EFFECT OF UPGRADES ON THE RELIABILITY OF THE AUTOSUB AUV

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Abstract

After the Autosub autonomous underwater vehicle had completed a 2-year series of science research missions in 2001 an extensive upgrade programme was undertaken to prepare the vehicle for three campaigns under floating polar ice shelves in 2002-4. The reliability of the vehicle had been assessed and documented prior to the upgrades by examining the instances of high-impact faults when the vehicle was underway. This paper examines what affect the programme of upgrades had on the vehicle and on its reliability. While many of the problems that were encountered were due to the new hardware and software, the most serious faults arose from the need to dive deeper than had previously been the norm. This need brought to light deficiencies in the wet-matable connectors used throughout the vehicle. Following a statistical analysis of the faults, a test programme is proposed to re-establish confidence in the vehicle.

1. Introduction

The Autosub project at the Southampton Oceanography Centre focuses on using AUV technology in the service of marine science (Millard et al., 1998; Millard et al., 2003). In order to achieve this broad objective the project includes periods of relative stability for the vehicle configuration (operational periods) and periods of development (upgrade periods). The purpose of this paper is to examine how a series of major upgrades during 2001-2 affected the reliability of the vehicle on its post-upgrade trials and what measures were taken to improve reliability, or at the least, to mitigate the risks on its return to operational service for an Antarctic campaign in 2003.

Little has been published on AUV reliability and even less on AUV reliability statistics. In an insightful paper, Stokey et al., (1998) described practical problems and solutions for the Remus vehicle. Griffiths *et al.* (2003b) attempted to quantify the reliability of the Autosub AUV from its very first missions within Empress Dock, Southampton in 1996 to midway through its first operational programme in mid 2000. That period comprised 153 missions that were, in a general sense, engineering test missions and 88 operational missions under the 'Autosub Science Missions' programme.

Here, we update our analysis to include the remaining 33 operational science missions to June 2001 (including missions under sea ice in the Antarctic), 34 engineering trial missions during major upgrades in 2002 and, after the upgrades, 18 operational missions in the Antarctic during 2003. The upgrade programme was in support of new science objectives for the 'Autosub Under Ice' programme whose first field campaign began in February-March 2003 on the RRS *James Clark Ross* (cruise JR84).

This paper is organised as follows: Section 2 outlines the upgrades to hardware and software carried out in 2002; Section 3 begins by describing the performance of the upgrades during two dedicated engineering trials cruises (TER1 in June 2002 and TER2 in September/October 2002). Both trials took place on continental shelf and shelf edge waters in the SW Approaches to the UK. A discussion follows on the Critical Items List approach that was taken to prioritise risks and to set out mitigation strategies. Section 3 closes with a review of the performance of the vehicle during its science cruise JR84. Section 4 describes a statistical analysis of vehicle performance, compares performance before and after the upgrades, and discusses what further trials may be needed to return the vehicle to its pre-upgrade state of reliability. Conclusions are set out in Section 5.

2. The upgrades to Autosub: 2001-2

The extensive changes to Autosub over the period July 2001 – May 2002 were intended to meet the requirements of the three science campaigns to be undertaken in 2003-4 underneath ice shelves in Antarctica and Greenland. The major modifications fell into two categories: new instruments and sensors and new software to extend the mission capability of the vehicle. Crucially, while not a true upgrade, the vehicle was to be tested for routine use at depths greater than 500 m – a depth only exceeded for some 10's of hours over the previous 272 missions.

Minor internal modifications were made within the four 2.8 m long 254 mm internal diameter carbon fibre battery tubes to improve the thermal insulation. Stevenson et al. (2002) had shown that the performance of the manganese alkaline energy source could be improved by at least 10% by (a) pre-heating the packs prior to launch and (b) improving the thermal insulation within the packs to make use of waste heat generated by the batteries. These modifications were entirely successful.

2.1 New Instruments and Sensors

These upgrades comprised adding:

- A 200 kHz swath bathymetric sonar; to be used for seabed mapping and (by physically inverting the transducer) swath observations of the underside of sea and shelf ice.
- A 4-12 kHz chirp sub-bottom profiler (penetration echo sounder) to obtain the stratigraphy within the sediments beneath the seabed.
- A water sampler capable of capturing up to 50 water samples, each of 250 ml, for later chemical analysis. This was an uprated instrument, Autosub had previously carried a version rated to 100 m.
- A 150 kHz acoustic Doppler velocity log and current profiler. This replaced the well-proven 300 kHz instrument and was needed to provide a bottom-track range of ~ 400 m.
- An inertial navigation system (INS) based on an integrated package of three fiber-optic gyrocompasses, three accelerometers and processing firmware based on a Kalman filter. This INS replaced the 3-component fluxgate magnetometer used previously as a heading and motion reference unit.
- A low frequency (4.5 kHz) acoustic beacon and low data rate telemetry link (1 bit.s^{-1} over ~40 km) that the vehicle would deploy on a lowered line in an emergency to aid relocation e.g. in the event of the vehicle becoming trapped beneath sea ice.

2.2 New Software

The upgrades to the vehicle software and firmware involved:

- A complete redesign of the mission control software: The main features added and changes made included:
    - Mission instruction format: the Opcode-Operand format was extended to allow 950 mission instructions per mission.
    - A disjunction (logical or) of up to 3 events was implemented (previously only 1) and ordered sequences of events to trigger the next mission element were added.
    - Total number of mission events was increased to 34 - including two from payload equipment, up from seven.
    - Two conditionally entered mission termination scripts were added.
    - Scripted control output to payload equipment.
    - A control mode for the vehicle's homing behaviour was added.
    - The mission compiler was modified and a new downloader was developed as a consequence of the mission control redesign.
- Improving the collision avoidance behaviour; in particular to implement a more robust procedure when the vehicle encountered an iceberg. In essence, the vehicle would turn to retreat along a (near) reciprocal course, offsetting across track while increasing its depth before reattempting forward progress towards its assigned waypoint.
- Adding a special collision avoidance response: to respond to minimum headroom (ice shelf), minimum separation of ice shelf and seabed (grounding line).
- Providing for synchronisation of acoustic instruments.
- Remote control via acoustic link of sub-bottom profiler, and mission initiation.

3. Performance of the upgrades

3.1 Engineering Trials: 2002

3.1.1 Instruments and Sensors

Trials TER1 in June 2002 provided the first opportunity to test all of the new systems in an operational environment. A number of minor faults were detected and corrected, such as an 'O' ring leak, a connector leak and a pulled-out crimp terminal. Electrical noise was found to be affecting the range and performance of two acoustic systems – the SeaPam telemetry link and the forward-looking altimeter. Noise levels were reduced through additional filtering on the power, data and control lines.

A more serious problem was with the swath bathymetry sonar. No data was obtained from the instrument, as the team was unable to effect the correct message format setting, despite communications with the manufacturer.

On one mission (m282) the motor failed to start on the surface, even though Mission Control had issued the start command, it had not been received by the Motor Control. The reason was not established at the time, it was logged as an 'unknown network issue'. The at-sea solution was to change the Mission Control software to send repetitive mission demands (nagging). No subsequent problems of this type were noted on these trials. With hindsight, this *may* have been an instance of the connector problem discussed in detail below.

As there remained a number of problems outstanding at the completion of the TER1 trials, a second trials cruise, TER2, was scheduled for Sept-Oct. 2002. The successes on TER2 included:

- Swath bathymetry data collected over 20-150 m range in water depths to 1400 m.
- Upward-looking swath data gathered.
- Sub-bottom profiler acoustics section proven.
- Bottom-track Doppler velocity log acquisition at ranges of 450 m demonstrated, and navigation at 350 m achieved, Figure 1.
- Successful digital data telemetry over 3 km; emergency beacon range >15 km when inside the vehicle.

Despite these successes, a number of problems remained with the instruments and sensors. The most severe was the realisation that several different problems could be traced to intermittent loss of contact through the wet-matable connectors used throughout the vehicle. As the

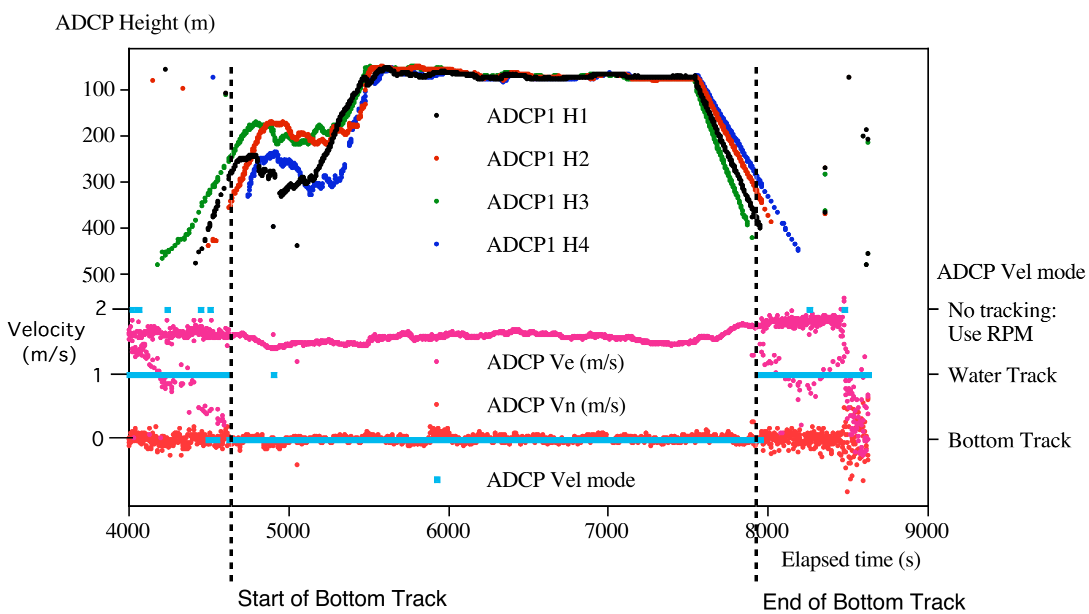

Figure 1 A composite figure showing (upper panel) ADCP height off bottom for the four beams while moving towards the UK shelf edge on m296. The forward-looking beam (green) shows the first return from the seabed, but it is not until the third beam (red) locks on that bottom tracking for velocity determination becomes possible. The forth beam (blue – looking aft) comes in a little later. The bottom panel shows the east and north velocity components together with the indicator of which velocity mode was being used (bottom or water track or the propeller rpm).

vehicle uses a distributed network architecture, matched by physical modularity, intermittent failure of any one of these connectors could (and did) result in interruption to network data and module power supplies with unpredictable results. Diagnosis and repair were difficult, not only because the faults were intermittent, but the faults only occurred under pressure (30-50 bar). Individual suspect connectors were replaced and the trials ended with an apparently stable network and power distribution system.

Problems persisted with the swath bathymetry sonar – its recorded data could only be viewed by playing back in real time and depth information was not being recorded. Ancillary data (depth, position, time) was not recorded by the sub-bottom profiler. Also, the down ADCP bottom track performance continued to be of concern (although an improvement over its performance on TER1). It was suspected that noise or interference resulted in only ~ 95% of pings tracking the bottom (up from ~ 88% on TER1), the remainder being water track (~ 1%) motor control speed (~ 0.5%) and absent data (~3.5%), Figure 2.

3.1.2 Software

On the TER1 trials 13 bugs came to light in the new vehicle software. These ranged from those that were easily fixed such as a wrong scale factor in the ADCP processing node to more complex ones, such as omitting to correctly bind the speed variable from the motor controller to the up and down ADCPs. This resulted in zero vehicle speed being recorded when the ADCP used for navigation lost both bottom *and* water track. In addition to software bugs, there were performance issues connected with traffic on the network, for example, an inadequate update rate from the INS system that manifested itself as poor track following performance. In this and similar cases, increasing the data buffer size effected an improvement.

With much of the TER1 trials given to fixing problems, the new vehicle control behaviours were not tested thoroughly. These tests were a priority on the subsequent TER2 trials, including:

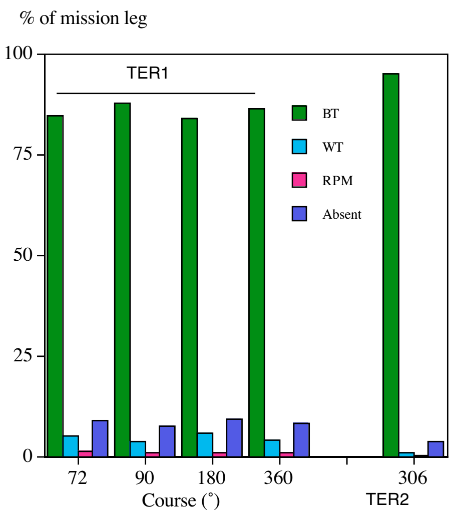

Figure 2 Histogram of the percentage of time that the vehicle was able to make use of bottom track velocity (green) on m285 during trials TER1 and on m306 during TER2, showing an improvement, but not to 100%.

- Successful tests of the 'minimum headroom' collision avoidance mode, using the sea surface to simulate the underside of an ice shelf.
- Simulated 'iceberg avoidance' missions, in which an air curtain was formed behind the ship to give acoustic returns that represented the side of an iceberg, Figure 3.
- Proving tests of the depth control modes (constant depth, constant altitude, constant distance to upper boundary, profiling between upper and lower boundaries), Figure 4.

Bugs continued to be identified and rectified on trials TER2 – four in the mission control software, two in the mission compiler and three in position control and collision avoidance. As described in section 3.1.1 network problems due to intermittent connectors dogged resolution of several software errors.

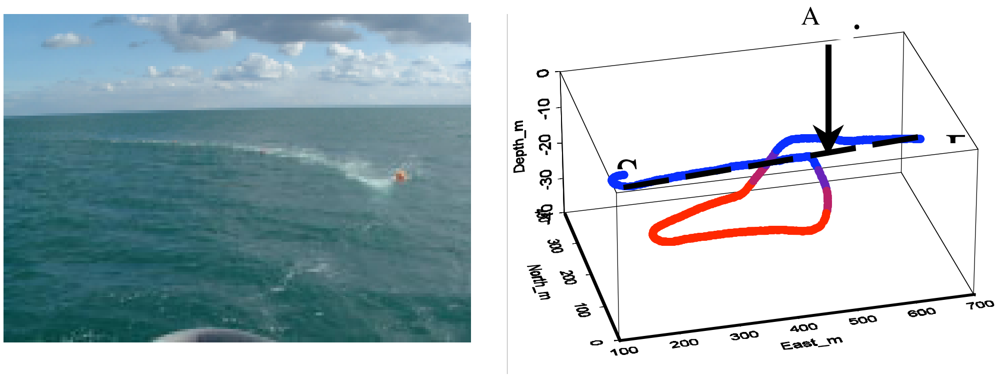

Figure 3(a) An air curtain formed by injecting compressed air into a pipe towed underwater behind MV *Terschelling* to allow the vehicle's sonar to obtain simulated iceberg echoes, (b) the vehicle track on an 'iceberg' avoidance mission (m302). When the 'iceberg' is detected (at 'A') the vehicle turns, dives deeper, and attempts to make progress towards its next waypoint.

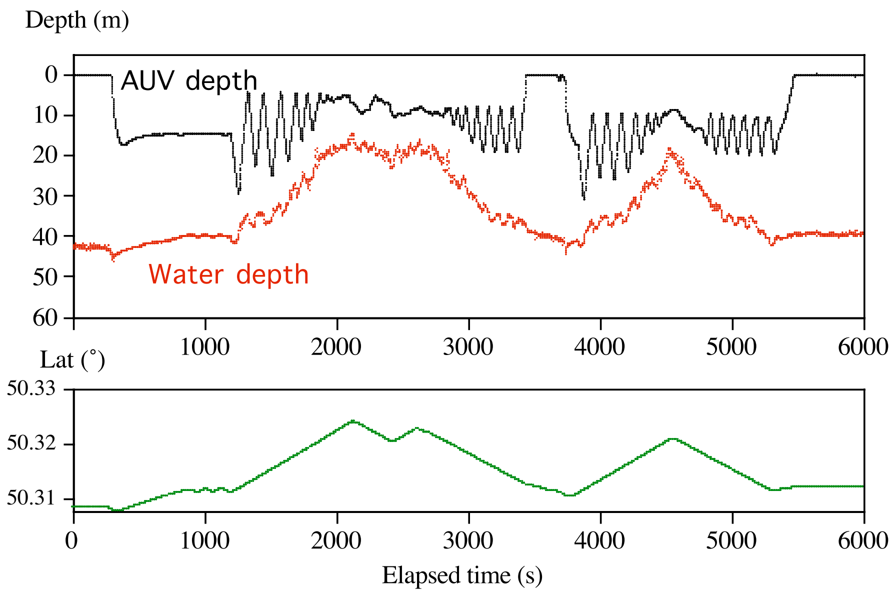

Figure 4 Depth control modes (upper panel) shown as different vehicle depth segments while approaching shore on m306, using the sea surface and the bottom to simulate the underside of an ice shelf and the seabed. The lower panel shows the latitude to illustrate vehicle track.

3.2 Managing risk

At the completion of the TER2 trials there were a number of problems that remained with the vehicle. Recognising this fact, and that AUV missions beneath ice shelves carry significant technical and logistical risk (Griffiths et al., 2003(a)) a risk analysis was undertaken based on knowledge gained during the trials. Each individual risk was assigned a score (P) based on an assessment of the probability of occurrence and an impact factor (I) based on the likely effect on the science campaign or the vehicle (Copley, 2003). Robust probabilities of occurrence for most of the risks were not available, despite previous fault analyses. As a consequence, values of P were assigned from the set [1 2 3 undefined] where 1 represented the lowest probability of occurrence (< 10%) and 3 represented the highest (~>70%). Values for I ranged from 1 (minimal impact) to 4 (vehicle loss).

This Critical Items List approach (O'Connor, 1995) enabled the technical and science teams to concentrate efforts on mitigating those risks with the highest P x I product and on devising contingency plans. Where risks were eliminated during trials or in the laboratory (i.e. when P became 0) they were retired from the register. At the beginning of science cruise JR84 in February

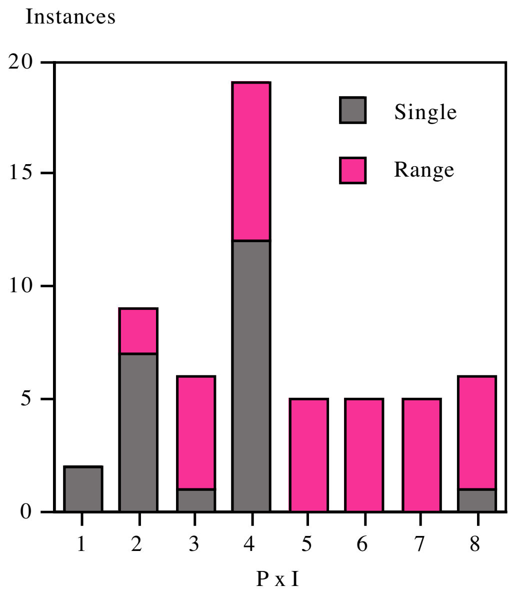

Figure 5 Histogram of instances of occurrence of the P x I product at the departure of Autosub on cruise JR84 in February 2003. Where the values of P x I spanned a range, these are shown separately.

2003 the risk register still contained 30 entries, summarised as a histogram of unmitigated P x I values in Figure 5. One risk was assigned the highest unmitigated single P x I value of 8, two were assigned a range of 4-8 and three a range of 3-8. From Copley (2003):

- P x I =8 - *Autosub encounters severe unknown bathymetry beyond the ability of the collision avoidance system*. Here, severe bathymetry is defined as a step in topography (up for the seabed, down for an ice ceiling) of equal or greater magnitude than the altitude (or headroom) of the vehicle with a slope of 45° or greater. In the case of the outer continental shelf of Pine Island Bay, 600 m of relief may exist in a water depth of 1400 m, with channels 1-10 km long, 1 km wide and 400 m deep. In mitigation, unpublished data suggests that topography is more subdued near the ice shelf and these data will be used in mission planning.
- P x I =4-8 - *Collision with vessel during launch/recovery*. Collision with the ship, most likely on recovery, is an established risk. AUVs have been lost, or damaged beyond immediate repair, through such collisions. The mitigation strategy covers four points: 1) formal briefing between the Autosub team leader, the Master of the vessel, the Principal Scientist and those involved in launch and recovery operations to establish clear procedures and channels of communication; 2) ship personnel already have experience operating Autosub in the Antarctic; 3) use an additional line on recovery to allow extra time for the procedure; (4) attach a buoy/fender on a long line to one of recovery lines to allow an "abort" option during recovery, whereby the ship can retreat to reassess the situation before continuing.
- P x I =4-8 - *Local sea ice conditions change during mission*. As missions may last tens of hours, sea ice concentration may increase, precluding recovery at the target position. Mitigation: 1) launch and recovery should be planned for areas with high confidence of sufficient open water; 2) drawing on the expertise of all aboard, together with available meteorological data, an assessment must be undertaken of the likelihood that open-water will become ice-covered during the period of a mission before clearance is given to proceed; 3) Autosub is programmed not to surface if it detects a sea ice ceiling, instead proceeding to an additional waypoint. The vehicle will continue attempting to surface along this course.
- P x I =3-8 - *Failure of bulkhead connector(s)*. Tests have shown that bulkhead connectors going open-circuit intermittently caused many of the problems encountered during both trials in 2002. Extensive testing provided some confidence in weeding out suspect connectors, but concern remained. There was insufficient time before the Antarctic campaign to change all of the connectors of the type causing the problem (34 pairs). A minority of connectors was critical and would result in vehicle loss; as failure of an individual connector cannot be predicted, the probability of greatest impact is therefore lower than that of lesser impact. Where bulkhead failure results in network failure, the vehicle surfaces on reserve buoyancy. Mitigation: 1) connectors will be further tested at appropriate water depth (300-400 m) during early trial missions on cruise JR84; 2) connectors will also be tested in "holding pattern" trials at the start of science missions, using deep water where possible.

Missions would not proceed unless the holding pattern tests were successful.

- P x I =3-8 - *Error in ice tracking by vehicle*. Autosub employs a bottom-tracking 150 kHz ADCP for navigation; tracking of a static shelf ice ceiling (by the upward-looking 300 kHz ADCP) may also be possible but may introduce greater risk if the nature of the signal from the ice is not checked in advance. Previous Autosub missions under icebergs suggest the ice surface is a very strong reflector (rather than scatterer), yielding either a good or very poor return signal depending on orientation. Missions beneath ice shelves to the grounding line, defined for this purpose as water column thickness of 150 m or less, depend on the ability to detect the ice ceiling and hence monitor diminishing headroom. Mitigation: test ice shelf ceiling tracking ability during initial ice shelf missions, collecting upward-looking ADCP data.
- P x I =3-8 - *Error in water column tracking by vehicle*. If bottom or ceiling tracking data are unavailable (as a result of being out-of-range of either surface), Autosub uses the ADCP to estimate speed through the water. This relies on sufficient scatterers in the water to provide a signal. Their abundance is unknown beneath an ice shelf. Mitigation: 1) examine ADCP backscatter from beneath sea ice missions to check the regional prevalence of scatterers; 2) check prevalence of scatterers using data collected during initial ice shelf missions.

In the event, five of these six risks with a P x I of up to 8 were encountered on the JR84 cruise. It is clear that without the mitigation strategies developed as part of the Critical Items List approach, unmitigated, these risks would have led to the loss of the vehicle. The occurrence and impact of these risks are described in the next section.

3.3 Antarctic campaign: 2003

3.3.1 Instruments and Sensors

The most serious technical set-back on the Antarctic campaign JR84 was the reappearance of intermittent contacts on the vehicle's network connectors. It became increasingly clear that this was not a problem with a few particular connectors e.g. due to dirty or corroded contacts, rather, it was a generic failure that could occur with any of the connectors of this type at any time. Demonstrating a working system once (e.g. as at the end of the TER2 trials) was not a good guide to future reliability. As on the TER2 trials, the intermittent behaviour was only seen when the connectors were under pressure, in the region 500-1000 m when descending and at shallower depths when ascending. Only on one mission (m316) did the vehicle surface not working.

Over seven missions (m311-m317) various connectors were replaced or exchanged. At best, a set was identified that showed minimal dropouts at depths shallower than 250 m. As a consequence, deep diving missions beneath the ice shelf were abandoned and the remainder of the campaign was limited to work beneath sea ice[1] - these missions (318-324) covered some 220 km.

The swath bathymetry sonar continued to be dogged with minor problems, including: near surface returns being discarded when in upward-looking mode, jumps in the position timestamps, bugs remaining in the manufacturer's control software and instances of reduction in data quality from electrical interference. The bottom tracking ADCP continued to suffer an unacceptably high proportion of dropouts to water track and propeller rpm, and the water track range was poor. Both continue to be investigated. Confidence in the water sampler was low; analysis showed that many samples appeared to be cross-contaminated.

3.3.2 Software

Only three minor problems were attributed to software on JR84: early ADCP data was bad/incomplete due to a programming error; an incorrectly set configuration variable meant that the vehicle aborted its dive at the very start of a mission and a timer was not being reset but just paused. This only manifested itself because of the particular way that a mission was scripted and made use of the timer. The result was that a subsequent mission element time-out occurred when one was not demanded and the position control was sent a navigation mode and demand early. This was detected on examination of the logged navigation data. Subsequent mission scripts were written to prevent the problem recurring.

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[1] For the record, the Master of the *James Clark Ross* had decided that there would be too great a risk in attempting a passage to the ice front of Pine Island Bay Glacier. Sea ice and iceberg conditions were also deteriorating as fall approached and he was not sanguine of the ship getting back out into open water.

3.3.3 Review of the Critical Items List

How useful was it to the team when on JR84 to have carried out the Critical Items List analysis? Did it have any correspondence with reality? Of the six risks afforded the highest P x I score, five were encountered on the cruise. The only risk not encountered was the first: *Autosub encounters severe unknown bathymetry beyond the ability of the collision avoidance system.*

- *Collision with vessel during launch/recovery*. A collision that resulted in damage to the nose of Autosub, to the sub-bottom profiler transducers and the CTD sensors occurred on m319. The damage was sustained on recovery in 35-40 kt winds (winds had been ~25 kt on deployment). The presence of ice hampered the recovery but the damage was done when the vehicle disappeared briefly under the counter. The vehicle, without the damaged instruments, was back in the water two days later.
- *Local sea ice conditions change during mission*. After successful completion of m320 the vehicle surfaced 200 m clear of the ice edge. It was left in the water while the next mission was downloaded, but in the meantime the ice conditions changed and ice surrounded Autosub. Recovery was difficult as the vehicle was difficult to see, however only minor damage was sustained (to the GPS antenna and the port sternplane).
- *Failure of bulkhead connector(s)*. This is discussed in section 3.3.1.
- *Error in ice tracking by the vehicle*. While not exactly the scenario envisaged, an attempt was made on m322 to navigate relative to the (moving) sea ice. However, the ice motion (~25 $cm.s^{-1}$) caused significant error in the navigation. This mission was in a water depth exceeding the bottom track range of the 150 kHz down ADCP.
- *Error in water tracking by vehicle*. Again, not the exact scenario envisaged, but reverting to water track in deep water for m324 resulted in navigation error due to a ~15 cm.s-1 current that resulted in the vehicle ending its 12 hour mission some 8 km east of its intended track. Finding the Autosub took several hours.

In all of these cases, the thinking process that had gone into preparing the Critical Items List helped in solving (or coping) with the problems encountered on JR84. The prior analysis and subsequent set of procedures were important factors in ensuring that the Autosub survived despite severe problems.

4. Fault statistics before and after the upgrades

A previous statistical analysis of Autosub reliability fitted a Weibull parametric model of reliability to Autosub fault data up to m240 using SAS Institute's JMP™ software (Griffiths et al., 2003b). For a Weibull parametric model, if the distance to a fault is represented by X, the distribution function – the probability that there will have been a fault before a distance x has been reached is given by:

$$\Pr(X < x) = F(x) = 1 - \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right] \tag{1}$$

where α is the characteristic life and β the shape parameter. In this analysis, as in Griffiths et al., (2003b), we confine ourselves to those high impact faults that occurred when the vehicle was underway. High impact faults comprise those faults that caused vehicle loss (none) or resulted in actual (or potential) damage to the vehicle or triggered the emergency abort system or resulted in failure to meet the primary objective of the mission. Not counted in the statistical analysis, therefore, are those faults that were caught while the vehicle was on deck or in the water before launch or, for example, where a sensor of secondary importance failed or recorded poor data.

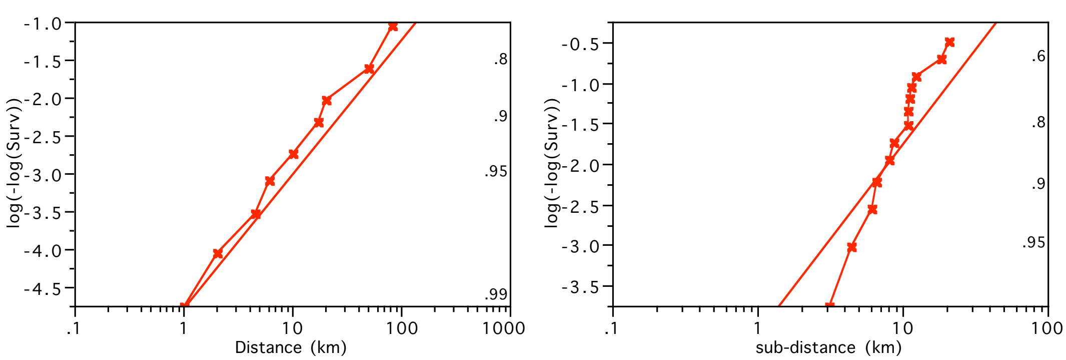
Table 1 The estimated parameters for the Weibull distribution for the missions before the upgrades (Group DEF) and for the post-upgrade missions (Group H).

Group	α	β	N_{fail}	$N_{censored}$	L95α	U95 α	L95 β	U95 β
DEF	483.1	0.776	9	109	173.4	5105	0.455	1.159
H	55.4	1.016	15	36	33.4	136.7	0.64	1.463

Examining the logs for missions 273-324, those after the upgrades, showed that 15 of the 51 missions that began suffered high impact faults when underway. This group we label Group H. Prior to the upgrades, over missions 123-240 (118 missions), 9 high impact faults were recorded. For consistency with Griffiths et al. (2003b) we label this Group DEF. Fitting a Weibull distribution to the post-upgrade data produced the parameter estimates listed in Table 1. Also listed are the parameter estimates for the missions prior to the upgrades. Figure 6 shows non-parametric Kaplan-Meier probability plots of high-impact fault occurrence for the groups of missions before and after the upgrades. These show the probability of survival for mission lengths of ~ 1 to > 100 km. Superimposed on the non-parametric plots are the "best fit" from the Weibull distributions. In both cases, these "best fit" lines lie to the right of the Kaplan-Meier estimates. This is not an error. Rather, the Weibull model takes into account the successful missions (censored data); that is, the missions that did not fail provide additional information. Including these censored data has the effect of increasing the modelled reliability compared to the Kaplan-Meier method, which only considers the missions that failed.

What is immediately clear is the much shorter characteristic life (α) for the post-upgrade missions: 55.4 compared to 483.1 before the upgrades. While these estimates of α have large standard deviations, Table 1 shows that the upper 95% confidence limit for αin Group H is less than the lower 95% confidence limit for Group DEF. Therefore, we consider that the characteristic life after the upgrades to be statistically different from the characteristic life before the upgrades. This implies that the high impact faults that occurred underway after the upgrades were not a random subset of the population of faults that had happened before the modifications. While this may seem to be stating the obvious, the statistical analysis does provide a reference against which the success of subsequent restorative and corrective work can be assessed.

To this end, we can assess how much trials time may be needed to demonstrate that the characteristic life has returned to its previous value (483) given a series of missions, where some high impact faults when underway could still occur. Of course, for a short series of missions even if the mean value of $\alpha$was acceptable, the 95% confidence limits would be large, reflecting the uncertainty in deriving the characteristic life from a small number of trials. In Table 2 three sets of trials missions are set out. Set A, with only two high impact faults when underway (on 5 and 12 km missions), meets the requirement for $\alpha > 480$. Set B does not; it has an extra failure on the 36 km mission. Following this failure, if two additional 144 km missions were run, as in Set C, then $\alpha > 480$ is again reached. As expected, the confidence limits on α are large and indicative of a highly non-normal distribution. However, if a transform $\log(\log(\alpha))$ is made, the distribution of α becomes reasonably normal and we can test the null hypothesis that the values of α for Sets A and C (the hypothetical missions after restorative work) are no different to Group H (before the corrective work was done).



(a) (b)

Figure 6 Probability of survival against mission lengths for Autosub (a) before the upgrades and (b) after the upgrades. The lines with crosses come from non-parametric Kaplan-Meier estimates, based only on the missions that failed. The solid straight lines are the Weibull model estimates that also use information from the missions that did not fail.

Calculating the z statistic gives z=2.18; as z > 1.645 we reject the null hypothesis at the 95% confidence level, accepting the alternative hypothesis that the values of α are indeed statistically different.

Table 2 also sets out the estimated time taken to complete these trails missions, based on a vehicle speed of 6 km.hr^{-1}, that for each hour in the water there would be an hour onboard the vessel, and that for each high impact fault when underway a time penalty of 8 hours would be incurred. Such trials will take place in late 2003.

5. Conclusions

The reliability of the Autosub AUV was reduced substantially by a major series of upgrades to its hardware and software in 2001-2. Two engineering trials in June and Sept-Oct. 2002 served to detect and correct many of the faults within the new software in the vehicle such that only three minor software errors were encountered on the science campaign in the Antarctic in 2003. For the reduction in reliability due to software, therefore, the trials cruises served their purpose; the reduction in reliability was temporary, and the vehicle returned to its pre-upgrade state for the science campaign.

That was not the case for key items of the new hardware. Some problems remained with the swath bathymetry sonar that, at times, reduced the quality of its data. Unresolved problems with the Doppler velocity log meant that bottom tracking was not achieved 100% of the time. The most serious problem, however, was not a direct consequence of the upgrades. Intermittent open circuits within the wet-matable connectors used throughout the vehicle, occurring mainly at depths greater than the vehicle had been used previously, had unpredictable consequences. Nevertheless, the error checking and emergency abort system within Autosub meant that the safety of the vehicle was not compromised, at least in open water. Strict adherence to operational procedures set out prior to the Antarctic campaign meant that under shelf ice missions would not have been attempted unless the vehicle was shown to be capable of operating at the necessary depths in open water. These procedures, and the thoughts behind them, raised formally in a Critical Items List, helped ensure that the vehicle returned to the UK where further diagnoses could take place. One consequence of the findings on the Antarctic cruise is that the entire set of wet-matable connectors will be replaced by those from another manufacturer before the vehicle is used again at sea.

Acknowledgements

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Table 2 Three hypothetical scenarios for Autosub trials missions that set out to re-establish α > 480 prior to the next polar campaign. The upper part of the table sets out the mission lengths. An (F) indicates that a mission failed. The 10th mission in set C comprises three segments of 144 km each. The lower part of the table sets out the Weibull distribution parameters and an estimate of the time needed for the missions of each set to be completed.

Mission (km)	1	2	3	4	5	6	7	8	9	10
Set	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)	(km)
A	5 (F)	5	5	12 (F)	12	12	36	72	144	144
B	5 (F)	5	5	12 (F)	12	12	36F)	72	144	144
C	5 (F)	5	5	12 (F)	12	12	36F)	72	144	144*3
Weibull	Set	α	β	N_{fail}	N_{censor}	L95α	U95 α	L95 β	U95 β	Time (days)
	A	632	0.54	2	8	74.7	7.5×10^8	0.11	1.36	7
	B	217	0.66	3	7	51.2	39223	0.20	1.41	7.25
	C	511	0.58	3	9	96.9	5.6×10^5	0.17	1.29	11

References

Copley, J. C., 2003. Available at: http://www.soc.soton.ac.uk/SOES/MSC/OC/CEO/aui/AUIriskregister270103.pdf

Griffiths, G., Millard, N.W. and Rogers, R., 2003(a). Logistics, risks and procedures concerning Autonomous Underwater Vehicles. In Griffiths, G. (editor), *The technology and applications of autonomous underwater vehicles*. Taylor and Francis, London, ISBN 0415-30154-8, pp. 279-293.

Griffiths, G., Millard, N. W., McPhail, S. D., Stevenson, P. and Challenor, P. G., 2003(b). On the Reliability of the Autosub Autonomous Underwater Vehicle. *Underwater Technology,* 25(4)

Millard, N.W., Griffiths, G., Finnegan, G., McPhail, S.D., Meldrum, D.T., Pebody, M., Perrett, J.R., Stevenson, P. and Webb, A.T., 1998. Versatile autonomous submersibles - the realising and testing of a practical vehicle. *Underwater Technology*, 23(1), pp. 7-17.

Millard, N.W. et al., 2003. Multidisciplinary ocean science applications of an AUV: The Autosub science missions programme. In Griffiths, G. (editor), The technology and applications of autonomous underwater vehicles. Taylor and Francis, London, ISBN 0415-30154-8, pp. 139-159.

O'Connor, P.D.T., 1995. *Practical Reliability Engineering*. Chichester, Wiley.

Stokey, R., Austin, T., von Alt, C., Purcell, M., Goldsborough, R., Forrester, N. and Allen, B., 1999. AUV bloopers or why Murphy must have been an optimist. *Proceedings of the 11th International Symposium on Unmanned Untethered Submersible Technology*, New Hampshire, 23-25 August 1999, AUSI, pp. 32-40.

Stevenson, P., Griffiths, G. and Webb, A. T., 2002. The Experience and Limitations of using Manganese Alkaline Primary Cells in a large Operational AUV. Proc. AUV 2002: *A workshop on AUV energy systems*, Piscataway: IEEE, pp. 27-34, ISBN 0-7803-7572-6/02.