RESULTS OF EXPERT JUDGMENTS ON THE FAULTS AND RISKS WITH AUTOSUB3 AND AN ANALYSIS OF ITS CAMPAIGN TO PINE ISLAND BAY, ANTARCTICA, 2009

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Abstract

Probabilistic risk assessment is a methodology that can be systematically applied to estimate the risk associated with the design and operation of complex systems. The National Oceanography Centre, Southampton, UK has developed a risk management process tailored to the operation of autonomous underwater vehicles. Central to the application of the risk management process is a probabilistic risk assessment. The risk management process was applied to estimate the risk associated with an Autosub3 science campaign in the Pine Island Glacier, Antarctica, and to support decision making. The campaign was successful. In this paper we present the Autosub3 risk model and we show how this model was used to assess the campaign risk.

1. Introduction

Risk and reliability assessment is an important exercise that guides a decision making process in any marine science, commercial or military exploration that involves the operation of underwater vehicles (AUVs). Traditionally, for a given campaign, the risk and reliability assessment is carried out by a group of experts on-board of the vessel; for example, in a marine science campaign the group of experts include science managers, engineers and the vessel operator. This process is highly subjective and often experts do not have access to statistical analysis of historical failure data. The National Oceanography Centre, Southampton, developed a risk management process tailored to AUV operations RMP-AUV[1]. This process model adds more formality to the risk assessment process (Griffiths and Trembranis, 2007a). The campaign risk estimation was an important factor in the management of Autosub3 operations for the joint UK-US campaign on the RV *Nathaniel B. Palmer* to Pine Island Bay, Antarctica in January 2009.

Autosub3 is an autonomous underwater vehicle designed and operated by the National Oceanography Centre, Southampton. The vehicle comprises complex mechatronics; the loss of a vehicle can be caused by one of many factors, for example: human error, environment factors and components faults, and these are often interrelated. Consequently in order to quantify the vehicle's reliability, we adopted a systems view, where faults caused by different sources were used to create a risk model for the system operation in four operating environments (open water, coastal, sea ice and ice shelf). The risk model was defined on the basis of 67 faults that emerged in previous Autosub3 operations, and expert judgements on the criticality of each fault (Brito, et. al, 2008). A formal judgment elicitation exercise was adopted, where faults were assessed by a group of 10 independent experts plus 3 internal experts. The experts were asked to assign a probability of loss given that a fault emerged in one of four possible operating environments; the experts were given a fault description and mission distance (Griffiths and Trembanis, 2007b). This paper briefly discusses the outcomes of the risk elicitation exercise. In short we will discuss:

- Graphical methods used to remove bias in the risk assessment process;
- Mathematical methods to aggregate expert judgments;
- Analysis of the most critical faults identified by the independent experts;
- A new Kaplan-Meier formulation to estimate AUV probability of survival with range.

Prior to the campaign to the Antarctic, the Principal Investigator was asked to provide a list of mission descriptions and distances, including distances under ice shelf and sea ice. In addition to quantifying the risk of

[1] Webpage: www.noc.soton.ac.uk/nmf/usl/gxg/RMP-AUV.html. [Accessed 12 July 2009].

each of these science missions, the new Kaplan-Meier formulation provided very good insight into possible mitigation strategies. The new formulation helped to devise an optimal monitoring distance for each science mission before committing to under ice shelf operation.

In the actual Pine Island Glacier (PIG) campaign Autosub3 carried out eight missions, 427-434. Six of these missions were successful science missions, two were test missions. Autosub3 covered 510km under the ice shelf. Mission 427 was a test mission; in missions 428, 429 and 430 Autosub3 covered approximately 180km under the ice shelf as planned. Whilst on mission 431 Autosub3 suffered a high impact incident when the vehicle was 55km into the ice shelf. Autosub3 risk model was used to assess the probability of losing the vehicle on the two outstanding missions. The risk was deemed acceptable and the mission was authorised by the responsible owner. Autosub3 survived the recent campaign to the PIG. In addition to discussing the risk analysis carried prior to the campaign to the Antarctic, this paper also reviews the risk assessment carried out after mission 431 that enabled the decision to continue the campaign.

The structure of the paper is as follows: section 2 provides a description of the risk management process. Section 3 provides a simple statistical analysis of Autosub3 failure history. Section 4 describes the formal judgment elicitation process followed in order to build the risk model. Section 5 gives insight of the graphical methods used for studying the expert judgments and briefly summarises the outcomes of the analysis. Section 6 explains how the expert judgments were aggregated. Section 7 lists the top critical hazards. Section 8 gives details concerning the survival statistical functions used to estimate Autosub3 probability of survival with range. Section 9 summarises the risk assessment conducted prior to the campaign to the PIG. Section 10 describes the process followed to update the campaign risk given the emergence of a critical fault whilst on mission 431. Section 11 provides a discussion of the results and highlights the benefits and shortcomings of the risk management process.

2. NOCS Risk Management Process

The NOCS RMP-AUV consists of 11 phases (Griffiths and Trembranis, 2007a). The acceptable risk (A) for a campaign is set by the AUV responsible owner, at the start of the process. This risk is expressed in terms of an acceptable probability of losing the vehicle. The acceptable risk is calculated based on the capital cost of the AUV, costs of operation, and replacement costs. The exact way in which these factors are combined to derive the acceptable risk is presented in (Griffiths and Trembranis, 2007a). In the second phase the campaign principal investigator (PI) sets the campaign requirements. These are expected to be presented in the form of a set of missions, and their distances, for a given environment (e.g. open water, coastal water, under sea ice or under ice shelf). In the third phase the technical team calculates the probability of loss for the proposed science campaign. The probability of AUV loss (L)[2] is calculated for each set of missions. If L is lower than A, then the missions set is authorised, otherwise, if L is greater than A, then the mission set is not authorised and the process directs the group (PI and engineers) to go through other phases that will either ensure that the missions set is accepted (because key risks were mitigated) or in the worst case scenario, it may lead the team to the conclusion that the mission set must be removed from the science plan.

The central task in applying the RMP-AUV is to determine probability of loss for the proposed science campaign, denoted as P(L) from hereafter. In a (hypothetical) case where there was a huge sample of previous Autosub3 missions in the same environment as the environment of the proposed mission, say a huge number of operations under ice shelf, with the same team, vessel and with the same sea conditions, and when vehicles had been lost, it would be possible to determine P(L) by simple frequency analysis. However such a databank does not exist for Autosub3. Subjectivist probability judgments provide a suitable alternative to the traditional frequency approach. The probability P(L) can be determined by human expert probability judgment. This discipline is called Probabilistic Risk Assessment (PRA). An early application of PRA was to estimate the probability of occurrence of major accidents in the nuclear industry. High profile accidents such as Chernobyl and Three Mile Island have accelerated the development of PRA approaches in this industrial sector (Apostolakis and Kafka, 1992).

3. Autosub3 Failure History

The Autosub3 risk model was designed based on experience gathered from 43 missions. Eleven of the missions resulted in no fault. The data was collected from five campaigns. Details of each Autosub3 campaign are given below:

- *Discovery* July 2005. AUV and other trials in Software approaches. Mission 384 to 387.

[2] As denoted in (Griffiths, Trembranis, 2007a).

- *Terscheling* May 2006 AUVtrials in Software approaches. Missions 388 to 389.
- *Discovery* June 2006. Biological measurements in NE Atlantic. Missions 400 to 404.
- *Terschelling* July 2006. Turbulence studies in the Irish Sea. Missions 405 to 408.
- *Terschelling* March 2007. Deepwater AUV reliability proving trials in Norway. Missions 409 to 422.
- *Terscheling* June 2008. Autosub3 reliability trials. Missions 423 to 426.

Table A.I in the appendix presents a list of missions with distances and number of faults.

The campaigns listed above took place in open water environment.

Figure 1 presents the pareto plot capturing the failure modes of Autosub3. Mechanical problems were the main cause for failure, they account for 20 instances, or approximately 30% (20/67) of all failures. This is in contrast to Autosub2 results, where 'mechanical problems' was the category with the least number of entries, 1 entry in 50 faults (2%) of the failures (Griffiths et al., 2003).

Also of interest is the fact that for Autosub3 (see Figure 1), the category 'human error' is the third (tied with 'bad GPS") most significant fault category, it accounts for 10% of all causes. For Autosub2, the 'human error' category accounts for 11 entries in 50 faults (22%) of all causes. This indicates a gain in human reliability, which may be explained by the more efficient operational practices used by the team.

It is also worth comparing the number of faults per mission and per km travelled for the two vehicles, Table I.

Table I Faults per mission and per km for Autosub2 and Autosub3.

Parameters	Autosub2	Autosub3
Number of missions	216	42
Number of faults	50	67
Number of km travelled	2125	2184.1
Number of faults per mission	0.23	1.60
Faults per km	0.024	0.031
Average km per mission	9.84	52.0
Mean distance between fault (MDBF) (km)	41.7	32.3
Mean time between fault (MTBF) (hrs)	7	5.4

The figures for MTBF comparable to those of unmanned aircraft vehicles (UAVs) used by the American Defence (OSD, 2003). Whilst the RQ-1A Predator presents a high MTBF of 32hrs other AUVs, such as RQ-2A Pioneer and the RQ-5 Hunter have a MTBF of 9.1hrs and 11.3hrs respectively.

The majority of Autosub3 campaigns had the purpose of improving the vehicle's reliability, the vehicle was put under severe tests, and thus it is not surprising that the number of faults per km has increased from Autosub2 to Autosub3. Of course, these figures do not tell us anything about the criticality of these failures.

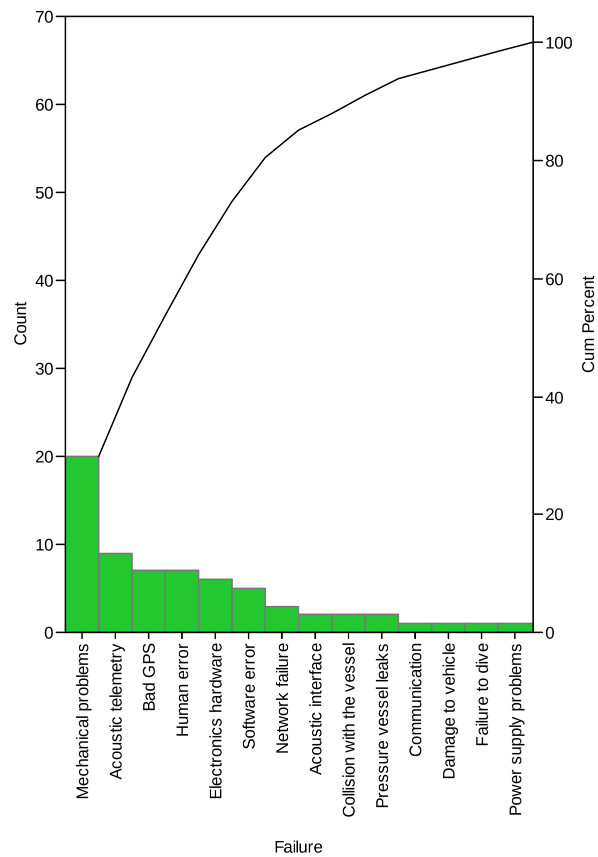

Figure 1 Pareto plot of Autosub3 failure modes for Missions 384-426.

4. Formal Judgment Elicitation Process

The Autosub3 risk model design was based on the probabilistic risk assessment provided by human experts. Such assessment is not error free. Research has shown that humans use mental shortcuts to assign probabilities to events, in the literature these are denoted as heuristics. Anchoring, representativeness and availability are three of the most debated heuristics (Tversky and Kuhenemann, 1986). Experts introduce biases when following one of these heuristics. It is generally accepted that the most effective way to reduce biases is by adopting a formal judgment elicitation process (Otway and Winterfeldt, 1992), (Keeney and Winterfeldt, 1991).

The judgements used for building the Autosub3 risk model were elicited via a formal judgment elicitation process (Griffiths and Trembranis, 2007b). This comprises seven sequential phases: 1) Setting out the issues; 2) Selecting the experts; 3) Training the experts; 4) Presenting the issue; 5) Analysis of the judgments; 6) Judgments aggregation; and 7) Write-up. Details of the results obtained in each phase of the elicitation process are given in Brito, Griffiths and Trembranis (2008). The process was inevitably time consuming and researchers have been working continuously on developing formal judgment elicitation process, that are both effective in reducing biases and can also be conducted in a short period of time (Griffiths, et al., 2009).

Table II presents the list of experts that took part in the risk assessment exercise for failures that occurred in missions 384-422. The experts were chosen for their experience in AUV operation. None of the experts works or has worked for NOCS. This ensures that there is a level of independence between the institution operating the vehicle and the experts. Ideally, the same experts should have assessed failures that occurred in missions 423-426. The judgments provided by the independent experts form the large proportion of the Autosub3 risk model. The last Autosub3 campaign, on board of *Terscheling* in June 2008, took place after the independent expert elicitation exercise. Thus faults that occurred on missions 423- 426 were assessed by NOCS AUV experts. Details concerning the experience of NOCS experts are presented listed in Table III.

Table II Experience of experts in EEJ(Annex A) group. Experts' names are abbreviated.

Expert	Application area	Years of experience
AS	Scientific research	1.5
BF	Military	8
CJ	Scientific research and Military	11
CW	Scientific research	10
DY	Scientific research	15
MM	Scientific research	6
RM	Scientific research	9
TC	Scientific research, Military and Commercial	20

Table III Experience of experts in EEJ (GG, PS, SM) group. Experts' names are abbreviated.

Expert	Application area	Years of experience
GG	Scientific research	22
PS	Scientific research	18
SM	Scientific research	15

The experts were asked to answer the following question: "What is the probability of loss of the vehicle in the given environment E given fault/incident F?". This questionnaire is refereed to as Annex A (Griffiths and Trembranis, 2007b). The experts provided judgments for all 67 faults.

5. Analysis of the Expert Judgements

Two people may have different, and defensible, views about the same problem. This is no different when it comes to assigning probability to events. Experts may disagree on the probability of an event taking place, or, in the RMP-AUV case, the probability of a failure leading to loss. When there is a huge disagreement between experts, rather than dismissing their hypothesis, one should try to understand the reason why experts do disagree. If both viewpoints are equally valid, the statistical model should somehow include both judgments.

In addition to the probability judgments, the experts also provided a narrative describing the reasoning in support for their judgements. The longitudinal distribution of the probability judgments provides a good insight as to when experts do disagree with respect to the probability judgments. Figure 2 presents the longitudinal distribution of the probability judgments, for a fraction of failures, in open water environment. A full longitudinal probability distribution, for all environments, is presented in Annexes D and I of (Brito et al., 2009). Fifteen recommendations (four for open water environment, two for coastal water, four for sea ice and five for ice shelf) were raised in that report.

The cumulative distribution of an expert's probability judgments provides a visual means to easily identify: 1) whether the expert tends to use lower or upper probability ranges; 2) how the expert probability ranges vary across different environments; and 3) how does an expert's cumulative distribution compares with another expert's cumulative distribution, in terms of shape and probability ranges. It was decided to use nine classes for probability ranges: [0, 0.0001], [0.0001, 0.0003], [0.0003, 0.001], [0.001, 0.003], [0.003, 0.01], [0.01, 0.03], [0.03, 0.1], [0.1, 0.3], [0.3, 1.0]. This set of classes would allow us to capture judgments of all order of magnitude. Since that no expert provided judgments between 10^-5 and 0, there was no need to create a suc a class. Figure 3 shows the cumulative distribution for the frequency in which experts use each class, for sea ice environment.

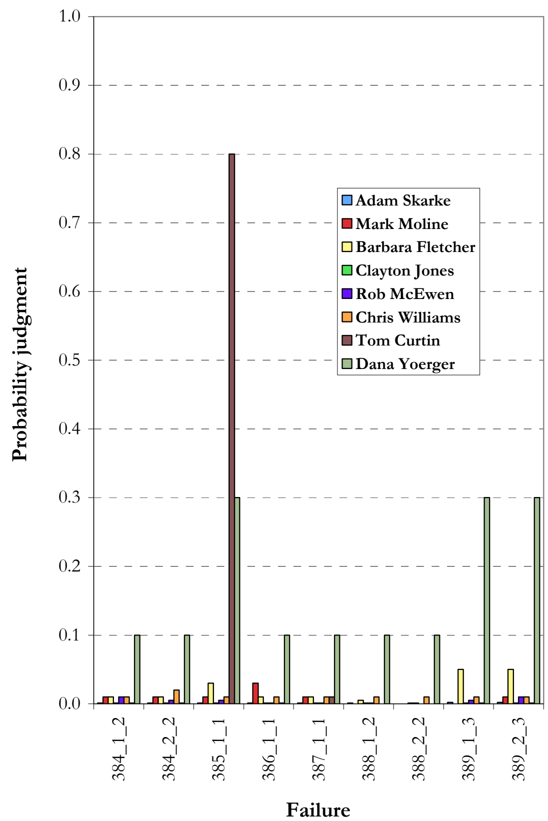

Figure 2 Longitudinal distribution for the probability judgments provided for open water. Only nine failures are presented of a total of sixty three.

Figure 3 shows that, for sea ice, expert CW does not use probability ranges lower than 0.1. CW probability judgments exhibit a similar distribution for open water, coastal and ice shelf (Brito, et al. 2008). This suggests a bias toward much higher risk in this expert's judgments.

In addition to providing insight concerning probability ranges used by experts, the analysis carried out using the cumulative distribution also highlighted a phenomenon that might otherwise be ignored.

Figure 3 shows that judgements for experts that often use lower probability ranges follow a narrow 'S' shape, whereas the judgments for experts that often use higher probability ranges follow a broad 'S' shape. This lead to the conclusion that, when it comes to assigning probability to events, there are two schools of thought, the optimists (those experts whose probability distributions follow a narrow 'S' shape) and the pessimists (those experts whose probability distributions follow a broad 'S' shape).

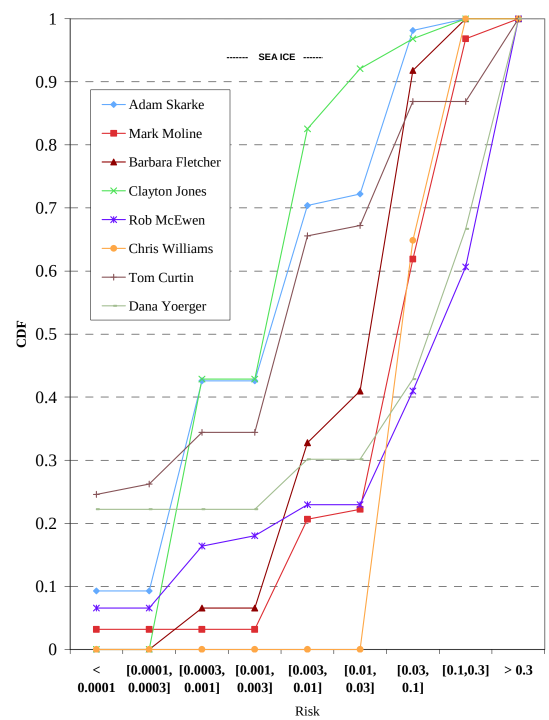

Figure 3 Cumulative distribution of expert judgments over nine different ranges.

The mean and standard deviation for each expert is given in Table IV.

Table IV Mean and standard deviation for the sixty three judgments provided by each expert. Results are presented for all four operating environments: open water, coastal water, sea ice and ice shelf.

		Experts							
		Adam Skarke	**Mark Moline**	**Barbara Fletcher**	**Clayton Jones**	**Rob McEwen**	**Chris Williams**	**Tom Curtin**	**Dana Yoerger**
Open water	Mean	0.00210	0.0105	0.0157	0.00284	0.00256	0.0452	0.0215	0.0722
	Std Dev	0.00638	0.0211	0.0173	0.00875	0.00642	0.104	0.101	0.0704
Coastal water	Mean	0.0113	0.0257	0.0157	0.00313	0.00625	0.0313	0.0214	0.0984
	Std Dev	0.0331	0.0506	0.0174	0.00884	0.0106	0.0322	0.0893	0.111
Sea ice	Mean	0.0179	0.116	0.0513	0.0166	0.282	0.0778	0.111	0.229
	Std Dev	0.0357	0.0917	0.0532	0.0381	0.232	0.0745	0.239	0.219
Ice shelf	Mean	0.2486	0.355	0.0720	0.0706	0.393	0.337	0.203	0.371
	Std Dev	0.301	0.346	0.101	0.168	0.324	0.421	0.325	0.394

6. Aggregating Expert Judgements

Once the expert judgments have been studied for discrepancies and misunderstandings, the next step is to aggregate the expert judgments. The end result of judgment aggregation is a single probability judgment for each failure or incident.

Expert judgment aggregation is an active research field for social scientists and cognitive psychologists. Expert judgments can be aggregated in a mathematical or a behavioural fashion (Winkler, 1968), (Clemen and Winkler, 1999). As the name indicates, mathematical aggregation methods use mathematical formulations to analytically aggregate individually elicited expert judgments . For behavioural aggregation methods on the other hand, experts are supposed to be in the same room and they are supposed to agree on the final judgments. The risk model presented in this paper was created based on the linear opinion pool mathematical aggregation method:

$$p(\theta)=k\sum_{i=1}^{n} w_i\, p_i(\theta) \quad with \quad k=\frac{1}{\sum_{i=1}^{n} w_i} \qquad 1.$$

The linear opinion pool was used to create two models per environment (one optimistic and one pessimistic). Table II lists the experts used by each model.

Table V Judgments used for the risk model, for four environments.

Model		Experts
Open water	Optimist	MM,CJ,RM,TC and AS
	Pessimist	BF, CW and DY
Coastal	Optimist	AS, CJ, RM and TC
	Pessimist	BF, MM, CW and DY
Sea ice	Optimist	TC, CJ and AS
	Pessimist	MM,BF, RM, CW and DY
Ice shelf	Optimist	CJ and TC
	Pessimist	AS,MM,BF,RM,CW and DY

7. Most Critical Failures for Ice shelf Environment

When possible, risk mitigation can be achieved by removing failures, or hazards, from the system. This could be a result of design improvements or of optimisation of operation practices. The top five critical failures for under ice shelf operations are listed in Tables V and VI, the first for the optimistic and the second for the pessimistic experts.

Table V Top five critical failures for ice shelf environment. Optimistic model, missions 384-422. The aggregated probability of loss is in bold and italic.

Mission	***Fault description***
395_1_1	*Jack-in-the-box line came out, wrapped around the propulsion motor and jammed.* ***0.9786***
402_1_5	*Stern Plane stuck up during attempt to dive, 2d 20h into mission. Stern plane actuator had flooded.* ***0.8929***
402_2_5	*Abort due to network failure. Abort release could not communicate with depth control node for 403s. Possibly side-effect of actuator or motor problems.* ***0.7333***
385_1_1	*Autosub headed off in an uncontrolled way, due to a side effect of the removal of the upwards-looking ADCP.* ***0.6500***
415_1_3	*Prior to dive, checks showed reduced torque on rudder actuator. Actuator replaced with new one - first use for this new design of actuator motor and gearbox. However, AUV spent most of mission "stuck" going around in circles at depth due to rudder actuator fault. The new actuator overheated, melting wires internally, the motor seized, and internal to the main pressure case, the power filter overheated. Some of the damage may have been caused by an excessive current limit (3A); correct setting was 0.3A. But this does not explain high motor current. Possible damage during testing when motor stalled on end stop? Compounded by wiring to motor held tightly to case with cable ties, and worse, covered with tape (acting as an insulator). Wires were not high temperature rated.* ***0.4143***

Table VI Top five critical failures for ice shelf environment. Pessimistic model, missions 384-422. The aggregated probability of loss is in bold and italic.

Mission	***Fault description***
384_1_2	*Mission aborted (to surface) due to network failure. (Much) later tests showed general problem with the harnesses (bad crimp joints).* ***0.8389***
395_1_1	*Jack-in-the-box line came out, wrapped around the propulsion motor and jammed.* ***0.8293***
385_1_1	*Autosub headed off in an uncontrolled way, due to a side effect of the removal of the upwards-looking ADCP.* ***0.7842***
402_2_5	*Abort due to network failure. Abort release could not communicate with depth control node for 403s. Possibly side-effect of actuator or motor problems.* ***0.7611***
402_3_5	*Motor windings had resistance of 330 ohm to case. Propeller speed dropping off gradually during a dive.* ***0.7250***

The probability judgments for failures that occurred in missions 423-426 were provided by NOCS' AUV experts. The judgements were aggregated using the linear opinion pool. A list of the top critical failures for these missions and the respective judgments is presented in Table VII.

Table VII Top five critical failures for ice shelf environment. Pessimistic model, missions 423-424. The aggregated probability of loss is in bold and italic. The same judgment was provided for optimistic and pessimistic model.

Mission	Fault no.	Aggregated judgment on the probability of loss			
		Open water	Coastal	Sea ice	Ice shelf
423	1	0.01	0.01	0.003	0.001
423	2	0.01	0.01	0.003	0.001
424	1	0.001	0.001	0.001	0.001
426	1	0.001	0.001	0.05	0.67

8. Survival Statistics

Simple statistics such as those presented in section 3 are useful for describing the vehicle's performance and to help in setting long term reliability targets. However, such statistics, alone, are not sufficient for supporting operational risk management. Operational risk management is better supported by the use of survival statistics (Griffiths, et al., 2003). Survival statistical functions can be used to estimate the AUV probability of survival with time or with range, as the two are dependent range will be used hereafter. Survival statistical methods can be either parametric or non parametric. In order to apply a parametric survival function one needs to: first define a lifetime table; and second, fit a parametric function such as Weibull to the data on the lifetime table. Non-parametric survival models do not make any assumption with regard to the shape of the survival function, they use analytical methods to manipulate the data (Kalbfleisch, 1980), (Kaplan and Meier, 1958).

The Autosub3 probability of survival with range was obtained using an extended version of the Kaplan Meier estimator:

$$\hat{S}(r) = \prod_{r_i<r} 1-\left(\frac{1}{n_i}\right)P(e_i) \qquad 2.$$

S is the probability of survival; r the range in km; n_i is the fault index and $P(e_i)$ is the probability of loss.

The Kaplan Meier survival distribution for ice shelf is presented in Figure 4.

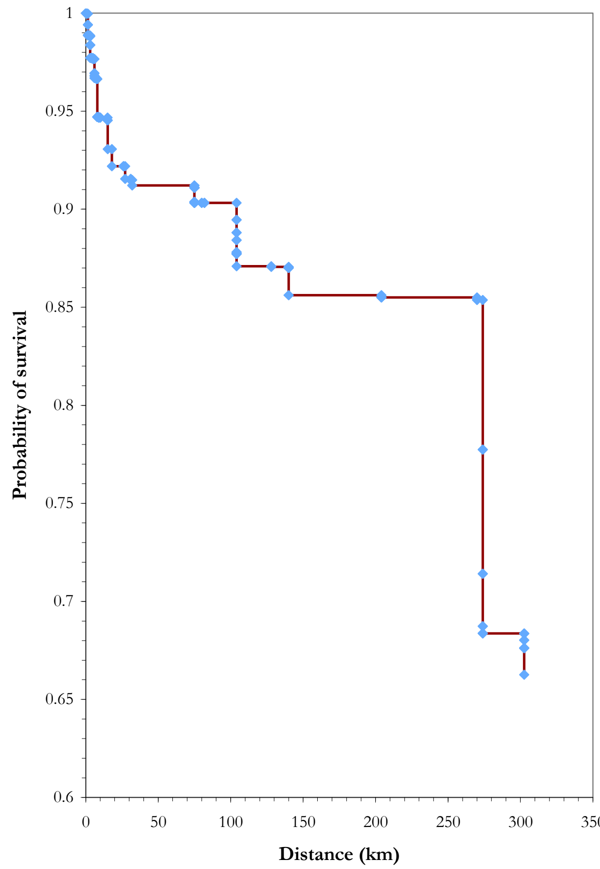

Figure 4 Kaplan Meier survival distribution for ice shelf environment. Optimistic model, missions 384-422.

The shape of the Kaplan Meier survival distribution is similar for all environments, but as predicted, the steps are smaller for more benign environments, e.g., open water, coastal and sea ice.

The figure shows that there is a steep decrease in probability of survival (approximately 0.1) in the first 30km, which is followed by a stretch of approximately 70km where the probability of survival decreases 0.02. In practical terms this means that if one manages to monitor the vehicle for the first 30 km, then the probability of surviving the first 70km under an ice shelf is approximately 0.98, given that it has survived the first 30km.

The use of a monitoring distance provides means for reducing the probability of losing the vehicle to acceptable levels. The condition probability function presented in [3] was used to accurately quantify the gain in probability of survival:

$$P(X < x \mid X > y) = \frac{F(x)-F(y)}{1-F(y)} \qquad 3.$$

where the expression to the left represents the probability of surviving distance X given that it has survived distance Y. F(x) is the probability of surviving distance X and F(y) stands for the probability of surviving distance y.

The conditional probability expression in [3] is not suitable for calculating the gain in probability of survival when this probability of survival is expressed in the Kaplan Meier form as a step function. The reason for this is because for most situations F(x) equals F(y) and therefore the gain in probability of survival is calculated to be zero, which is not the case. Thus a different survival function had to be used; this survival function would have to allow the quantification of gain in probability of survival given that a monitoring distance was introduced. The Weibull survival function meets this requirement (Brito et al., 2008).

The following two sections show how this approach was used to mitigate the risk of loosing Autosub3 in the campaign to the Pine Island Glacier.

9. Pine Island Glacier, Antarctica: Pre-Campaign Risk Assessment

9.1 Purpose of the Campaign

The main goal of the campaign was to gather data that would help determine how the warm Circumpolar Deep Water (CDW) gets beneath the glacier and how it determines the rate at which the glacier melts. Three subsidiary objectives had to be met: 1) map the seabed beneath the glacier; 2) map the underside of the glacier; 3) and determine where and how heat is transferred from the inflowing CDW to the outflowing ice-ocean boundary layer.

Figure 5 shows the track chart of Autosub3 mission 434 superimposed on a satellite image of the glacier. The original plan was to send the AUV on six missions, three 30km under the ice shelf and three 60kms under the ice shelf.

The planning for waypoints and profiles was guided by a combination of data, which included: ice thickness collected by radar sounding, sea bed soundings from cruise NBP0402, and multi-beam data collected over the course of NBP0901 from seaward of the glacier. It was originally assumed that the sea bed was fairly flat.

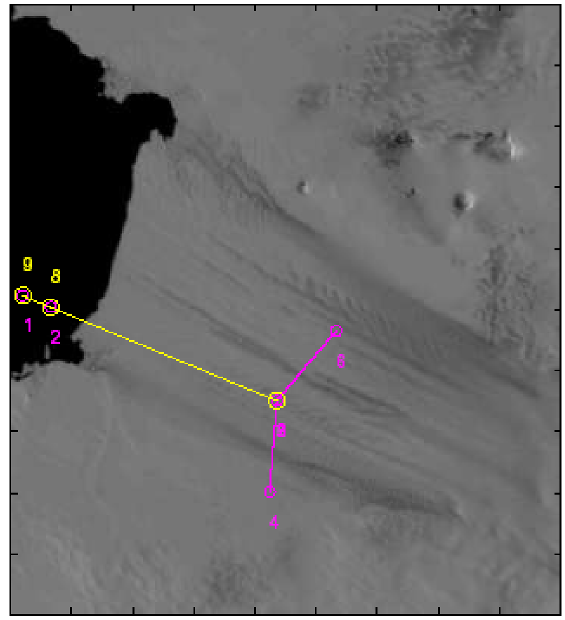

Figure 5 Autsub3 Mission 434. Autosub3 went 45km into ice, turned south for 10km at 200m altitude then return to turn point at 100m altitude, then went north for 10km at 100m altitude, returned to turn point at 200m then returned to safe way point profiling from 500 to 900m depth.

9.2 Operational Requirements

The campaign requirements for Autosub3 were set by the Principal Investigator, Dr. Adrian Jenkins, British Antarctic Survey (BAS) (Jenkins, 2007).

Dr. Jenkins provided the minimum and the desirable set of missions. These missions consisted of a combination of several open water and under sea ice missions in the Amundsen Sea and ice shelf missions under Pine Island Bay glacier. A brief description of the requirements for each mission set is given below:

- *Scenario 1* – Minimum set with no fast ice: 1) Three 60 km open water missions and 2) Three 60 km missions under outer half of the ice shelf cavity.
- *Scenario 2* – Minimum set with fast ice: 1) Three 120 km under fast ice missions; and 2) Three 120 km missions: 60 km under fast ice and 60 km under outer half of the ice shelf cavity.
- *Scenario 3* – Desirable set with no sea ice: 1) Three 60 km open water missions; 2) Three 60 km missions under outer half of the ice shelf cavity; and 3) Three 120 km missions under ice shelf cavity.
- *Scenario 4* – Desirable set with fast ice: 1)Three 120 km under fast ice missions; 2) Three 120 km missions: 60 km under fast ice and 60 km under outer half of the

ice shelf cavity; and 3) Three 180 km missions: 60 km under fast ice and 120 km under ice shelf cavity.

Scenario 1 and 3 consider that there is no sea ice in front of the glacier; this would be the ideal scenario. However it is also possible to encounter sea ice in front of the glacier, scenarios 2 and 4 were introduced to capture this, more likely, scenario.

The Autosub3's responsible owner, the NOCS Director, was asked to define an acceptable probability of loss for each mission set. The figures provided by the Director were as follows: 1) Scenario 1: A = 0.1; 2) Scenario 2: A = 0.17; 3) Scenario 3: A = 0.20 ; and 4) Scenario 4: A = 0.23. Based on the risk analysis scenarios 1-4 must be less than the acceptable probability of loss defined by the Director.

9.3 Risk Assessment

The Kaplan Meier survival function was used for estimating the probability of Autosub3 surviving the campaign to the Antarctica. The probability of losing the vehicle was calculated for all four scenarios. Table VIII provides a summary of the results.

Table VIII Probability of losing Autosub3 based on Kaplan Meier estimator (first row) and based on Weibull function (second row). Optimistic on the left and pessimistic on the right. No monitoring distance mitigation is considered.

Estimator	Scenario 1	Scenario 2	Scenario 3	Scenario 4
K-M	0.26 - 0.56	0.40 - 0.81	0.53 - 0.86	0.64 - 0.96
Weibull	0.29 - 0.63	0.47 - 0.85	0.57 - 0.90	0.72 - 0.97

The initial risk estimates were deemed too high for the campaign. The calculated risk for all scenarios exceeded the accept risk level defined by the NOCS Director. Thus, the subsequent analysis aimed at finding risk mitigation strategies. The following two actions were taken in order to mitigate the risk:

1. Re-design of the servo-actuator that caused fault in mission 402. This fault has been completely understood and removed from the system. Judgments for faults in mission 402 were therefore removed from the database.
2. Introduction of a monitoring distance.

The risk assessment presented in this section was conducted prior to the Autosub3 campaign to Norway. It was assumed that the Autosub3 would survive 10 missions of 5km range, with no faults.

Our analysis showed that the campaign risk would meet the Director requirements if a monitoring distance of 28km was set for scenario 1, 33km for scenario 2, 43 km for scenario 3 and 48km for scenario 4.

10. Pine Island Glacier, Antarctica: Post-Campaign Risk Assessment

10.1 Vehicle Configuration

A detailed description of Autosub3 is given elsewhere in the literature (Stevenson et. al, 2003), (Pebody, 2008). In brief, Autosub3 is a 6.7m long autonomous underwater vehicle (AUV). The vehicle is 0.9m diameter and it weights 3.6 tonnes, has an operating depth of 1600m and a range of 400km at a forward speed of 1.7ms^{-1}. Figure 6 depicts Autosub3 whilst in the container.

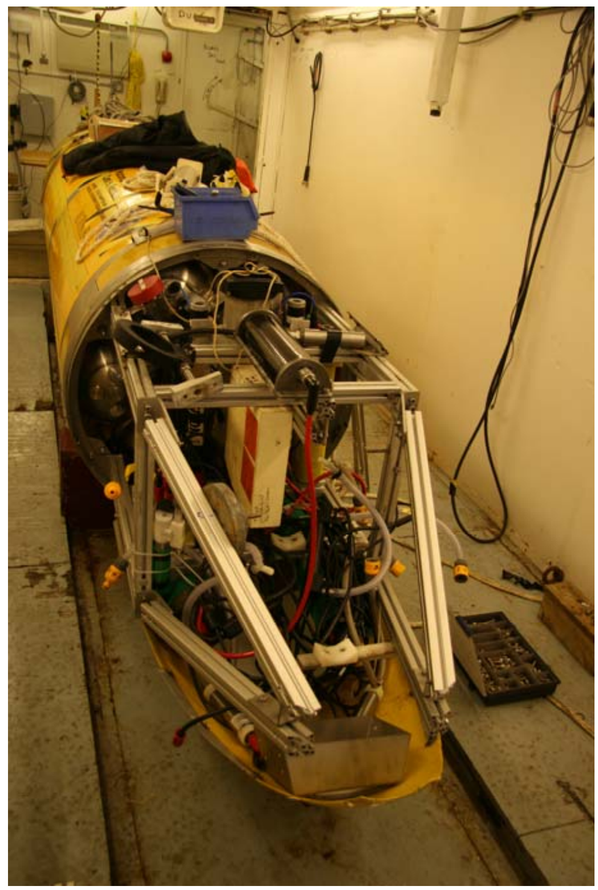

Figure 6 Autosub3 getting reading for mission 432, under the Pine Island Glacier

The vehicle structure is divided in three main sections. The front section houses most of the science sensors, the middle section houses the alkaline batteries and the rear section houses the motor controls and other systems for the navigation of the vehicle.

In order to carry out this campaign the vehicle was fitted with a special suite of sensors, the vehicle payload included: Sea bird CTD, with dual C and T sensors plus dissolved oxygen sensor and transmissometer; Kongsberg EM2000 multi-beam echo-sounder; upward-looking Teledyne RDI 300 kHz ADCP; downward looking Teledyne RDI 150 kHz ADCP.

10.2 Missions 427-430

On arrival at Pine Island Bay there was, unusually, no sea ice present, and the decision was to run scenario 1 followed by the remaining missions to give the desirable set, scenario 3.

Mission 427. This was a test mission. Autosub reached a maximum depth of 836m and it travelled approximately 37.5km. Minor failures were discovered, such as the CTD appeared intermittent. Corrective actions were taken to address these minor faults. Figure 7 presents an overview of mission 327's track.

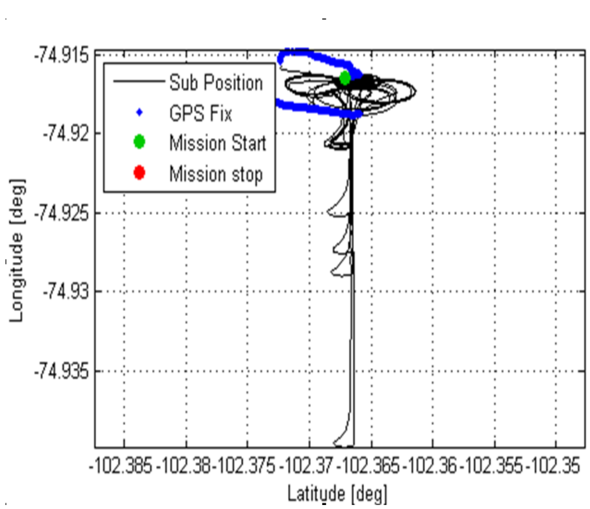

Figure 7 Overview of Autosub3 mission 427. The starting point and the ending point are superimposed. Coordinates for the starting point were (-74.9164 lat, -102.3671 long); the coordinates for the ending point were (-74.9179 lat, -102.3737 long).

Mission 428. First under the ice shelf mission. The mission started with a 2hrs test mission, followed by data retrieval and checking. Autosub3 took approximately 18.4 hrs to cover 101 km, 60km under ice-shelf (30km on the way into the cavity plus 30km on the way out of the cavity). The AUV run into the ice shelf at 200 m constant altitude, then turn and 100 m up altitude.

Figure 8 depicts the path taken by Autosub3 during this mission. Missions 429 and 430 were similar in the sense that that same distance was covered under the ice shelf and the same altitude was set for different phases of the mission. On mission 429, Autosub3 took 21hrs to cover 113 km and in mission 430 Autosub3 covered 107 km in 19hrs. All missions were successful, and Autosub3 collected good data. Figure 8 provides a 3D plot of Autsoub3 trajectory for mission 428.

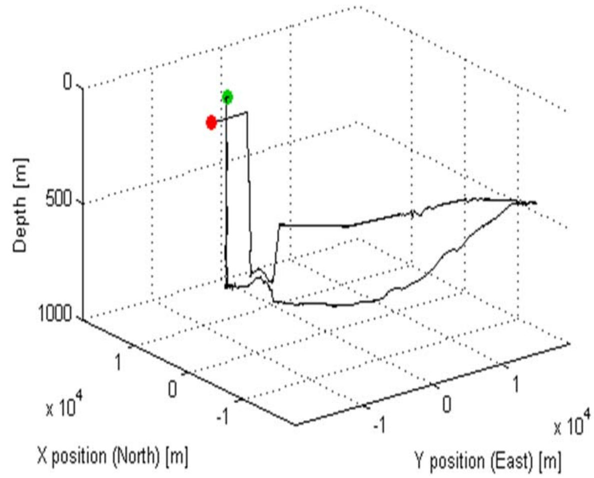

Figure 8 Overview of Autosub3 mission 428. The starting point is in green, and the ending point is in red. Coordinates for the starting point were (-74.9950 lat, -101.8029 long); the coordinates for the ending point were (-75.0364 lat, -102.0086 long).

10.3 Mission 431

Mission 431 was intended to be the first mission of the second set of missions in Dr. Jenkins scenario 3. A description is given below:

Mission 431. Fourth under ice shelf run. The objective was to run 60km into the glacier at 100m altitude, turn when reached position or collision avoided. The AUV travelled for approximately 183km and reached a maximum depth of 978m. However, the mission was aborted 55km from the ice shelf edge. The mission terminated early due to the emergency exception being called (failed collision avoidance). The vehicle suffered structural damage due to collision with ice but managed to navigate its way to the rendezvous point in open water. The damaged was caused to the Port CTD plumbing; and to the Linkquest transducer bulkhead connector (the telemetry system was working properly on recovery).

Figure 9 Autosub3 post mission 431. Damage to the nose is visible on the left hand side of Autosub3. Courtesy of Mr. Steve McPhail (NOCS).

10.4 Updated Science Requirement

During mission 431, Autosub3 discovered a substantial transverse ridge, ridge some 300m high. This was an important discovery for glaciology and oceanography under the ice sheet. As a result two missions were requested by the PI to further study the characteristics of this ridge.

The following two missions were requested, as the 30km missions turned around before the ridge was fully delineated:

1. A run on the north side of the cavity to ~50km from the ice edge, not attempting to get near the grounding line, the end point determined by waypoint, with the back up of a water cavity thickness parameter. This run would use bottom track in and out, ice track would not be called for. But, if the water cavity thickness limit was reached before the waypoint specified, this would require the upward ADCP to be working correctly. Under ice distance would be ~100km.
2. A run in of ~30km to the ridge crest then a transverse run of ~30km followed by a ~30km run out, all in bottom track. Under ice distance would be ~100km.

10.5 Updated Risk Assessment

The collision on mission 431 presented a huge problem to the science campaign. The failure was fixable and damaged components were easily replaced. However given that Autosub2 was lost under the Fimbulisen in 2005, given the high risk of the operation and given the importance of the new discovery, the research team faced a dilemma; should the campaign pursue the remaining missions or should the campaign be interrupted. This called for re-assessment of the risk.

Three NOCS experts (details of whom are present in Table III) provided judgments for faults on missions 429 and 431, these judgments were aggregated based on averaging. A summary of the results is presented in table IX.

Table IX Risk Assessment conducted by NOCS experts on faults that emerged in missions 427-431. Missions where there have been no faults have been censored.

Mission	Fault no.	Aggregated judgment on the probability of loss
427	0	0
428	0	0
429	1	0.01
430	0	0
431	1	0.58

These judgments were added to the risk model. The Weibull survival distribution

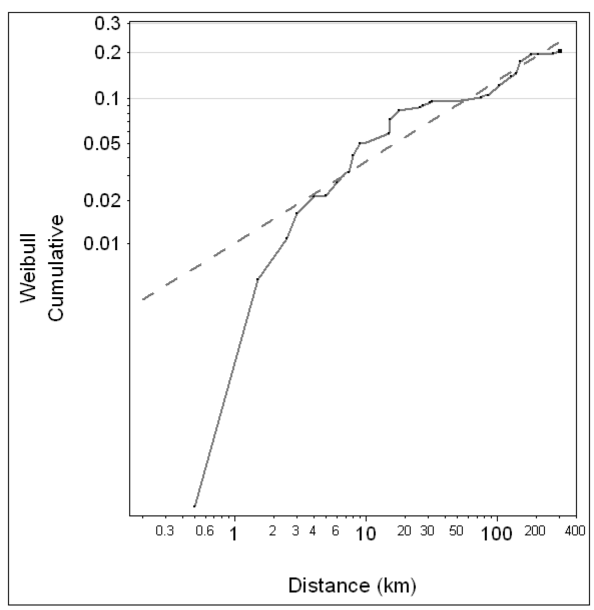

Figure 10 Weibull survival distribution of the updated risk model. With a scale parameter of 3055 and a shape parameter of 0.5716.

Using the Weibull survival function presented in Figure 10, it was estimated that the risk of loss on each of the missions outlined in 10.4 was ~5% based on a distance of 100km under shelf ice and a monitoring distance of 48km. The risk of loss for the two missions being 9%.

10.6 Missions 432-434

Following the risk assessment presented in the previous section, the NOCS Director decided to authorise the proposed new set of missions. The text below gives a brief description of these missions.

Mission 432. Post-collision test mission. The vehicle covered 27.2km and reached a maximum depth of 888m. No failures noted. Figure 11 presents an overview of the mission.

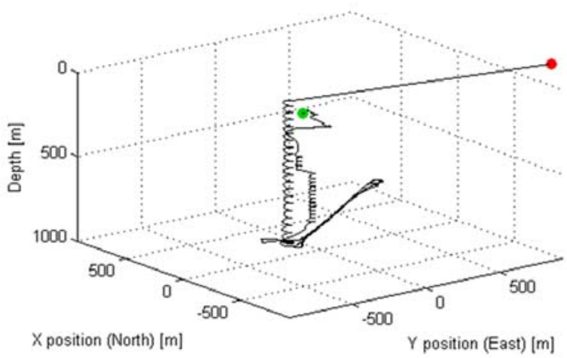

Figure 11 Overview of Autosub3 mission 432. The starting point is in green, and the ending point is in red. Coordinates for the starting point were (-74.9637 lat, -101.9238 long); the coordinates for the ending point were (-74.9644 lat, -101.8672 long).

Mission 433. Successful science mission. The vehicle travelled 157km; it reached a maximum depth of 903m. Autosub3 went 55km into ice shelf at 100 m altitude. Turn on minimum headroom setting. Profile out the last 30 km.

Mission 434. Successful science mission. The vehicle travelled 167 km: 45km into ice, turn south for 10km at 200m altitude then return to turn point at 100m altitude, then go north for 10km at 100m altitude, return to turn point at 200m then return to safe way point profiling from 500 to 900m depth. Battery changed pre mission.

11. Discussion

The NOCS risk management process tailored for AUV operations was successfully applied to estimate the risk of an Autosub3 science campaign to the Pine Island Glacier, Antarctica.

The risk model was developed based on expert judgments on the probability of a fault leading to AUV loss. A total of 69 faults were considered by the experts. The independent experts provided judgments for 63 faults (92% of all faults). NOCS AUV experts provided judgments for 6 faults (8% of all faults).

Autosub3 survived the mission to the PIG because of its good reliability, which is a result of many years constant improvement of its design and operational processes. However, if one does not know how reliable the vehicle is, one is in a vulnerable position where it would be a guess as to whether or not the vehicle would survive a mission or a campaign.

Often the task of risk assessment has a negative connotation; the general impression is that the risk exercise is typically conducted to support an argument that will stop a mission or activity from taking place. Here we showed how the risk model can be used for building an argument in favour of a mission or a deployment. So it stops being a case of avoiding risks and it becomes more the case of choosing between risks. The RMV-AUV uses risk quantification to enable rational decision making.

The risk assessment should be conducted well before the start of the campaign; this was the case for our initial assessment. However, once the risk model has been set up it can be systematically applied to support real time decisions. This is the huge benefit of this approach. When operating in extreme environments it is not unusual for the environment or other circumstances to change. A flexible risk assessment approach should be able to update the risk estimates whenever this is the case.

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APPENDIX A

Table A.1 Autosub3 failure history. A detailed failure description is given in (Brito, Griffiths and Trembanis, 2008).

Mission	Distance (km)	Number of Failures
384	1.5	2
385	15.2	1
386	26	1
387	27.2	1
388	0.5	2
389	3	3
390	10	0
391	31	3
392	32	1
393	5	1
394	3	1
395	8	1
396	4	1
397	4	1
398	8	1
399	7	0
400	4	0
401	7.5	2
402	274	5
403	140	3
404	75	7
405	2.5	2
406	104	7
407	204	2
408	302.5	5
409	1.5	1
410	9	1
411	128	1
412	270	2
413	0.2	0
414	7	0
415	6	3
416	18	1
417	80	0
418	15	1
419	80	0
420	8	0
421	9	0
422	4	0
423	0.5	2
424	181	1
425	53	0
426	15	1

APPENDIX B

Table B1 Fault description for missions M423, M424, 426. Terscheling July 2009.

Mission	Fault no.	Description
423	1	Logger – LonWorks Interface card. The failed to start properly pre missions 423. The system reported problems with the (LonWorks) network card interface. Following discussions with James Perrett, who remembered similar problems with Autosub2, we increased the supply voltage of the logger from 4.97 volts to 5.1 volts, by means of a potential divider from the supply to the sense+ line on the SMPS. Also increased the power supply capacitance from 470 to 2000 mF.
423	2	Autosub WiFi Access Point failed to connect. Despite a strong signal, the Netgear Access point in the AUV was unable to connect to the network at the end of mission 424. Cured by using the Netgear configuration utility, and setting the "Country" to "Canada", and then back to "Europe". This has the effect of resetting the access point, after which it connects normally.
424	1	GPS receiver fault. Following pre launch checks (M423), the AUV GPS receiver failed to get GPS fixes. Two other antennae were tried with no success. During the trails, with little spare time, we decided to work around this problem by sending the AUV its position through the WiFi radio.
426	1	On Mission 426, the mission stopped prematurely after 3 hours running time. The "Mission Timer" had been set at 3 hours by the configuration tool. It should have been (automatically) set to the release abort system time of 14 hours. This is a serious vulnerability in the configuration tool. It seems likely that best action is to remove the timer from the mission control system.