal ADCP measurements of waves and currents

in the very nearshore," in *Current, Waves and Turbulence Measurements (CWTM), 2011 IEEE/OES 10th*, 2011, pp. 159-166.

[5] M. R. Simpson, *Discharge measurements using a broad-band acoustic Doppler current profiler*: US Department of the Interior, US Geological Survey, 2001.

[6] M. J. Doble, A. L. Forrest, P. Wadhams, and B. E. Laval, "Through-ice AUV deployment: Operational and technical experience from two seasons of Arctic fieldwork," *Cold Regions Science and Technology,* vol. 56, pp. 90-97, 2009.

[7] D. A. Fong and N. L. Jones, "Evaluation of AUV‐based ADCP measurements," *Limnology and Oceanography: Methods,* vol. 4, pp. 58-67, 2006.

[8] G. G. Acosta, H. Curti, O. C. Ibáñez, and S. Rossi, "Some issues on the design of a low-cost autonomous underwater vehicle with an intelligent dynamic mission planner for pipeline and cable tracking," *I-Tech Online Books, Robotics Series, I-Tech Education and Publishing KG, Vienna, Austria, Editor: A. Inzartsev,(ISBN 978-953-7619-49-7),* pp. 1-18, 2009.

[9] B. Anderson and J. Crowell, "Workhorse AUV-a cost-sensible new autonomous underwater vehicle for surveys/soundings, search & rescue, and research," in *OCEANS, 2005. Proceedings of MTS/IEEE*, 2005, pp. 1-6.

[10] B. Javier, "Low-cost AUV based on Arduino open source microcontroller board for oceanographic research applications in a collaborative long term deployment missions and suitable for combining with an USV as autonomous automatic recharging platform Autonomous Underwater Vehicles (AUV)," in *2012 IEEE/OES*, Sauthampton, UK, 2012.

[11] S. A. T. Randeni, A. L. Forrest, R. Cossu, Z. Q. Leong, G. A. Zarruk, and D. Ranmuthugala, "Determining the Horizontal and Vertical Water Velocity Components of a Turbulent Water Column Using the Motion Response of an Autonomous Underwater Vehicle," *Journal of Atmospheric and Oceanic Technology,* 2015 (under review).

[12] R. Yeo, "Surveying the underside of an Arctic ice ridge using a man-portable GAVIA AUV deployed through the ice," in *OCEANS 2007*, 2007, pp. 1-8.

[13] K. Kim and T. Ura, "Fuel-optimal guidance and tracking control of AUV under current interaction," in *The Thirteenth International Offshore and Polar Engineering Conference*, 2003.

[14] E. V. Lewis, *Principles of Naval Architecture: Motions in waves and controllability* vol. 3: Society of Naval Architects &, 1988.

[15] K. Granlund, "Steady and Unsteady Maneuvering Forces and Moments on Slender Bodies," PhD in Aerospace Engineering, Virginia Polytechnic Institute and State University, Virginia, USA, 2009.

[16] J. Devore, *Probability and Statistics for Engineering and the Sciences*: Cengage Learning, 2011.

[17] S. A. T. Randeni, Z. Q. Leong, D. Ranmuthugala, A. L. Forrest, and J. Duffy, "Numerical investigation of the hydrodynamic interaction between two underwater bodies in relative motion," *Applied Ocean Research,* vol. 51, pp. 14-24, 6// 2015.

[18] L. Ljung, *System identification*: Springer, 1998.