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Shallow Water Bathymetry using the REMUS 100 Autonomous Underwater Vehicle

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DSTO-TR-2916

ABSTRACT

This report describes assessments of a REMUS 100 autonomous underwater vehicle owned by DSTO as a tool for hydrographic survey. It concludes that DSTO's vehicle as currently configured cannot meet horizontal and vertical uncertainty standards for Special Order and Order 1 surveys as defined by the International Hydrographic Organization. In particular, the GPS sensor and the depth sensor are deficient and should be upgraded if the vehicle is to be used for hydrographic surveying. The settings of the Doppler velocity log should also be optimized to provide the best altitude resolution, or a dedicated single-beam echo sounder should be integrated into the vehicle. Hydrographic vehicles such as the REMUS 100-S and the Gavia are more appropriately configured for this application.

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Executive Summary

Small, man-portable Autonomous Unmanned Vehicles like the REMUS 100 and the Gavia, when fitted with Inertial Navigation Systems, are capable of accurately navigating complex mission plans independent of external inputs. On-board sensors record position, depth and altitude enabling measurement of bathymetry along the vehicle track.

The Defence Science and Technology Organisation (DSTO) conducted trials using the DSTO's REMUS 100 to test and assess the capability of the vehicle to measure bathymetry sufficiently accurately to satisfy requirements for survey accuracy specified by the International Hydrographic Organisation.

DSTO concluded that the DSTO's REMUS 100 could not meet Special Order and Order 1 standards for total horizontal uncertainty and total vertical uncertainty.

DSTO's REMUS 100 cannot meet horizontal uncertainty standards because it is fitted with a standard, single-band GPS receiver and a tactical-grade inertial navigation system.

DSTO's REMUS 100 cannot meet vertical uncertainty standards because its pressure sensor has a scale error that causes it to underestimate the depth of the vehicle, and therefore the total water depth, by approximately 1 metre when the vehicle is 25 m underwater. Additional effects due to quantization of the altitude measurements from the on-board Doppler velocity log can be controlled by parameter settings.

DSTO's REMUS 100 cannot meet bottom coverage requirements for Special Order and Order 1a surveys because it is not fitted with a swath echo sounder. This limitation does not apply to Order 1b.

If the REMUS 100 is to be used as a hydrographic survey platform, it should be fitted with a pressure sensor accurate to 0.1% of water depth or better, a dual-band GPS receiver and an inertial navigation system capable of maintaining a drift rate better than 0.1% of distance travelled. Consideration should also be given to the integration of a survey-grade single-beam echo sounder.

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List of Acronyms

ADCP	Acoustic Doppler Current Profiler
AUV	Autonomous Underwater Vehicle
DVL	Doppler Velocity Log
GPS	Global Positioning System
IHO	International Hydrographic Office
INS	Inertial Navigation System
REMUS	Remote Environmental measuring UnitS
THU	Total Horizontal Uncertainty
TVU	Total Vertical Uncertainty

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1. Introduction

Small, manually deployable Autonomous Underwater Vehicles (AUV) like the Remote Environmental Measuring UnitS (REMUS) 100¹ and the Gavia² are increasingly being considered as tools to conduct maritime Rapid Environmental Assessment (REA) and mainstream hydrography.

This document is an assessment of the performance of a small AUV configured with sidescan sonar and navigational sensors, but no dedicated bathymetric sensors, as a tool for bathymetric measurement. The bulk of this document relates to measurements made using DSTO's REMUS 100 AUV, but much of the content is relevant to small AUVs in general.

The International Hydrographic Office (IHO) Standards for Hydrographic Surveys provide a yardstick by which to assess the REMUS 100 in the form of Special Publication No. 44³, which provides a set of minimum standards for the execution of hydrographic survey. These include specifications for the maximum permissible Total Vertical Uncertainty (TVU) and Total Horizontal Uncertainty (THU) of bathymetric measurements, and requirements for the proportion of the seabed that must be covered during the survey. To be compliant with an S-44 Order of Survey, bathymetric measurements must be compliant with all specifications associated with that Order. Standards for four Orders of survey are specified in Table 1. They can be interpreted roughly as follows:

- Special Order – full seabed coverage in waters typically shallower than 40 metres, with sufficient resolution and positional accuracy to exclude undetected shoals and isolated obstacles to navigation in environments where under-keel clearance is critical.
- Order 1a – full seabed coverage in waters shallower than 100 metres where under-keel clearance is less critical, with sufficient resolution and positional accuracy that shoals and isolated obstacles to navigation are unlikely to have remained undetected.
- Order 1b – partial seabed coverage in waters shallower than 100 metres with sufficient sounding density that areas of concern to shipping are unlikely to be present.
- Order 2 – partial seabed coverage in waters typically deeper than 100 m with no requirement for coverage of the areas between survey lines.

The capacity of an AUV to provide data satisfying an Order of survey depends on its instrumentation.

¹ Manufacturers Kongsberg Hydroid of the USA, www.hydroid.com

² Manufacturers Teledyne Gavia of Iceland, www.gavia.is

³ IHO Standards for Hydrographic Surveys, Special Publication No. 44, 5th Edition, February 2008

Table 1: Minimum Standards for Hydrographic Surveys

Order	Special	1a	1b	2
Allowable Total Horizontal Uncertainty (THU)	2 metres	5 metres + 5% of depth	5 metres + 5% of depth	20 metres + 10% of depth
Allowable Total Vertical Uncertainty (TVU) $\sqrt{a^2 + b^2 \text{depth}^2}$	$a = 0.25 \text{ m}$ $b = 0.0075$	$a = 0.5 \text{ m}$	$a = 0.5 \text{ m}$	$a = 1.0 \text{ m}$
		$b = 0.013$	$b = 0.013$	$b = 0.023$
Full seafloor search	Required	Required	Not required	Not required
Feature detection	Cubic features > 1 metre	Cubic features > 2 metres	Not applicable	Not applicable
		10% of depth for depths > 40 m		
Maximum line spacing	Full sea floor search	Full sea floor search	Maximum of 3 × average depth or 25 m	4 × average depth
Position of fixed aids/topography	2 metres	2 metres	2 metres	5 metres
Position of coastline	10 metres	20 metres	20 metres	20 metres
Position of floating aids	10 metres	10 metres	10 metres	20 metres

AUVs fitted with swath echo sounders and high-grade navigation systems can potentially provide soundings meeting Special Order or Order 1a; however, the standard configuration of the REMUS 100 AUV does not include any bathymetric sensors. The REMUS 100 variant owned by DSTO includes a GPS receiver, a tactical-grade inertial navigation system (INS), a pressure sensor for depth estimation and acoustic Doppler current profilers (ADCPs). The downwards-looking ADCP also functions as an altimeter and a ground-relative velocity sensor; that is, as a Doppler velocity log (DVL). Other lower-cost variants of the REMUS 100 omit the INS and provide only a magnetic compass as an attitude sensor.

This work considers whether DSTO's REMUS 100 and other similarly equipped AUVs are able to meet Order 1b prescriptions for vertical bathymetric uncertainty. To summarise, the prerequisites for Order 1b are a navigation system that can determine horizontal position to within a few metres and a combination of on-board depth and altitude sensors that can determine the water depth to within a few decimetres.

2. Navigation and Horizontal Uncertainty

The following section is a brief consideration of the REMUS 100 navigation system and its performance versus the S44 requirements for horizontal uncertainty.

2.1 Navigation System

The core of the REMUS 100 navigation system is a dead-reckoning (DR) system based around on-board orientation and velocity sensors, 'aided' by position sensors. The dead-reckoning system extrapolates sparse position sensor inputs to give continuous, high-rate estimates of the position, orientation, velocity and rates of turn of the vehicle.

The primary velocity sensor in the REMUS 100 and most AUVs is a downwards-looking ADCP configured as a DVL.

The orientation sensor in a base-model REMUS 100 is a magnetic compass. The orientation sensor in DSTO's vehicle is a tactical-grade ring-laser gyroscope (RLG) in a Kearfott INS. The INS comprises the RLG, linear accelerometers and a micro-computer that integrates their outputs with those of other vehicle sensors to estimate position, orientation, velocity and rotation rates in the 'world coordinate system'.

DSTO's REMUS 100 contains two independent navigation systems: the Kearfott INS, and an alternative subsystem of the REMUS navigation system that utilises the raw outputs of the sensors in the INS. Both systems use velocity and altitude estimates from the DVL, depth estimates from a pressure sensor, position estimates from the GPS receiver and optionally, acoustic position fixes from acoustic long-baseline (LBL) and digital ultra-short baseline (DUSBL) systems on the vehicle. In most modes of operation, the two navigation systems have very similar outputs.

The LBL and DUSBL systems use coded acoustic pulses from precisely positioned stationary transponders to estimate the vehicle's position. The advantage of these systems is that when employed the DR system typically extrapolates only a few seconds between position updates. The disadvantage is that the transponders must be installed prior to the mission. Due to the limited range of the acoustic signals, they must be situated within 2000 m of each other and the area of operation. The positions of the transponders must also be entered into the REMUS mission plan prior to launching the vehicle, as the vehicle cannot independently determine them. The overheads associated with this process discourage the use of transponder-based navigation when other options are available; in particular, the precision afforded by an INS obviates the need for frequent position updates from acoustic transponders and other off-board position references.

2.1.1 Inertial Navigation System

The dead-reckoning accuracy of the Kearfott INS in the REMUS 100 is quoted as 0.5% of distance travelled when velocity estimates from the DVL are continuously

available. In practice, navigational errors are typically less than 0.3%. INS performance may degrade in currents and when the DVL is too far above the seabed so it does not have good 'bottom-lock'. During such times, the INS lacks an accurate velocity input and thus it may 'drift' rapidly with respect to the true position of the vehicle. This occurs because the REMUS navigation system uses lower-quality velocity estimates from two sources: the propeller revolution rate, and acceleration measurements. Velocity estimates from the propeller revolution rate are of low quality at all times, but particularly when the propeller cavitates; for example when the vehicle accelerates while diving. Estimation of velocity by integration of acceleration measurements is accurate over short periods, but measurement errors accumulate, resulting in large drifts in position after a few tens of seconds.

By periodically surfacing during a mission to obtain a GPS fix, the INS can update its position estimate. However, this procedure may not always be beneficial as, when surfacing at steep angles or when diving in deep water, the DVL can lose bottom-lock and hence the principal velocity input to the INS, thus degrading the navigational accuracy.

2.2 Garmin GPS Receiver

Prior to April 2012 the DSTO's REMUS 100 was fitted with a Garmin 15-H single-band (L1) GPS receiver. The vehicle has since been upgraded and the 15-H replaced with a Garmin model 15-xH. The 15-xH has a lower noise level than the 15-H but is functionally identical. All of the trials discussed in following sections were conducted prior to April 2012.

The GPS receiver is the primary horizontal position reference for an INS-equipped vehicle like DSTO's REMUS 100. When the vehicle is turned on and the INS first receives power, it has no information about its orientation relative to the world. It uses position estimates ('fixes') from the GPS receiver to establish its position and velocity, orient itself with respect to gravity and the rotation of the earth, and 'align' to true North. GPS fixes are not available when the vehicle is underwater, but the navigation system updates its position estimate each time the vehicle returns to the surface, if it receives a GPS fix of sufficient quality within a specified time window. Because the INS accumulates a sequence of GPS fixes during the alignment process, its position estimate prior to commencing a mission is usually an order of magnitude more precise than a single GPS fix. This precision does not necessarily imply a similar level of accuracy, because the entire sequence of GPS fixes may be subject to long-period systematic errors due to ionospheric refraction effects that the single-band (L1) Garmin GPS receiver is unable to sense.

Standard GPS horizontal uncertainty can be better than 3 metres at the 95% confidence level, but high-quality GPS receivers in GPS reference stations occasionally report horizontal uncertainty values larger than 5 metres⁴. GPS performance may be further degraded if the vehicle is operating at sea in conditions that cause waves to wash over the antenna.

⁴ For further discussion, see <http://www.gps.gov/systems/gps/performance/accuracy/> and linked documents therein, particularly the GPS SPS Performance Analysis Report series

The Garmin GPS receiver in the REMUS 100 is capable of receiving differential corrections from a satellite-based augmentation system such as the North American WAAS system, but SBAS corrections are not available in Australian waters and the SBAS capability in the DSTO REMUS 100 is not utilized. The GPS receiver therefore functions as a stand-alone non-augmented GPS receiver.

2.3 Teledyne RD Instruments Acoustic Doppler Current Profilers

The REMUS 100 is fitted with two customised 'Workhorse' acoustic Doppler current profilers (ADCPs) from Teledyne RD Instruments (RDI). One looks upwards and functions purely as an ADCP. The other looks downwards and functions primarily as a Doppler velocity log: it measures the three components of vehicle velocity relative to the seabed and the altitude of the vehicle above the seabed. It also functions as an ADCP. To summarise, the navigation system receives forwards, sideways and vertical velocity measurements relative to the seabed from the downwards-looking ADCP, and forwards, sideways and vertical velocity measurements relative to the water volume from both ADCPs.



Figure 1: Acoustic Doppler current profiler transducers on the REMUS 100. The upwards and downwards-looking transducer arrays are identical.

In following sections, the downwards-looking ADCP is referred to as the 'DVL' and the upwards-looking ADCP is referred to as the 'ADCP'.

The ADCP/DVL transducer arrays on the REMUS 100 (Figure 1) comprise four upwards-looking and four downwards-looking transducers oriented at 90° intervals and inclined at 20° from the horizontal. The beams they project are perpendicular to the transducer faces, so they are inclined 20° away from the vehicle's vertical axis. The operating frequency is 1200 kHz and the beamwidth of the individual beams is about 1.5°.

The maximum bottom tracking range of the DVL is influenced by bottom type, but is typically between 30 and 45 metres. In seabed search operations, the vehicle operates at about 3 metres altitude, so the DVL almost always has bottom-lock, other than when surfacing or diving from the surface in deep water.

2.4 Total Horizontal Uncertainty

The total horizontal uncertainty associated with bathymetric measurements from the REMUS 100 is a function of the uncertainty of the reference position, which is determined by the INS from GPS fixes and other measurements, the lever-arm parameters associated with the offset between the DVL and the INS, and the uncertainty in the orientation of the vehicle. The lever-arm between the INS reference point and the coordinate reference point of the DVL is unknown to DSTO, but it is certainly no larger than 20 cm. Its contribution to the total uncertainty is negligible in the context of GPS horizontal uncertainty, which is assumed to approximate the THU in following discussions.

For the purposes of this discussion, the THU while the system is underwater is given by:

$$\sqrt{\Delta P_{GPS}^2 + (\alpha \cdot DT)^2},$$

where ΔP_{GPS} is the GPS positional uncertainty, α is the rate of drift and DT is the distance travelled. Kearfott specify that $\alpha \leq 0.005$, while DSTO experience is that $\alpha \leq 0.003$ is typical. The important factor in this expression is that THU is never less than ΔP_{GPS} , which is normally assumed to be 3 to 5 metres.

Maximum allowable total horizontal uncertainty (THU) values for IHO survey orders are shown graphically in Figure 2 and numerically in Table 1.

- The REMUS 100 cannot meet the THU standards for Special Order survey, requiring that THU be less than 2 m regardless of depth, even at the surface when its positional uncertainty is at a minimum.
- Under some conditions, the REMUS 100 may satisfy the THU standards for Order 1 surveys; however, due to the GPS uncertainty, the operators will probably not be able to identify which records satisfy the standards and which do not.

- The REMUS 100 will almost always meet the THU requirements for Order 2 surveys in shallow water. The REMUS 100 may not meet Order 2 THU requirements if the vehicle is unable to surface for GPS after an extended transit, or is working in waters where the DVL loses bottom-lock for tens of seconds.

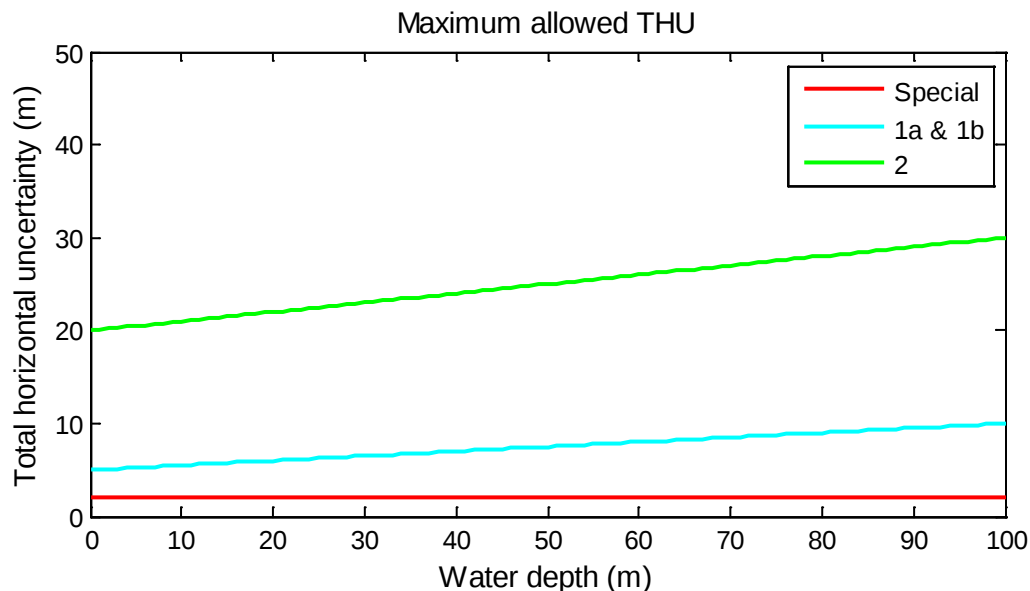


Figure 2: Maximum permitted total horizontal uncertainty for hydrographic survey to Special Order, Order 1a and 1b (identical) and Order 2

3. Uncertainty in Vehicle Depth

The REMUS 100 derives estimates of total water depth as the sum of the vehicle depth and the vehicle altitude, which are measured independently. This section is an assessment of the performance of the pressure sensor, from which the REMUS estimates its depth.

3.1 Operation

A standard REMUS 100 estimates its depth using hydrostatic pressure measurements from a Honeywell SA200PA1C1D automotive strain gauge pressure transducer and water density estimates derived from the outputs of its on-board salinometer. The pressure transducer is temperature-compensated and its accuracy is specified as 1% full scale, best fit straight line (BFSL), with a response time less than 0.5 milliseconds. The pressure range of the sensor is 0 - 200 PSI, equivalent to 0 - 137 metres in seawater, which comfortably exceeds the operating depth limit of the REMUS 100.

On receiving the RUN command to start a mission and on surfacing during a mission to obtain a GPS fix, the REMUS control program zeros the depth sensor to eliminate offset errors due to variations in the ambient atmospheric pressure and hysteresis in the transducer. The last depth offset used to zero the depth sensor is recorded in the vehicle configuration file from the mission.

3.2 Pressure Sensor Testing

DSTO staff identified a potential problem with the pressure sensor during analysis of data collected at Jervis Bay during a trial conducted in March 2012. This prompted a check of REMUS depth measurements during a subsequent trial in Sydney in September 2012.

To check the sensor, the REMUS and a recently calibrated Teledyne RDI 'Citadel' CTD-NV oceanographic profiling instrument with a pressure accuracy of 0.05% full scale were strapped to a carrying frame, lowered by rope to approximately 25 metres depth and recovered, using a sling arrangement to maintain the platform horizontal. The CTD was attached so that its pressure sensor was within a few centimetres of the level of the REMUS pressure sensor.

The carrying frame was lowered into the water until the REMUS was submerged by a few centimetres, where it could receive acoustic commands. On receiving the RUN command, the REMUS control program zeroed the depth sensor and started logging. The vehicle and the CTD sensor logged data independently during the descent and ascent, but both data sets were time-stamped for later comparison.

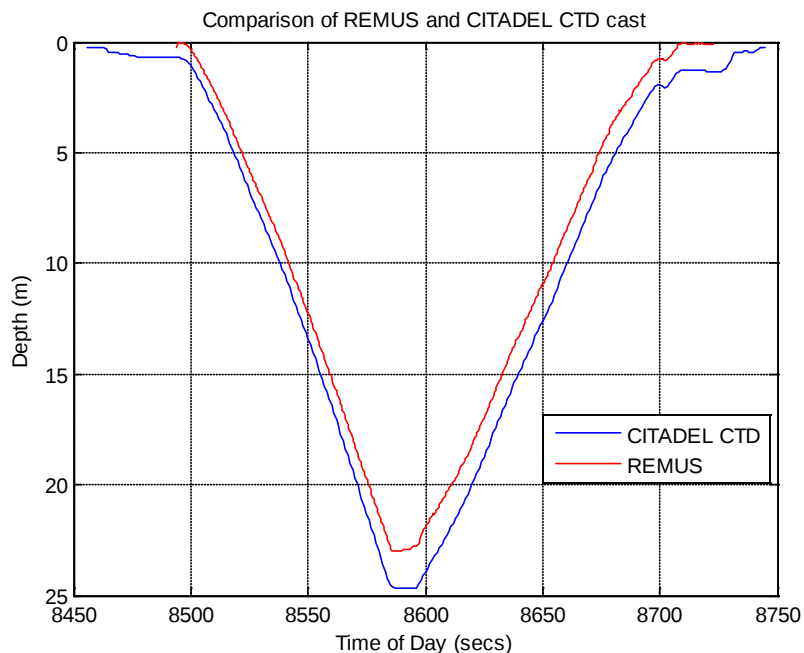


Figure 3: Comparison of REMUS and Citadel CTD depth measurement.

Figure 3 compares the depth estimates from the REMUS and the CTD sensors. The depth profiles show that the maximum depth logged by the REMUS was almost 1.5 metres shallower than the maximum depth logged by the CTD. They also show a hysteresis between the downward and upward measurements. Although some of the offset was due to the requirement to start the REMUS mission with the vehicle pressure sensor approximately 0.3 metres underwater, much of the difference is due to a scale variation between the two instruments. This result, which covers only 25% of the vehicle's operating depth range, shows that the pressure sensor probably did not perform to its specified accuracy of 1% full scale BFSL – a maximum of 1.37 m.

3.3 Pressure Sensor Upgrade

DSTO returned the REMUS 100 to Kongsberg Hydroid for service and upgrades early in 2013 and funded the integration of a more accurate pressure sensor, a Honeywell MLH150PGB06G. This entailed significant non-recurring engineering costs, but the cost of the sensor was small in comparison to the cost of the integration and it should now be available as an option on all new vehicles.

Honeywell specify that the new sensor is accurate to $\pm 0.5\%$ of full scale for pressures up to 100 psi, equivalent to a depth of about 70 metres, and $\pm 0.25\%$ for larger pressures. The maximum expected uncertainty in typical working depths is therefore approximately ± 0.36 m.

DSTO has not repeated the pressure sensor test it conducted in September 2012 with the new sensor, but DSTO and RAN personnel have employed the vehicle for set-to-work, search and reacquisition missions in Jervis Bay and Middle Harbour, Sydney. Some preliminary assessments are reported in Appendix C.

3.4 Total Vertical Uncertainty

Figure 4 displays the maximum values for total vertical uncertainty that are permitted under the IHO orders of survey, as calculated from the values and expression appearing in Table 1. Total vertical uncertainty can be no less than the uncertainty due to the pressure sensor.

If the Honeywell SA200PA1C1D sensor that was originally installed in DSTO's REMUS 100 is typical, then it should not be used in a vehicle intended for bathymetric survey. The magnitudes of offset and hysteresis that are visible in Figure 3 at a depth of 20 m are sufficiently large to prevent the REMUS 100 from satisfying the requirements for total vertical uncertainty to any Order 2.

If the Honeywell MLH150PGB06G sensor now installed in DSTO's REMUS 100 performs to its specification, then the REMUS 100 will not be able to achieve Special Order vertical accuracy. Depending on the level of uncertainty in the altitude measurement, it may be able to achieve Order 1 vertical accuracy.

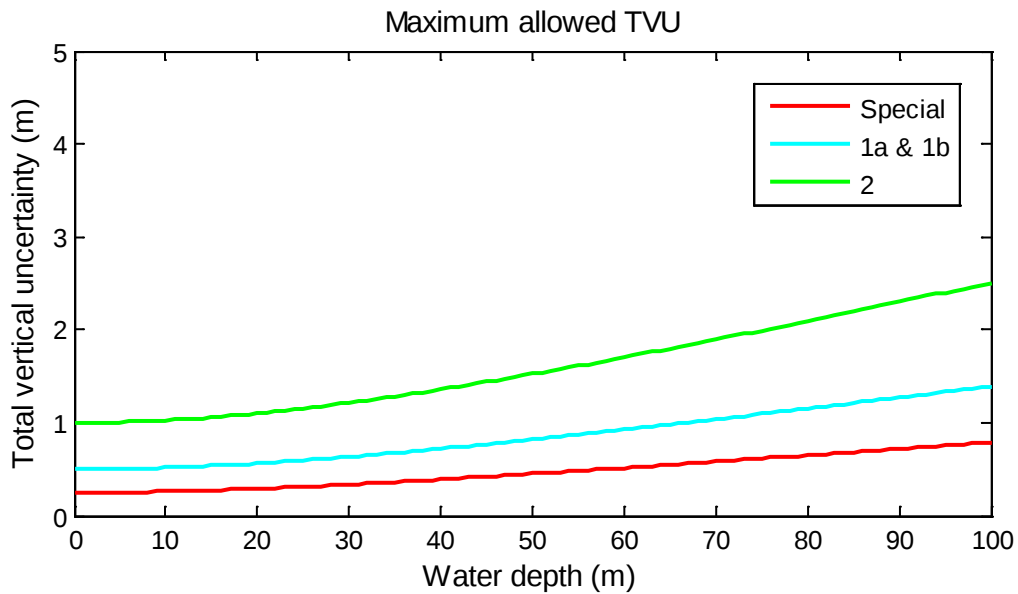


Figure 4: Maximum permitted total vertical uncertainty for hydrographic survey to Special Order, Order 1a and 1b (identical) and Order 2

4. Uncertainty in Altitude

The analysis in Section 3.4 implies that bathymetric measurements made with DSTO's REMUS 100 prior to April 2013 are unlikely to meet IHO requirements for total vertical uncertainty. However, the scale error visible in Figure 3 appears regular. This section is an assessment of the accuracy of altitude measurements. Trials results are interpreted with the assumption that the error in the pressure sensor measurement is invariant over the course of a single dive.

4.1 Using the DVL as an Altimeter

On level terrain, the downward-looking beams of the DVL essentially ensconify the vertices of a square. The 'altitude' measurement returned by the DVL is an average of the altitude of these four points. If the terrain is known sufficiently well for the vehicle to swim at a 'search' altitude of 3 metres, the side length of the square is 1.5 metres, so the altitude estimate is likely to correspond closely with the true altitude unless the terrain is very rough or has a high rate of curvature.

If the terrain is unfamiliar and the vehicle is operating in constant-depth mode or at a high constant altitude for safety reasons, the vehicle may be far above the bottom. The separation of the four corners of the square may then increase to the point where the average of the altitudes at the corners is no longer likely to be a good approximation for the altitude in the centre, under the vehicle.

4.2 Roll and Pitch Effects

The DVL estimates altitude above the sea floor by averaging the ranges measured by the downwards-looking beams and correcting for beam inclination from the vehicle's vertical axis. It does not correct the altitude estimates for roll and pitch, but if necessary these effects may be compensated for in post-processing, since the individual beam data is logged.

At a survey speed of 4 knots, the REMUS vehicle typically rolls approximately 3° away from vertical due to torque from the propeller. It also typically pitches about 2° nose-down to counteract the 0.5 kg positive buoyancy of the vehicle. At these angles, the error induced in the altitude by neglecting to compensate for roll and pitch is less than 0.3%, as the longer beam ranges on one side of the vehicle are compensated by the shorter beam ranges on the opposite side.

4.3 Quantisation Effects

The DVL uses a dynamic quantisation process to record beam ranges with a fixed digital resolution. The process is software-configurable, such that the resolution or bin size of the beam range measurement can be set to 4%, 2% or 1% of the measured beam range, through settings 'BR0', 'BR1' and 'BR2'. The manufacturer, RDI, explains the effect of the different resolution settings as:

"BR sets the vertical depth resolution as a percentage of the overall range detected: the lower the resolution, the finer the depth reading. With BR0 set, if you had a depth of 100 meters, then the depth would read 100 meters until you passed 104 meters. If you had BR2 set, then it would change when you reached 101 meters. Setting a higher resolution (e.g. 1%) results in longer ping times."

The above explanation is slightly confusing in that in this context, lower resolution really means better resolution. Nevertheless, if the accuracy of the altitude measurement can be optimised by setting the beam range resolution, it should also improve the accuracy of the bathymetry estimate. This is an important consideration in the context of total vertical uncertainty.

4.3.1 Quantisation and Total Vertical Uncertainty

Table 2: RDI beam range resolution settings and theoretical vertical resolution values

Setting	Resolution (%)	Resolution at 3 m Altitude (cm)	Resolution at 9 m Altitude (cm)
BR0	4	12	36
BR1	2	6	18
BR2	1	3 [actually 5]	9

Table 2 lists the beam range resolution modes and corresponding altitude resolutions for two altitudes: 3 metres, which is typical when the vehicle is searching for objects on the seabed, and 9 metres, which is more representative of an altitude value used when the vehicle is operating in unfamiliar waters, or in constant-depth mode. The default DVL beam range resolution mode in the REMUS 100 is BR0, or 4% of the beam range below the vehicle.

One entry in Table 2 suggests that the DVL could achieve a vertical resolution of 3 cm when operated at 3 m altitude in BR2 mode. In practice, the minimum vertical resolution for the 1200 kHz model in the REMUS 100 is 5 cm.

If vertical accuracy were the only consideration, then the REMUS 100 should always be operated with the DVL in BR2 mode; however, BR2 mode may be inappropriate when the vehicle is operating at low altitude because of the longer pulse length, which may restrict the minimum altitude. Given the negligible difference in altitude measurement between settings BR1 and BR2 when surveying at 3 m altitude, BR1 is the preferred setting.

Considering the values for 9 m altitude, the resolution of the altitude measurements in BR0 mode exceeds the maximum TVU for Special Order and is comparable to the maximum TVU for Order 1. This suggests that the BR2 setting is the most appropriate when the vehicle is expected to operate far above the seabed. DSTO has not tested this hypothesis.

4.3.2 Trials in Sydney

DSTO conducted a short trial in White Bay, Sydney, to assess the effect of the DVL beam range resolution settings on bathymetric measurements from the REMUS 100. The trial comprised three missions with a fixed mission plan, as shown in Figure 5.

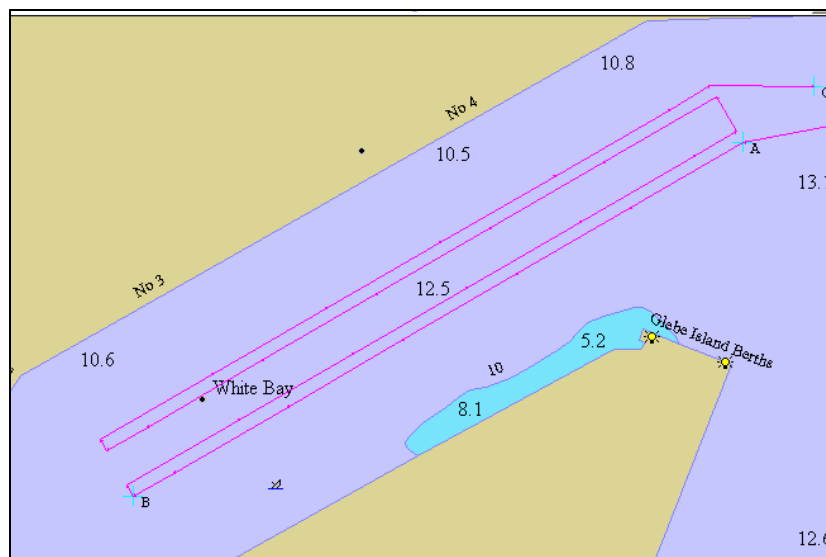


Figure 5: Mission plan for assessment of DVL beam range resolution settings at White Bay

The trials and the analysis discussed in more detail in Appendix A. The following is a summary of the analysis.

Each mission ran for about 22 minutes and was about 2350 metres in length. Vehicle speed was programmed as a propeller revolution rate of 1250 rpm, corresponding to 3.6 knots. The only difference between the missions was the beam range resolution settings, which were successively BR0, BR1 and BR2.

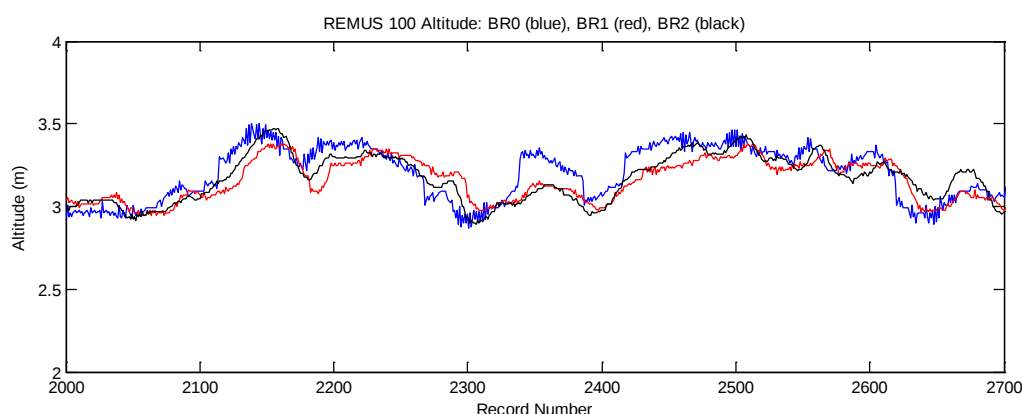


Figure 6: A section of REMUS altitude records from three missions with a fixed mission plan. DVL beam resolution settings were BR0 (blue), BR1 (red) and BR2 (black)

Figure 6 shows a 150 second section of the altitude records from the three missions. In this figure, the recorded altitude during the BR0 mission exhibits irregular step changes 10 to 15 centimetres in magnitude, and intermittent noise-like bursts of a few seconds duration where the altitude rapidly fluctuates by a few centimetres. The vehicle altitude recorded during the higher-resolution BR1 and BR2 missions are smoother, less variable and in better agreement. While some of the variability between missions may be attributed to the REMUS following slightly different tracks, the majority of the variation between the BR0 mission and the BR1 and BR2 missions appears to be due to quantisation effects. This is in agreement with Table 2, which predicts quantisation effects of the order of 12 cm in BR0 mode, and 5 to 6 cm in BR1 and BR2 modes.

Figure 7 compares bathymetry along the vehicle's tracks derived from the REMUS 100 records and taken from a reference data set for White Bay that was produced by Sydney Ports using a hydrographic survey system including a Reson 7125 multibeam echo sounder. Tidal corrections have been applied to the REMUS data.

The REMUS bathymetry is always shallower than the reference bathymetry. This is in agreement with the pressure sensor scale variation visible in Figure 3. The remainder of the variation is consistent with quantisation effects as previously discussed – the results from the BR0 mission include obvious jumps, while the results from the BR1 and BR2 missions are smoother and in better agreement with each other and with the reference bathymetry, if an offset is ignored.

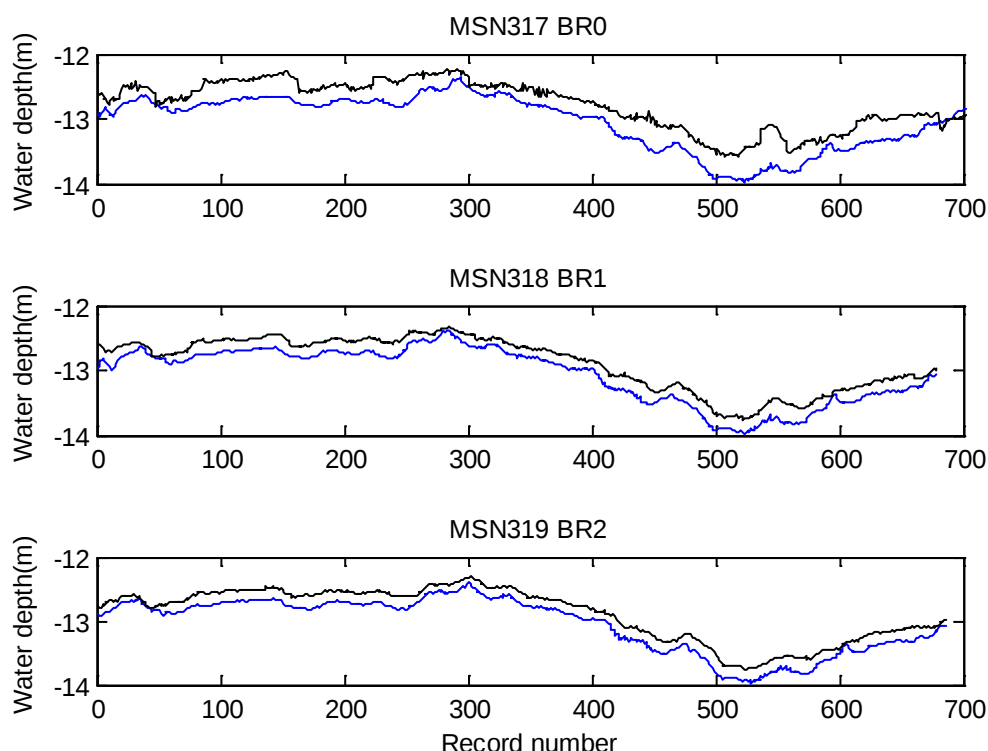


Figure 7: Comparison of REMUS bathymetry and White Bay reference bathymetry along the first leg of each mission. Reference bathymetry (blue), REMUS bathymetry (black)

4.3.3 Trials in Jervis Bay

Prior to the White Bay missions, the DSTO REMUS vehicle had been always operated with the default BR0 parameter, corresponding to a 4% DVL beam range resolution setting. The White Bay missions were conducted over a relatively flat sea bottom; however, data from other missions with the REMUS using the default DVL beam range resolution had shown that, when navigating down-slope, the recorded altitude exhibited cyclic step jumps as the vehicle adjusted the depth window and manoeuvred to follow the specified altitude.

Two missions were run in a sloping section of Jervis Bay to investigate whether setting finer beam range resolution in the DVL resulted in a smoother altitude record, particularly when the vehicle was navigating down-slope. The plans for the two missions were identical, comprising four survey legs 1000 metres long and spaced 15 metres apart running into and out from Captains Beach, as illustrated in Figure 19. Each mission ran for about 41 minutes. Vehicle speed was 4 knots. Water depth shoaled from 15.5 metres at the seaward end of the survey pattern to 6.5 metres at the shore end. The slope of the bottom was about 0.5° . The beam range resolution was set to BR0 (4%) and BR1 (2%) during the missions.

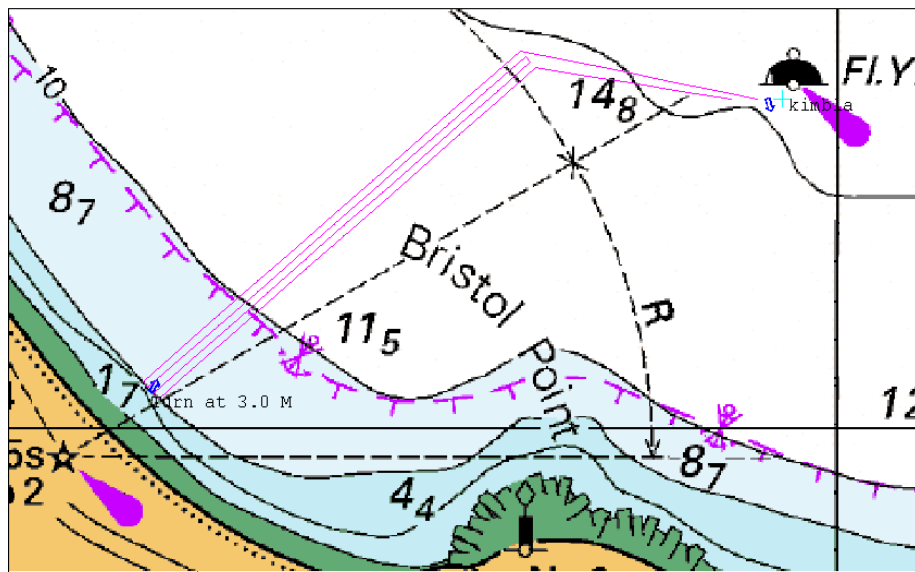


Figure 8: Plans for the Jervis Bay missions running into Captains Beach

The effect of DVL beam range resolution on the up-slope altitude measurements when navigating upslope is shown in Figure 22. The blue trace corresponding to the BR0 mission shows a fairly regular and distinct pattern of step changes in altitude between 0.1 and 0.2 metres as the DVL adjusts the depth window to track the sea bottom. Data from the BR1 mission are more continuous and exhibit much smaller changes in altitude, although steps remain visible.

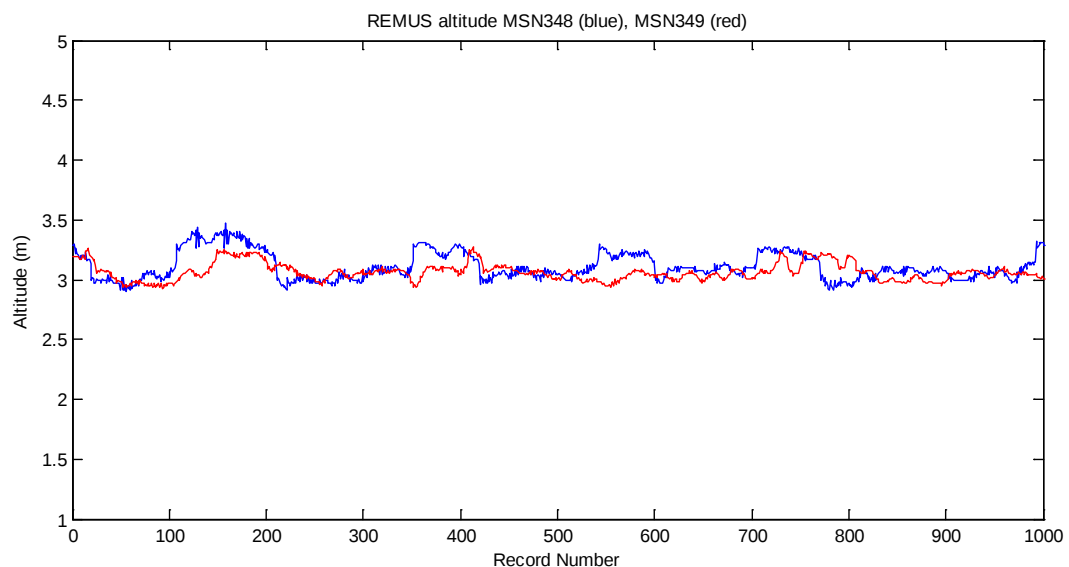


Figure 9: REMUS 100 altitude navigating upslope, BR0 mission (blue) and BR1 mission (red).

Figure 10 compares Jervis Bay reference bathymetry, as derived from soundings provided to DSTO by the Australian Hydrographic Office, with bathymetric records from the

REMUS 100 missions. The reference bathymetry shows a distinct change in bottom slope at about 14 metres depth. This is not evident in the REMUS derived bathymetry which, other than the small scale variations, shows a smooth and continuous transition between deep and shallow. It appears that the reference bathymetry in this region is unreliable, possibly as a result of sand migration over the intervening years.

While it is not possible to assess the accuracy of the REMUS measured bathymetry from this data, it is apparent from Figure 10 that bathymetry measured navigating upslope at both DVL beam range resolution settings matches fairly well, with the finer resolution setting yielding a slightly smoother profile. Bathymetry measured navigating down-slope is more irregular and there is a larger difference between the DVL resolution settings. This is consistent with mode of operation of the altitude control resulting in different altitude-keeping characteristics when navigating upslope compared to when navigating down-slope. This effect is discussed further in Appendix B.

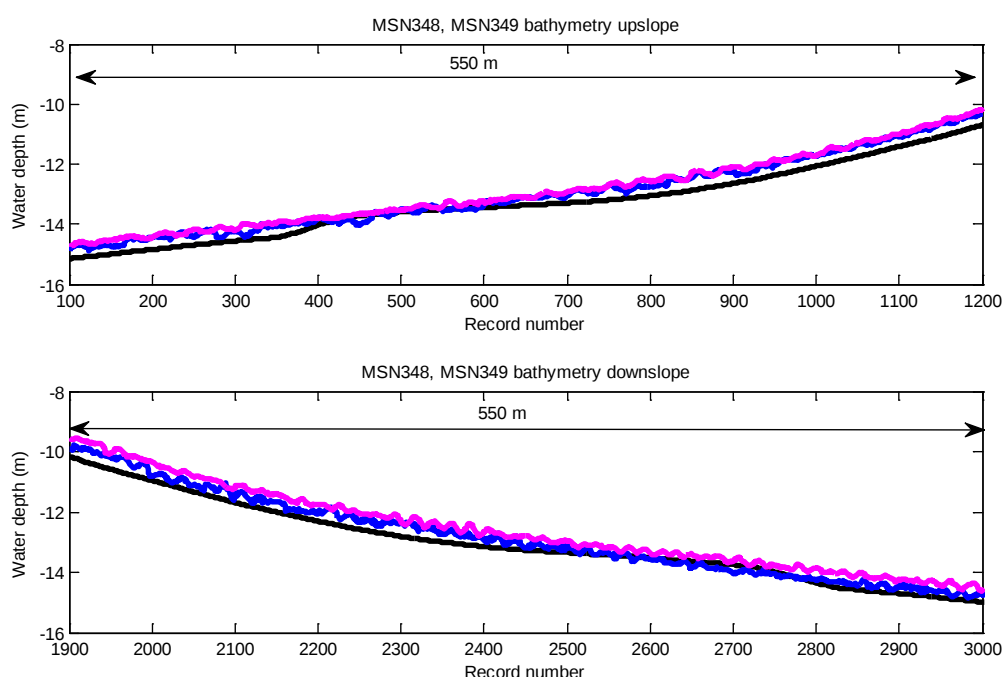


Figure 10: Comparison of Jervis Bay reference bathymetry (black) with REMUS bathymetry from the BR0 mission (blue) and the BR1 mission (magenta), while navigating up-slope and down-slope

4.4 Summary

The DVL beam range resolution is an important parameter, with the potential to determine whether or not a REMUS 100 bathymetric survey has the potential to meet IHO survey accuracy requirements.

In survey applications, it is necessary to use the highest resolution setting that is compatible with the mode of operation. This is BR1 when the vehicle is operating at 3 m altitude and potentially BR2 when the vehicle is operating higher than 6 m. The latter mode requires further investigation to confirm the effect of longer ping times.

If the REMUS 100 is expected to be used for surveying in unfamiliar waters, integration of a high-resolution, survey-grade single-beam echo sounder should be considered.

5. Summary of Performance versus IHO Standards

Table 3 summarises DSTO's assessment of the DSTO REMUS 100, in its original configuration, against IHO requirements for hydrographic survey accuracy. Red cells indicate failure to meet the IHO criteria; orange cells indicate that the REMUS is unlikely to meet the requirements. Yellow cells signify that the REMUS is likely to satisfy the IHO criteria under some circumstances, while green cells show criteria that the REMUS 100 meets or surpasses.

Table 3: Summary of performance of DSTO's REMUS 100 against S44 criteria

Order	Special	1a	1b	2
Allowable THU	2 metres	5 metres + 5% of depth	5 metres + 5% of depth	20 metres + 10% of depth
Allowable TVU	a=0.25 m b=0.0075	a=0.5 m	a=0.5 m	a=1.0 m
		b=0.013	b=0.013	b=0.023
Full seafloor search	Required	Required	Not required	Not required
Feature detection	Cubic >1m	Cubic >2m	Not applicable	Not applicable
		(up to 40 m)		
Max. line spacing	Full sea floor search	Full sea floor search	3 x average depth or 25m	4 x average depth
Position of fixed aids/topography	2 metres	2 metres	2 metres	5 metres
Position of coastline	10 metres	20 metres	20 metres	20 metres
Position of floating aids	10 metres	10 metres	10 metres	20 metres

5.1.1 THU

The DSTO REMUS 100 with the current implementation of GPS navigation does not meet IHO specification for Special Order even when it on the surface and GPS reception is available. Dual-band GPS receivers and augmentation systems like SBAS have the potential to improve precision in position significantly but navigation error increases when the vehicle dives as navigation is then reliant on the INS and the DVL. Acoustic long-baseline augmentation of INS navigation may improve precision in position sufficient to meet IHO criteria for Orders 1a and 1b but this requires very accurate positioning of static acoustic transponders and increases the operational overheads connected with the survey.

Even if the uncertainty associated with GPS were zero, the drift rate of the T-16 INS is such that the THU would be likely to exceed 5 metres after a transit of less than 1 nautical mile.

More accurate INS systems in combination with more accurate GPS receivers may enable AUVs to meet IHO standards for horizontal uncertainty but the requirement to maintain DVL bottom-lock at all times to provide accurate velocity inputs to the navigation system may restrict operations to water depths less than 40 metres.

5.1.2 TVU

In the present configuration the REMUS 100 does not meet IHO TVU specification for Special Order and Orders 1a and 1b. DSTO tests and trials results have shown consistent errors in depth measurement that exceed IHO criteria. The precision and linearity of the pressure transducer should be at least an order of magnitude better than the Honeywell automotive transducer installed in the REMUS 100. Better pressure transducers with much higher specification are available and should be used in AUVs intended for hydrographic survey.

The vertical uncertainty resulting from altitude measurements is setting-dependent and altitude-dependent. At low altitude, errors due to quantisation can be contained to the order of a decimetre. At higher altitude, quantisation errors can be reduced to similar magnitudes by adjustment of DVL parameters, but the validity of the altitude measurement becomes questionable as the points on the seabed being measured move further away from the point under the vehicle. Incorporation of a dedicated hydrographic echo sounder should be considered.

Depth-like signals due to waves passing over the vehicle may induce further bathymetric uncertainty. This effect will be considered in later reports.

5.1.3 Full Sea Floor Search

The normal practice when conducting search surveys with the REMUS 100 is to stagger the pattern of survey lines to ensure 100% sidescan sonar coverage of the sea bottom thus enabling detection and localization of objects on the sea floor. However, the

sidescan is not capable of bathymetric measurement. Altitude and depth are measured only along the track directly under the vehicle.

Swath bathymetric sonar systems that offer simultaneous swath echo sounding and side scan seabed mapping, potentially meeting IHO Standards for Hydrographic Surveys, are advertised but Kongsberg Hydroid do not recommend the REMUS 100 as a platform for these sonars. Instead, they market a survey-specific variant called the REMUS 100-S for this purpose.

5.1.4 Feature Detection

High frequency sidescan sonars fitted to small AUVs like the REMUS 100 are capable of detecting mine like objects and features smaller than specified in the IHO standards for Special Order.

5.1.5 Position of Fixed Aids and Topography

The sidescan sonar in the REMUS 100 is designed to detect and localize objects on the sea bottom. There is limited capability to detect objects mid-water. The REMUS 100 is not capable of surveying fixed aids to navigation to the required standard as the uncertainty in horizontal position exceeds the IHO criterion.

6. Conclusion and Recommendations

The REMUS 100 AUV, in the configuration reported here, cannot reliably meet IHO specification for hydrographic survey for Special Order and Orders 1a and 1b. The principal failing is uncertainty in positional accuracy that exceeds standards for Total Horizontal Uncertainty when submerged. A better GPS receiver would improve positional accuracy by a few metres when the vehicle is surfaced but this by itself is insufficient to reduce the uncertainty in horizontal position when dived and will need to be augmented by better underwater navigation if the THU criteria are to be satisfied.

Navigation accuracy relies on the downwards-looking DVL continuously providing forward and transverse velocities to the inertial navigation system. Better INS systems may enable AUVs to meet IHO standards for positional uncertainty but maintaining bottom lock at all times to provide accurate velocity inputs to the navigation system may restrict operations to water depths less than 40 metres. In shallower water, periodically surfacing during a mission to obtain a GPS fix to update the navigation solution will minimize the positional uncertainty.

When checked against a higher-precision depth sensor in a CTD profiler, the depth sensor in the DSTO REMUS 100 reported depths that were about a metre shallower than the profiler at 25 metres depth. This discrepancy exceeds the IHO TVU specification for Special Order and Orders 1a and 1b in water depths less than 40 metres. DSTO has

replaced the standard pressure transducer in the REMUS 100 with a better specified version but has yet to check this sensor's characteristics.

DVL beam range resolution settings BR1 (measurements quantised at 2% of range) or BR2 (quantised at 1% of range) are preferred for bathymetric survey. DVL altitude measurement is better and more consistent at these settings compared to the standard BR0 (quantised at 4% of range) setting. The effect will be more pronounced if the vehicle is operated at higher altitudes.

6.1 Recommended Configuration

Given that there is no standard for hydrographic survey in the course of Rapid Environmental Assessment, IHO Order 1b may be a useful guideline for the accuracy to be expected from a REMUS 100-style AUV fitted with sidescan sonar, but not swath sonar. The following instrumentation is recommended for use in that context:

- Pressure/depth sensor with accuracy equivalent to 0.1% of depth and resolution in excess of this value
- Survey-grade inertial navigation system, capable of maintaining the growth of positional uncertainty to better than 0.1% of distance travelled.
- Survey-grade single-beam echo sounder with accuracy better than 5 cm for altitudes from 0.5 to 100 m
- Dual-frequency GPS receiver, preferably with the capacity to log pseudo-ranges for application of carrier-phase differential corrections in post-processing

7. Reference

International Hydrographic Organization, *IHO Standards for Hydrographic Surveys* (5th Edition, February 2008), *Special Publication No. 44*

Appendix A: Bathymetric Trials

DSTO conducted two trials to characterise the bathymetric accuracy of the REMUS 100, along with its dependence on the depth control mode and the DVL depth resolution setting. The first trial was conducted in White Bay, Sydney and the second in Jervis Bay, NSW. Tide data recorded at nearby tide stations were used to reduce water depths measured by the REMUS to the local vertical datum.

A.1. White Bay

DSTO conducted a short trial in White Bay, Sydney, to assess the effect of the DVL beam range resolution settings on bathymetric measurements from the REMUS 100. At the time, White Bay was a relatively benign environment, away from busy harbour shipping channels and with little surface vessel traffic to interfere with vehicle operations. Importantly, high resolution bathymetry of the bay was available from a multibeam sonar survey conducted by Sydney Ports.

7.1.1 Mission Profile

The trial comprised three missions. The missions were identical, other than for the beam range resolution settings and consisted of four legs down the length of the bay as shown in Figure 11. The beam range resolution settings used were, in order, BR0, BR1 and BR2. Each mission ran for about 22 minutes as shown in Table 4, and was about 2350 metres in length. Vehicle speed was programmed as a propeller revolution rate of 1250 rpm, corresponding to 3.6 knots.

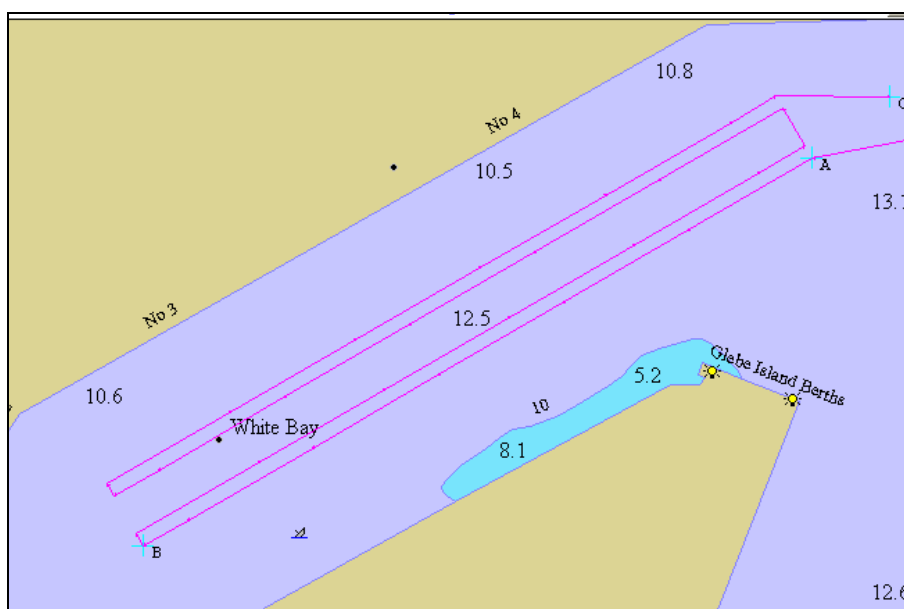


Figure 11: Mission plan for REMUS White Bay bathymetry assessment

The vehicle entered the survey area at point A and executed four legs of the bay before loitering at point C, where the mission was terminated by acoustic command. The sensitivity of the ADCP was changed by modifying the BR parameter in the ADCP configuration file via WiFi, restarting the vehicle to load the new configuration and sending the 'RUN' command to start the mission.

Table 4: Mission BR settings, start and end times

Mission Number	BR Setting	Time (K)	
		Start	End
MSN317	BR0	08:33	08:56
MSN318	BR1	09:10	09:32
MSN319	BR2	09:40	10:02

7.1.2 White Bay Reference Bathymetry

Reference bathymetry of White Bay at 0.5 metre contour intervals on a 1 metre grid, extracted from a larger multibeam survey of Sydney Harbour conducted by Sydney Ports is shown in Figure 12. The red line in the figure marks the vehicle's track during MSN319. Water depth along the track varied between 12 and 14 metres.

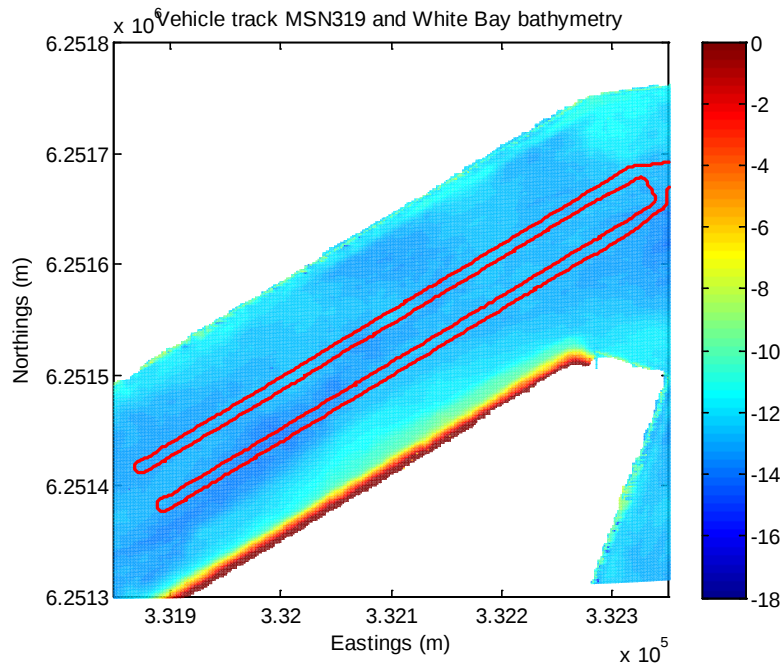


Figure 12: REMUS track in White Bay during MSN319, overlaid on bathymetric data from Sydney Ports

A.1.1 Correction for Tide

Tidal corrections corresponding to each data record during the missions were calculated by curve fitting and interpolating tide height data measured at Fort Denison during the missions. Tide heights recorded at six minute intervals during the mission period are shown in Figure 13. The red sections of the curve represent the tide data during the missions.

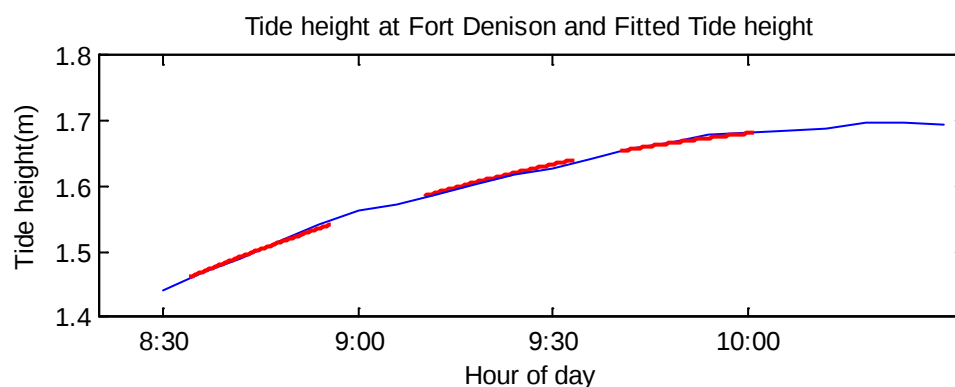


Figure 13: Observed tide at Fort Denison on 25 November. Red sections show tide during missions.

A.1.2 Analysis

Post mission, ADCP and vehicle State data files were extracted from the mission log file using the REMUS Vehicle Interface Program (VIP) and exported as MATLAB data files. The REMUS logged ADCP data slightly faster than 4 times a second. Hence, at speed 3.5 knots, altitude, depth, latitude and longitude were available at about 0.4 metre intervals along track. At speed 4 knots data were spaced about 0.5 metres apart. Vehicle state data were logged slightly slower than 1 Hz.

REMUS altitude and depth measurements were available only along the vehicle track and, as line spacing during the surveys varied between 10 metres and 30 metres, the data density was too low to reliably contour the bathymetry to enable direct comparison with the reference bathymetry data in Figure 12 and Figure 20. As an alternative, water depth measured by the REMUS was compared with the bathymetry along the vehicle track.

A.1.3 Vehicle Altitude

Figure 14 compares the vehicle altitude recorded during missions MSN317 (blue), MSN318 (red) and MSN319 (black). Altitudes near 4 metres occur when the REMUS turns to a new heading. The data appear to match well with only minor differences, but on this scale it is difficult to determine if the different resolution settings have any significant effect. The large deviations below 1.5 metres in the altitude traces near records 3000 and

4600 are caused by the Kearfott INS resetting and re-synchronising the DVL. The high excursions approaching 4 metres correspond to turns.

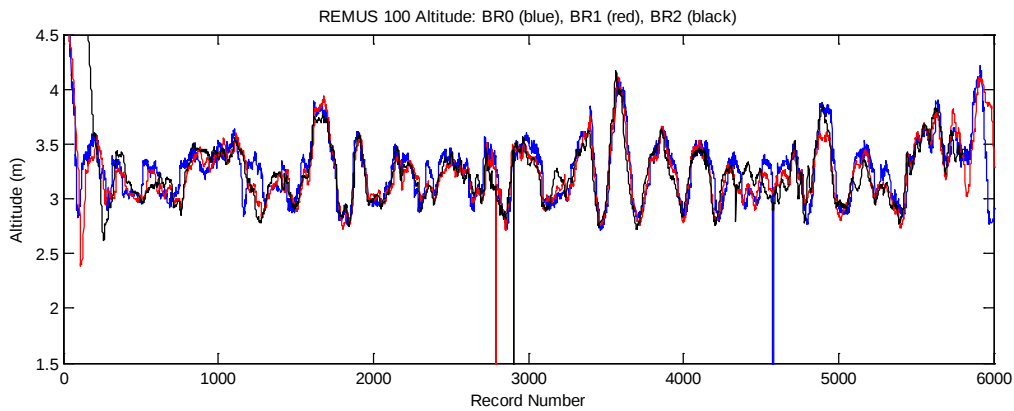


Figure 14: REMUS 100 altitude MSN317 (blue), MSN318 (red) and MSN319 (black)

Figure 15 is an expanded 150 second section of Figure 14. In this figure, the recorded altitude during MSN317 exhibits irregular step-like changes 10 to 15 centimetres in magnitude, and intermittent noise like bursts of a few seconds duration where the altitude rapidly fluctuates by a few centimetres. The vehicle altitude recorded during MSN318 and MSN319 with the higher depth resolution settings are smoother and less variable. The only difference in the vehicle configuration between the missions was the setting of the BR parameter. While some of the variability between missions may be attributed to the REMUS following slightly different tracks on each mission, there appears to be benefit in using a higher ADCP resolution than the default.

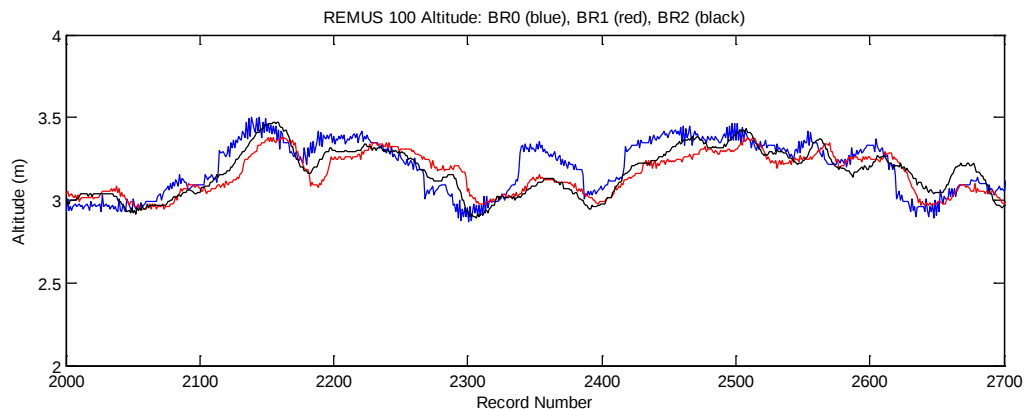


Figure 15: Comparison of altitude traces MSN317 (blue), MSN318 (red) and MSN319 (black)

A.1.4 Comparison with Reference Bathymetry

Bathymetry measured by REMUS along the first leg of each mission (heading 240°) and the White Bay reference bathymetry along the vehicle track are plotted in Figure 16. Minor differences in the reference bathymetry between the plots are attributed to small differences in the positions logged by the DVL during the missions.

Bathymetry measured using the default 4% depth resolution window, tends to be irregular and deviates most from the Sydney Ports data with differences up to 0.5 metre. Bathymetry at the higher resolution settings of the DVL is more regular and more closely follows the reference bathymetry but, as expected at 3 metres altitude, there appears to be only marginal improvement at the highest 1% depth resolution setting compared to the 2% setting.

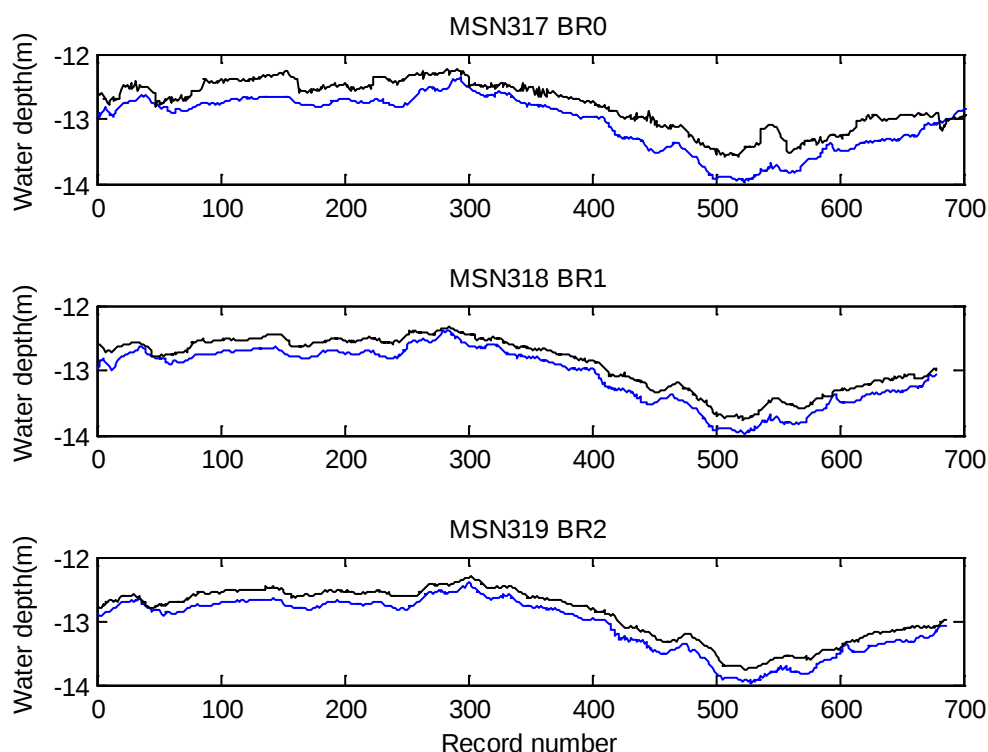


Figure 16: Comparison of REMUS bathymetry and White Bay reference bathymetry along the first leg of each mission. Reference bathymetry (blue), REMUS bathymetry (black)

Differences between REMUS bathymetry data and the reference bathymetry are plotted in Figure 17. The record for MSN317 with setting BR0 is the noisiest and exhibits the largest deviations from the reference bathymetry. The traces for MSN318 and MSN319, corresponding to resolution settings BR1 and BR2, are very similar, as expected.

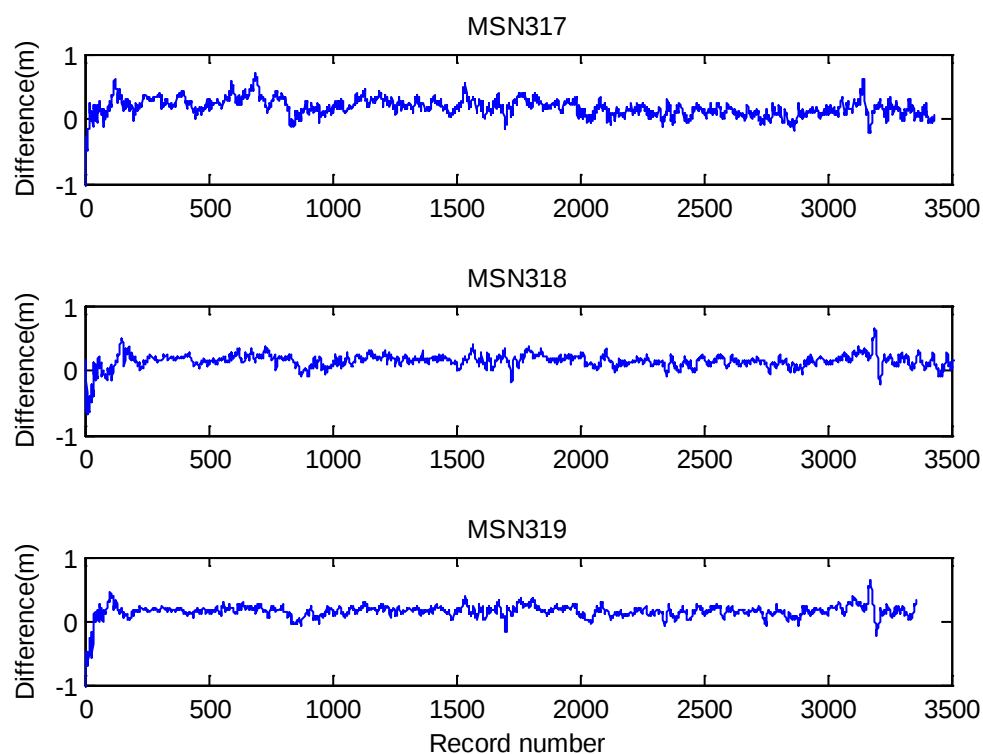


Figure 17: Difference between REMUS bathymetry and White Bay reference bathymetry for DVL beam range resolution settings BR0, BR1 and BR2

A.1.5 REMUS VIP Contour Bathymetry

The REMUS VIP can generate contour bathymetry plots. However, as bathymetry is available only along the vehicle track there is significant extrapolation and interpolation in contouring the data and consequent reduction in resolution.

Figure 18 shows interpolated bathymetry from MSN319 calculated using the REMUS Vehicle Interface Program (VIP). This data is not corrected for tide so indicated depths are approximately 1.5 metres deeper than shown in the Sydney Ports survey. The grid size is 7 metres. Plots using a finer grid do not completely fill the wide area between the vehicle tracks.

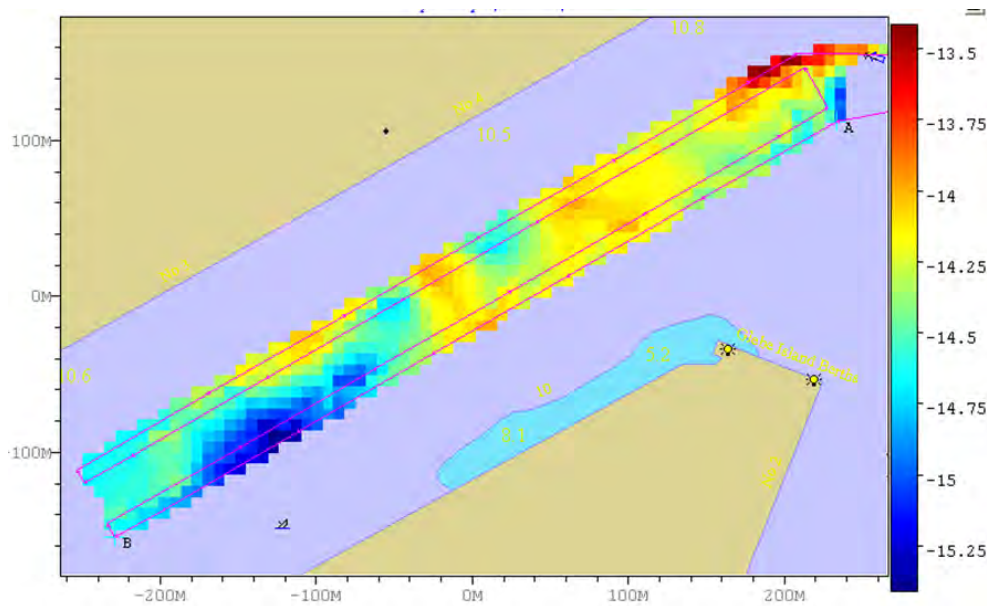


Figure 18: White Bay bathymetry calculated using the REMUS Vehicle Interface Program (VIP) plotter. Grid spacing 7 is metres

A.2. Jervis Bay

Prior to the White Bay missions, the DSTO REMUS vehicle had been always operated with the default BR0 parameter, corresponding to a 4% DVL depth resolution setting. The White Bay missions were conducted over a relatively flat sea bottom; however, data from other missions with the REMUS using the default DVL depth resolution had shown that, when navigating down-slope, the recorded altitude exhibited cyclic step jumps as the vehicle adjusted the depth window and manoeuvred to follow the specified altitude.

As part of a series of experiments in Jervis Bay, two missions were run with the REMUS to investigate whether setting finer resolution in the DVL resulted in a smoother altitude record, particularly when the vehicle was navigating down-slope.

A.2.1 Mission Profile

The mission plans for MSN348 and MSN349 were identical, but used different DVL depth resolution settings 4% and 2% respectively. The mission plan comprising four survey legs 1000 metres long and spaced 15 metres apart running into and out from Captains Beach, Jervis Bay is illustrated in Figure 19. Each mission, listed in Table 5, ran for about 41 minutes. Vehicle speed was 4 knots. Water depth shoaled from 15.5 metres at the seaward end of the survey pattern to 6.5 metres at the shore end. The line length was 1000 metres so the bottom slope was about 0.5°.

Table 5 Mission BR settings, start and end times

Mission Number	BR Setting	Time (K)	
		Start	End
MSN348	BR0	13:02	13:43
MSN349	BR1	13:53	14:33

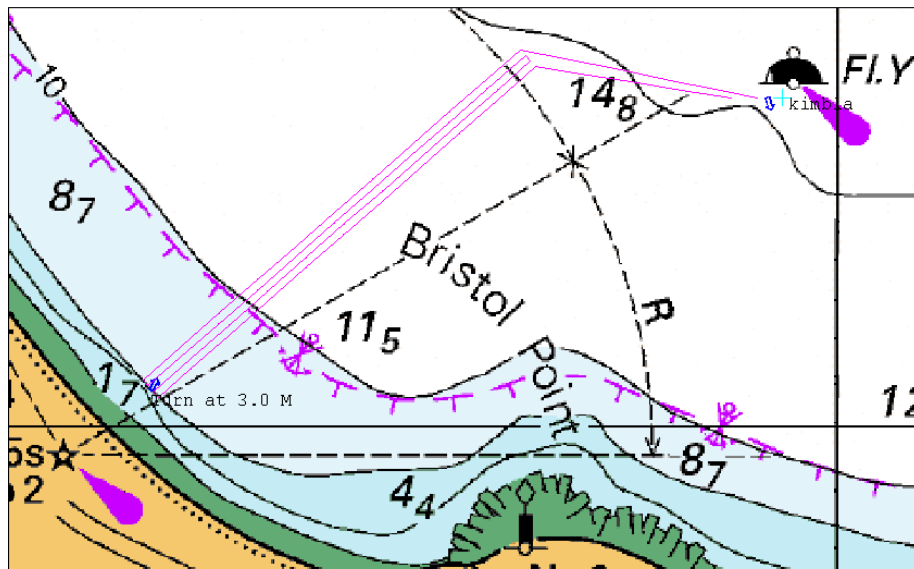


Figure 19: Mission plan for MSN348 and MSN349 REMUS bathymetry assessment

A.2.2 Jervis Bay Reference Bathymetry

Reference bathymetry for Jervis Bay was derived from several sources including a LADS survey of the southern shore area of Jervis Bay conducted several years previously. Grid spacing was 5 metres. Figure 20 shows the recorded track for mission MSN348 overlaid on bathymetry of Captains beach, Jervis Bay.

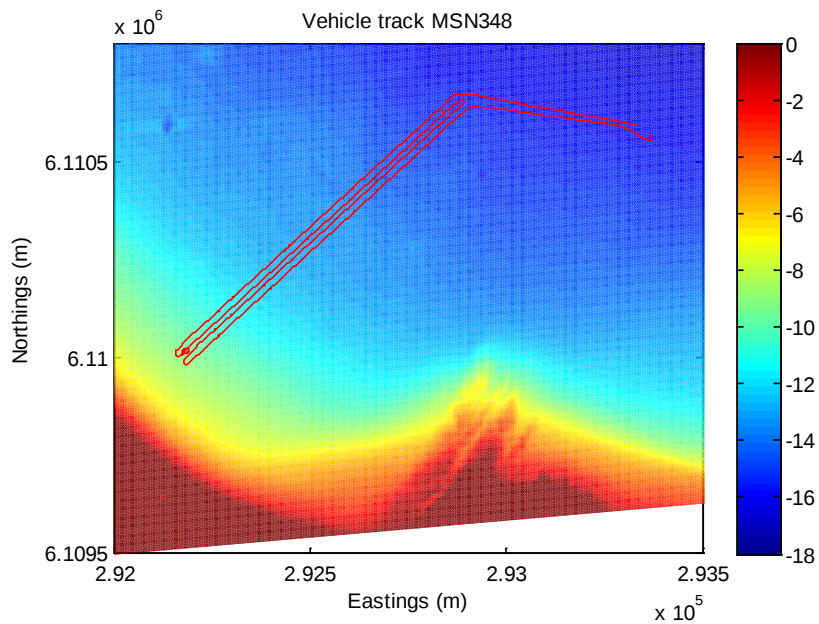


Figure 20: Vehicle track during MSN348 overlaid on Jervis Bay reference bathymetry

A.2.3 Correction for Tide

Tide heights recorded at 15 minute intervals by the gauge at HMAS Creswell on the day of the missions are plotted in Figure 21. Data in the interval marked red, spanning missions MSN348 and MSN349, were smoothed and interpolated to provide tidal corrections to water depths calculated from the REMUS data.

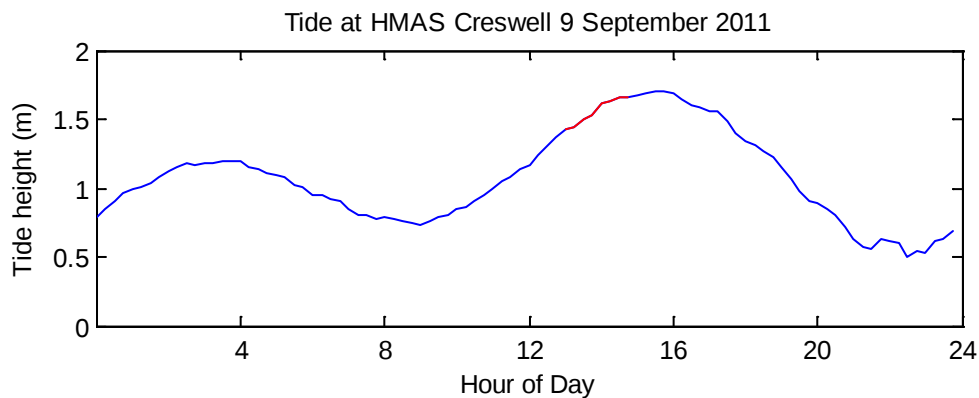


Figure 21: Tide recorded at HMAS Creswell 6 September 2011. Section marked red spans time of MSN438 and MSN439.

A.2.4 Vehicle Altitude

The effect of DVL depth resolution in the altitude measurement when navigating upslope is shown in Figure 22. The blue trace corresponding to MSN348, with the default parameter BR0 set, shows a fairly regular and distinct pattern of step changes in altitude of between 0.1 and 0.2 metres as the DVL adjusts the depth window to track the sea bottom. Data from MSN349 (shown in red), where the depth resolution was 2% of altitude, are more continuous and exhibit much smaller step changes in altitude.

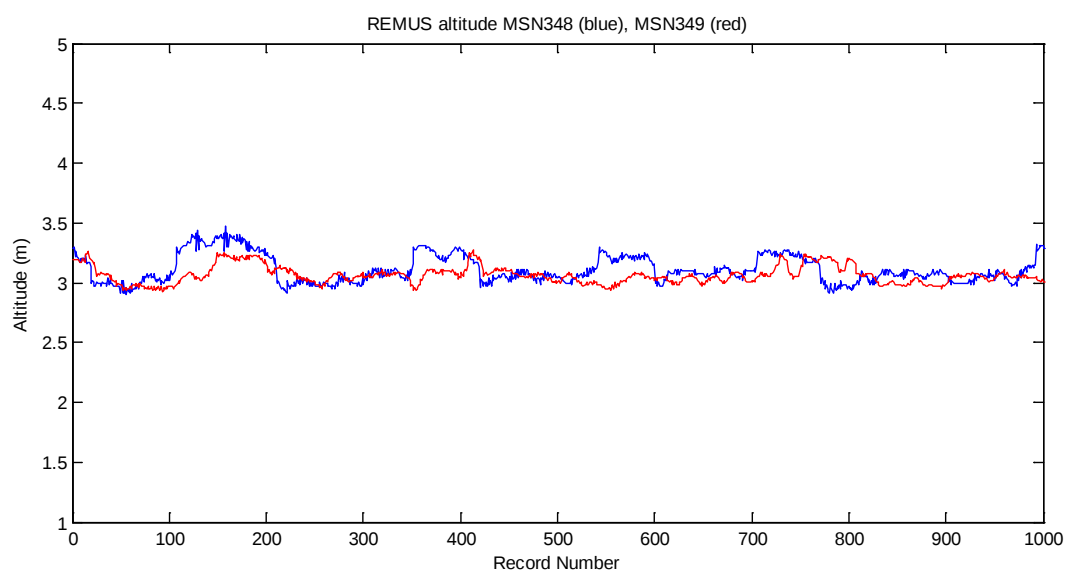


Figure 22: REMUS 100 altitude navigating upslope, MSN348 (blue) and MSN349 (red).

A.2.5 Comparison with Reference Bathymetry

Up-slope and down-slope bathymetry measured by REMUS are compared to the Jervis Bay reference bathymetry in Figure 23. The reference bathymetry shows a distinct change in bottom slope at about 14 metres depth. This is not evident in the REMUS derived bathymetry which, other than the small scale variations, shows a smooth and continuous transition between deep and shallow. It appears that the reference bathymetry in this region is unreliable, possibly as a result of sand migration over the intervening years.

While it is not possible to assess the accuracy of the REMUS measured bathymetry from this data, it is apparent from Figure 23 that bathymetry measured navigating upslope at both DVL depth resolution settings matches fairly well, with the finer resolution setting yielding a slightly smoother profile. Bathymetry measured navigating down-slope is more irregular and there is a larger difference between the DVL resolution settings. This is consistent with mode of operation of the altitude control resulting in different altitude keeping characteristics when navigating upslope compared to when navigating down-slope.

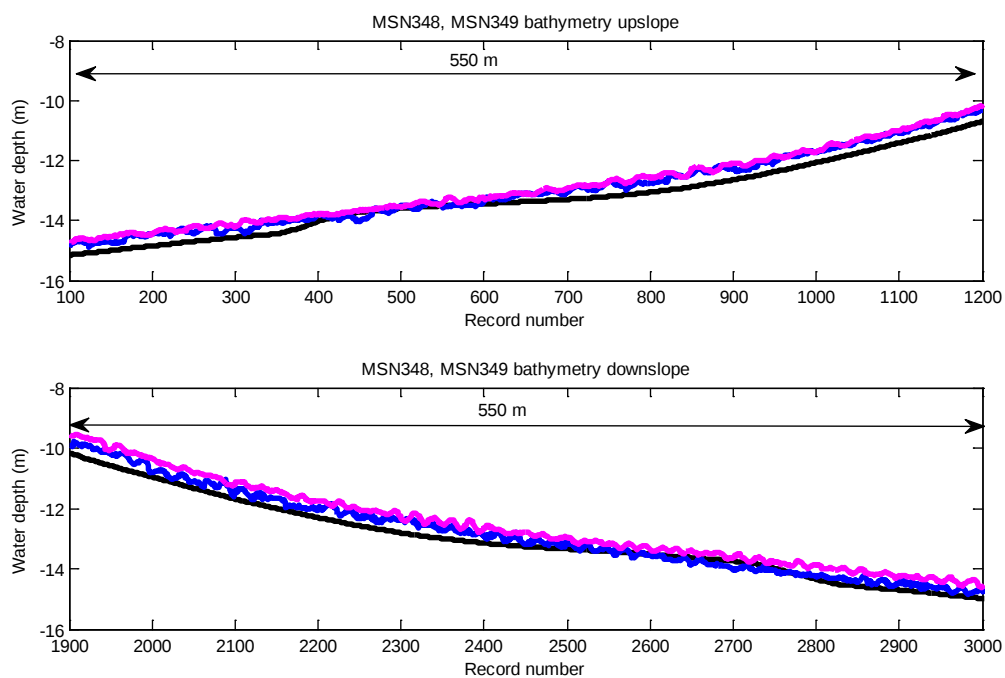


Figure 23: Comparison of REMUS bathymetry upslope and down-slope with Jervis Bay reference bathymetry (black). MSN438 (blue) and MSN439 (magenta)

Appendix B: Depth Controller Effects

Bathymetric records from some missions suggest that the depth or altitude-control behaviour of the REMUS 100 vehicle may influence the altitude measurements.

When navigating in altitude mode close to the sea floor, the REMUS control software program continuously monitors the vehicle's altitude in a running 20 second buffer or watch interval. If the measured altitude drops below the specified value, the REMUS climbs to attain the programmed altitude, updates the minimum altitude and restarts the watch interval. The new minimum altitude is retained in the buffer until the 20 seconds has elapsed or a lower altitude is recorded.

On an upward-sloping bottom, the vehicle's altitude will constantly decrease as the vehicle attempts to fly level and the bottom rises towards it. The measured altitude will fall below the programmed altitude frequently and the vehicle will continually respond to increase the altitude on a regular basis, resulting in a fairly smooth altitude record.

The converse is true when navigating down-slope, as in this case the altitude tends to increase as the bottom falls away from the vehicle. As the minimum altitude is unlikely to fall below the programmed altitude in the 20 second watch interval the altitude adjustments will be less frequent but larger as the vehicle manoeuvres to maintain the required height above the sea bottom.

This behaviour was observed during a ladder search in Jervis Bay near Scottish Rocks. Water depth varied from 16 metres offshore to 10 metres inshore. Vehicle speed was 3 knots.

The mission progressed normally and no anomalous behaviour or vehicle fault was observable. Analysis of mission ADCP altitude data showed a distinct up-and-down cycle that was repeated at about 50 second or 75 metre intervals on the seaward legs as the water gradually deepened.

This effect is illustrated in Figure 24, a section of the REMUS altitude record during the mission. At a distance of 14600 metres from the start of the mission, the REMUS started navigating up-slope, before turning at 15200 metres to navigate down-slope on the reciprocal course. During the up-slope leg where the water depth gradually decreased, the vehicle maintained altitude within a few centimetres of the specified 3 metres. However, when navigating down-slope towards deeper water, the altitude exhibited a cyclic pattern of up-and-down variations that typically exceeded 40 centimetres.

The overall pattern of stable altitude on the shoreward legs but relatively large altitude oscillations on the seaward down-slope legs was repeated throughout the survey.

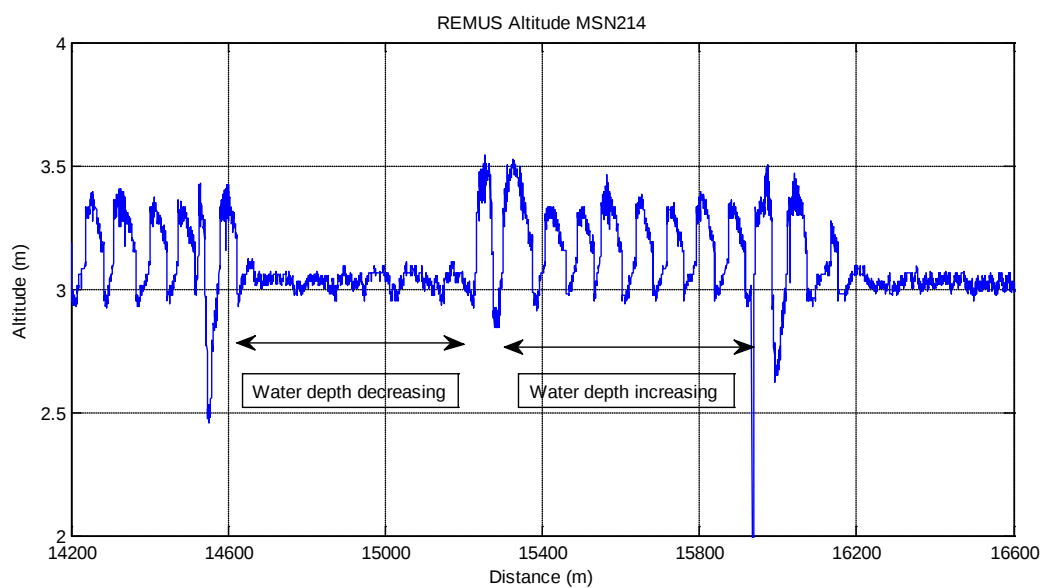


Figure 24: REMUS altitude during the initial part of MSN214, a ladder search survey mission conducted in Jervis Bay

Appendix C: Trials of Opportunity

The following section is a brief discussion of the results of some trials of opportunity that DSTO performed with the REMUS 100 after the integration of the Honeywell MLH150PGB06G pressure sensor. The quality of the bathymetric soundings available for Jervis Bay is variable and their accuracy and currency is suspect. Therefore, the following results cannot be considered conclusive.

C.1. Beach Survey Mission

The RAN conducted a beach survey mission, MSX008, during a tactical development period in April-May 2013. The mission plan is shown in Figure 25.

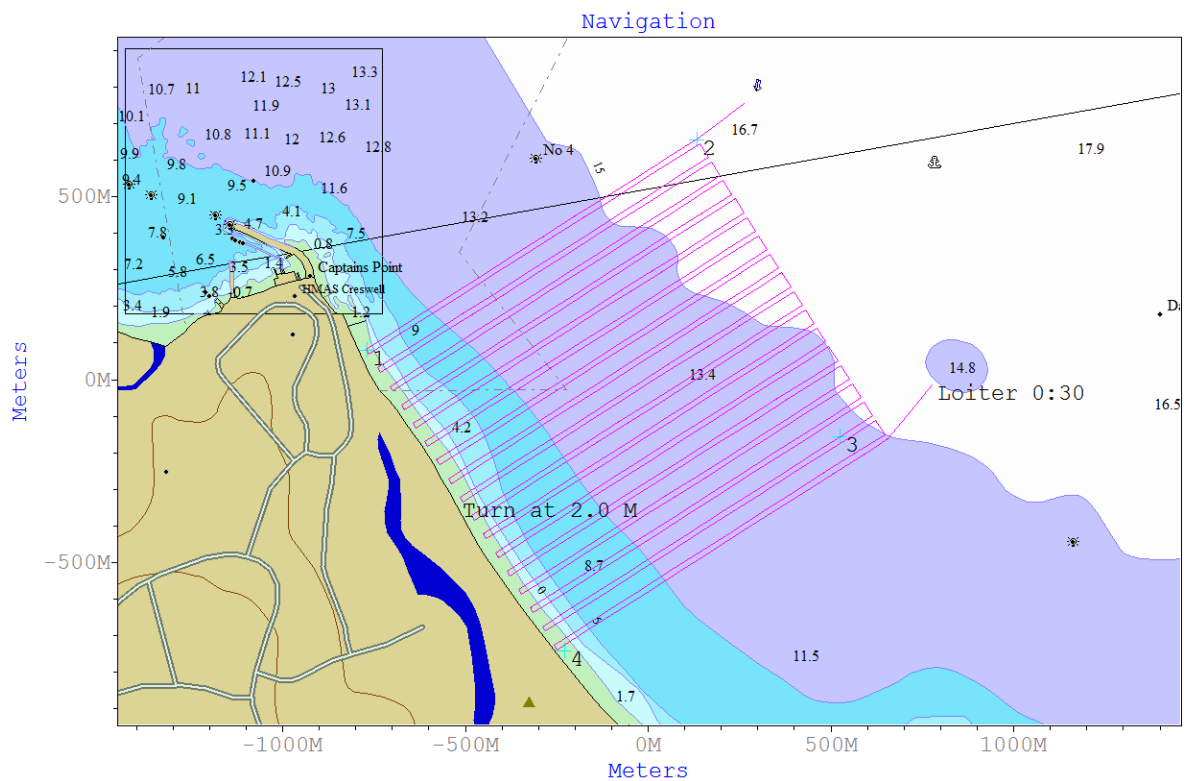


Figure 25: Plan of the REMUS 100 very shallow water beach survey mission

The beach survey mission partially overlapped an area of high sounding density in the Jervis Bay reference data set (Figure 26), so it was potentially useful as a means of quantifying the performance of the new depth sensor.

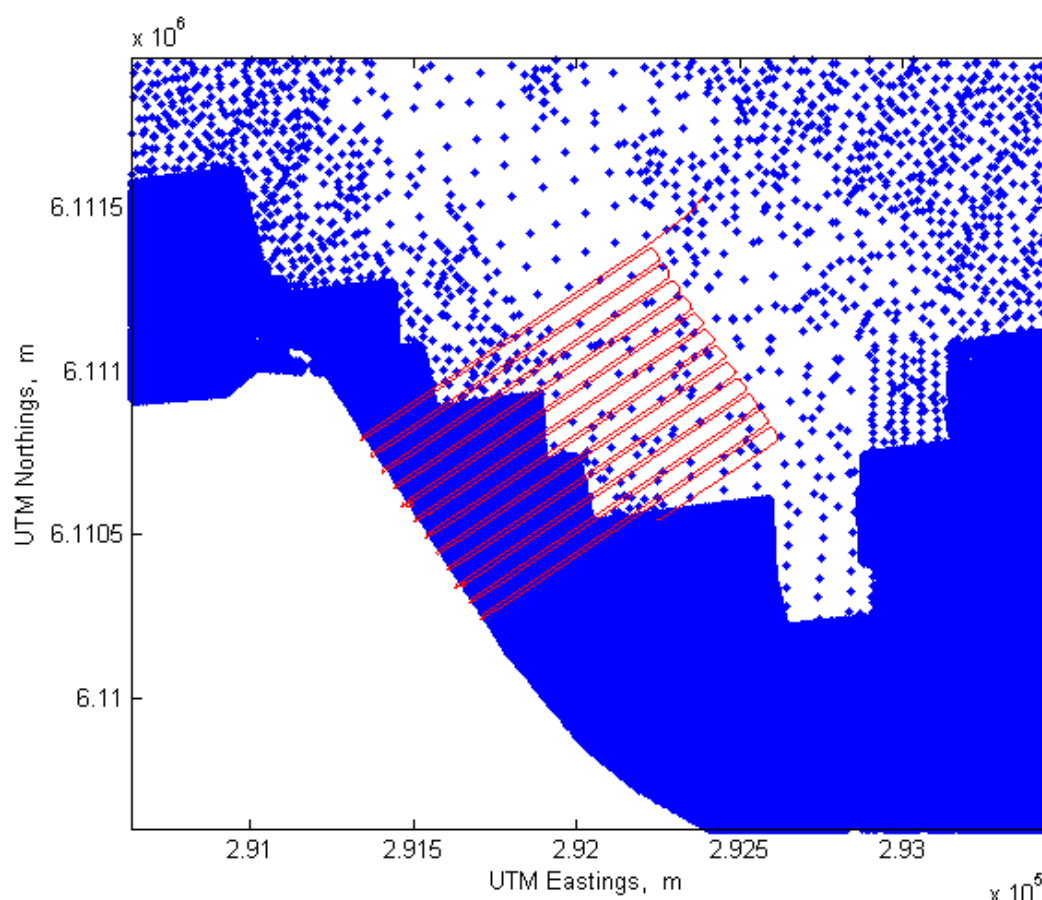


Figure 26: Jervis Bay reference data set sounding density (blue dots) and the track of the REMUS 100 during the beach survey mission

The soundings from the REMUS vehicle were tidally corrected using records from the HMAS Creswell tide gauge and compared with soundings interpolated from the reference dataset using the Matlab routine 'griddata'. The histogram of the resultant sounding differences is shown in Figure 27.

An empirical cumulative distribution function evaluated from the soundings, after removal of outliers, gave a median difference between the two sets of soundings of 0.33 m, with 95% confidence intervals at 0.04 m and 0.64 m. Examination of the associated difference surface (Figure 28) showed features that may be seafloor morphology, with the implication that the reference soundings may be out of date and that sand transport has altered the local bathymetry.

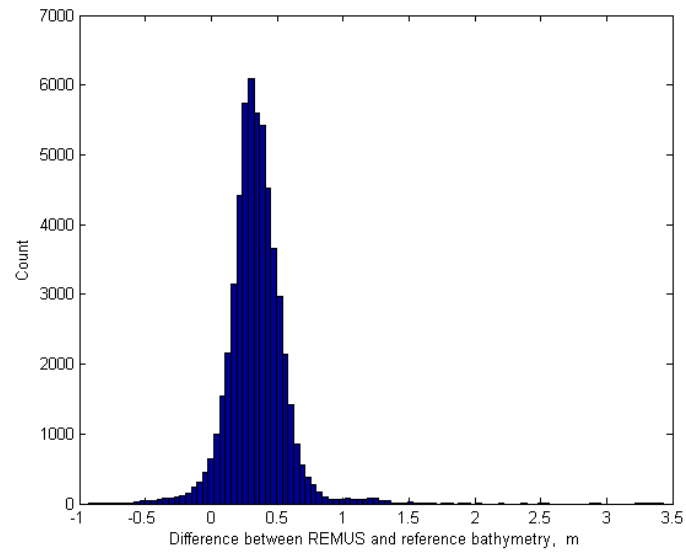


Figure 27: Histogram of the difference between the REMUS 100 bathymetric soundings, after tidal correction, and the Jervis Bay reference data set. Outlier soundings due to measurement errors have been discarded

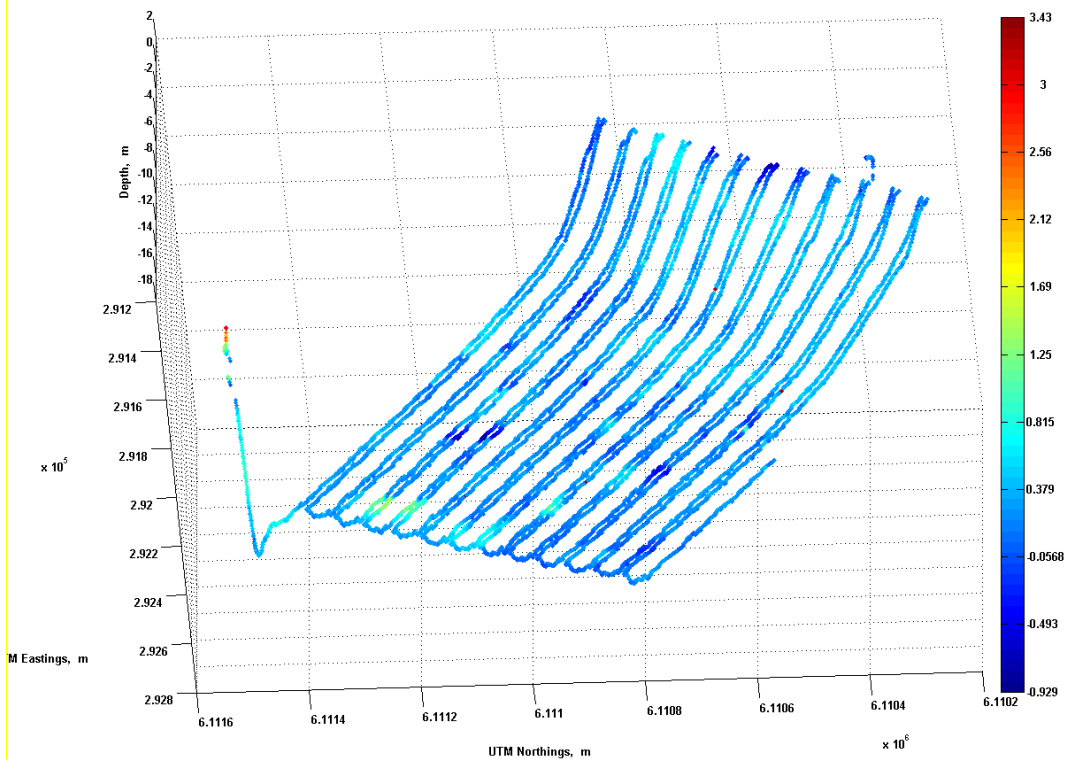


Figure 28: REMUS 100 depth soundings in isometric projection, coloured by their difference from the reference bathymetric data

C.2. Central Bay Reacquisition Mission

DSTO conducted a mission to re-survey some sonar contacts in the middle part of Jervis Bay, with a mission plan as show in Figure 29.

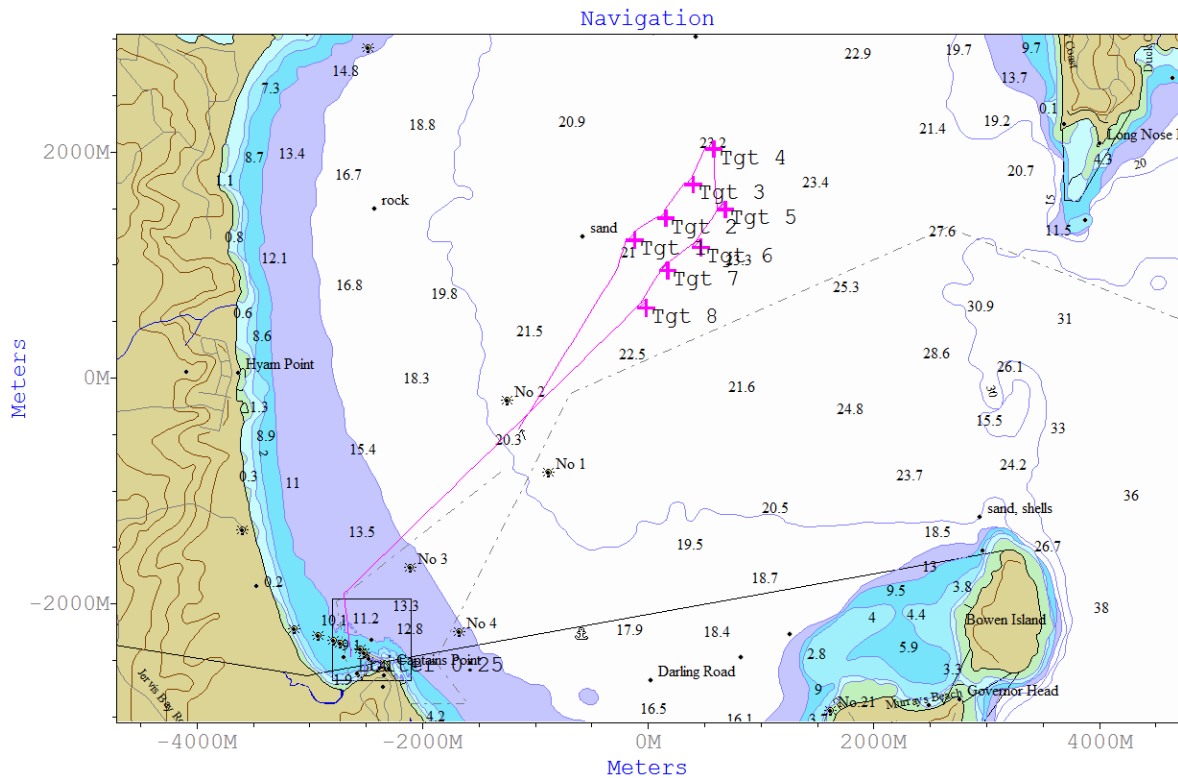


Figure 29: Plan for contact reacquisition mission

The mission carried the vehicle across approximately 50% of the extent of Jervis Bay, and included areas of moderate water depth and very low slope that might be expected to be bathymetrically stable.

The associated histogram of sounding differences is shown in Figure 30. An empirical cumulative distribution function evaluated from the soundings, after removal of outliers, gave a median difference between the two sets of soundings of 0.33 m, with 95% confidence intervals at -0.13 m and 0.96 m. The median value is identical to the beach survey, but the confidence intervals are approximately twice as wide.

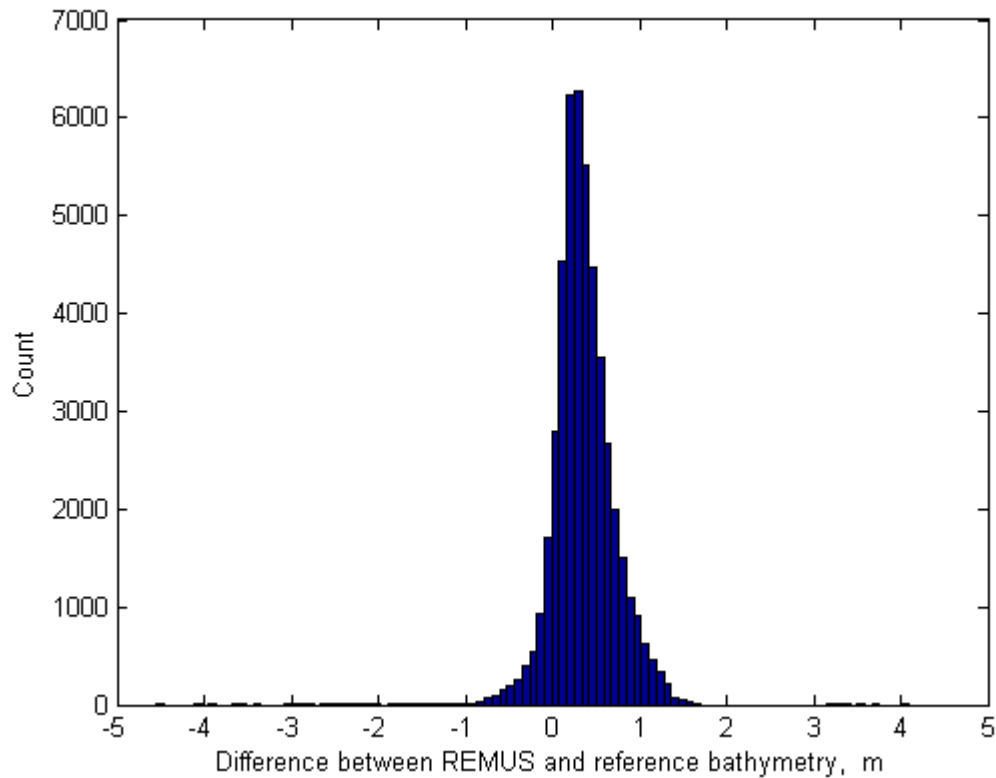
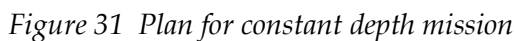


Figure 30: Histogram of the difference between the REMUS 100 bathymetric soundings, after tidal correction, and the Jervis Bay reference data set. Outlier soundings due to measurement errors have been discarded

C.3. Middle Harbour Depth Mode Mission

A short mission to test the effectiveness of conducting REA by operating the REMUS in depth mode rather than at constant altitude was conducted in Middle Harbour, Sydney. The REMUS was programmed to run several times over the same north-south track between points A and B, Figure 31.



The mission log file indicated that, on each leg, the vehicle maintained depth within about 0.2 metres of the programmed depth. This result appeared to be inconsistent with the derived bathymetry which showed the water depth increasing by more than 0.5 metres between leg 1 and leg 4 of the mission as shown in Figure 2. The tide rose by about 0.12 metres during the mission but this was insufficient to cause the observed increase in water depth. The inference is that the depth sensor in the REMUS overestimated the depth of the vehicle and that even over the short range of depths reported here was in error by almost 0.5 metres.

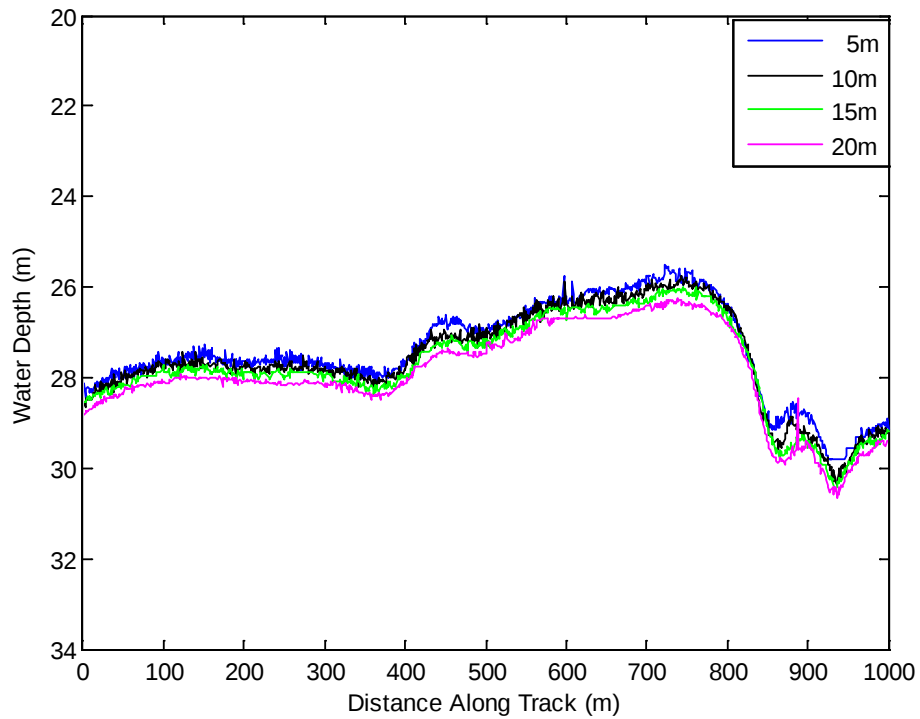


Figure 2 Middle harbour bathymetry measured during mission MSX026

C.4. Summary

The preliminary analysis presented here shows systematic offsets and uncertainty margins in excess of IHO total vertical uncertainty limits for Special Order and Order 1 bathymetric surveys. It is possible that these results will not survive more exhaustive scrutiny.

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19. ABSTRACT This report describes assessments of a REMUS 100 autonomous underwater vehicle owned by DSTO as a tool for hydrographic survey. It concludes that DSTO's vehicle as currently configured cannot meet horizontal and vertical uncertainty standards for Special Order and Order 1 surveys as defined by the International Hydrographic Organization. In particular, the GPS sensor and the depth sensor are deficient and should be upgraded if the vehicle is to be used for hydrographic surveying. The settings of the Doppler velocity log should also be optimized to provide the best altitude resolution, or a dedicated single-beam echo sounder should be integrated into the vehicle. Hydrographic vehicles such as the REMUS 100-S and the Gavia are more appropriately configured for this application.					